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# ICT diffusion and environmental sustainability, 2nd edition

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# ICT diffusion and environmental sustainability, 2nd edition

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# Physical education and emergency response system using deep learning: A step toward sustainable development of physical education environment

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The physical education (PE) system's key goal is to educate individuals and the large community of participating students to achieve self-fulfillment. Deep learning uses integrated expertise to help students master challenging conditions in unfamiliar contexts. It is normal to get injuries while training or playing, and as an emergency response to mitigating students' future risks by the availability of first aid, safety steps are promptly taken. Therefore, this article suggests a "physical education and emergency response system using deep learning" (PSERS-DL) to handle such situations effectively. In real-time, the PE environment can be tracked using a global positioning system-enabled surveillance system to immediately provide the wounded student with protective measures. The acquired visuals are immediately analyzed using a deep learning model, convolutional neural network (CNN). The 27 layers proposed in the CNN model have been evaluated compared with other deep learning models. The simulation results showed that the proposed PSERS-DL can assure the emergency response with the highest accuracy of 97.61%. The experimental results showed that the proposed PSERS-DL model enhances an accuracy ratio of 95.6%, a performance ratio of 97.6%, movement detection analysis ratio of 96.3%, a learning rate of 95.2%, an efficiency ratio of 98.1%, a security ratio of 93.5%, a delay time ratio of 33.2%, and a behavior analysis ratio of 90.7% when compared to other existing approaches.

KEYWORDS

**deep learning, emergency response system, physical education, students, sustainable development**

## 1 Introduction

Physical education is intended to improve students' physical experiences, competencies, safety, and capacity to use them in a broad range of wellness behaviors. Physical education is commonly understood as an organization of events in athletics, sports, or physical training (Lakhani & Sundaram, 2017). During such events, it is found that most students are either left to play the matches in their way or taken to the field

where they practice various sports without the teacher's instruction or supervision (Manogara et al., 2018; Raizada et al., 2021). All these experiences together provide an essential comprehension of the idea of physical education (Abdel-Basset, et al., 2019). Physical education is focused on physical fitness and the ability to conduct and relish daily physical exercise (Wang et al., 2016; Li et al., 2020). Children gain the skills required for participating in a broad array of sports, including football, basketball, and swimming. Daily physical training course prepares the children to be involved, fit, and stable in their own physical and mental growth (Vinayakumar et al., 2019; Thakur et al., 2021; Sohail et al., 2022a; Sohail et al., 2022b). A successful physical education curriculum should include teaching students, psychiatrists, and teachers; proper education; and student assessment. Learning to develop body fitness starts from basic physical exercises to a training course in grooming, gymnastics, and athletic game performance and management (Janarthanan et al., 2020; Awan et al., 2021).

Physical training assists students in developing physical skills and confidence. For instance, primary and secondary schools' curricula involve activities that allow children to gain or develop their abilities, such as running, catching, throwing, or karate (Janarthanan et al., 2020). High school education should concentrate on tennis or aerobic dance, focusing on competitive sports (Kumar et al., 2018). Physical education creates strength and encourages the ability to be involved in physical activity for a lifetime (Xu et al., 2020). Physical education programs teach the health benefits and hazards of a dysfunctional and unhealthy diet and the importance of daily exercise and balanced food choices (Zhao et al., 2019; Kumaran et al., 2021; Zhao et al., 2022a; Zhao et al., 2022b; Zhenyu and Sohali, 2022). Students of all ages may be required to focus on a few minor dietary and exercise changes over six weeks (Kumar et al., 2019). Physical training can enhance the behavior, cognitive, and social capacity of students (Huifeng et al., 2020; Mustafa et al., 2022b). Team sports help students value others, contribute to a team objective, and socialize as positive team members (Anbarasan et al., 2020; Raizada et al., 2021). Physical training includes holistic training for the complete growth of the child's personality and body, mind, and spirit excellence through daily engagement (Sohail et al., 2015; Zhou et al., 2016; Mustafa et al., 2022a). The medium of physical fitness, physical exercises, allows us to achieve and sustain a fitness shape. It helps achieve high physical and mental performance (Kang and Choo, 2016; Rathore et al., 2016). Alertness and abilities such as perseverance, team spirit, teamwork, and rule-making are developing. Therefore, it improves the students' personal and social skills and positively impacts their physical, social, emotional, and mental growth (Okumura et al., 2003; Upadhyay et al., 2008). Thus, physical training can be described as a field that does not focus on physical fitness but aims to develop a range of skills and behavior. Physical training teaches cooperation, respect, integrity, trust, the gain of grace, and the loss of hope (Redd et al., 1992).

To achieve and maintain a healthy lifestyle with abilities, skills, values, and enthusiasm, higher education institutions must concentrate on designing physical education courses (Sohail et al., 2014b; Popp et al., 2018; Sohail et al., 2022c; Lu and Sohali, 2022). To encourage exercise, motor skills, the comprehension of games and sports rules, principles, and strategies, the trainer needs to monitor the student (Kanchanasut et al., 2007). Students are either trained in a team or in a range of competitive activities as individuals. Learn motor skills such as strength, speed, stamina, coordination, flexibility, agility, and balance since these are crucial aspects of success in various games and sports (Trudeau and Shephard, 2008; Sohail et al., 2022d). Building sustainable strategies and methods involved in physical activity (Sohail and Delin, 2013a; Sohail et al., 2013b; Sohail et al., 2014a; Yen et al., 2017; Yat et al., 2018; Liu et al., 2020; Yen et al., 2021). The main contributions of this article are as follows: 1) designing a PSERS-DL has been proposed to reduce physical education students' risk factors for learning and handle such situations effectively; 2) analyzing the PE environment by a global surveillance system and predicting the injured student to take safeguards instantly; and 3) the experimental results have been analyzed, and the proposed system PSERS-DL has been improving safety measures for students and enhancing learning outcomes in physical education. The rest of the article is organized as follows: Section 1 and Section 2 discuss the physical education and emergency response system and existing methods. In Section 3, the PSERS-DL model is

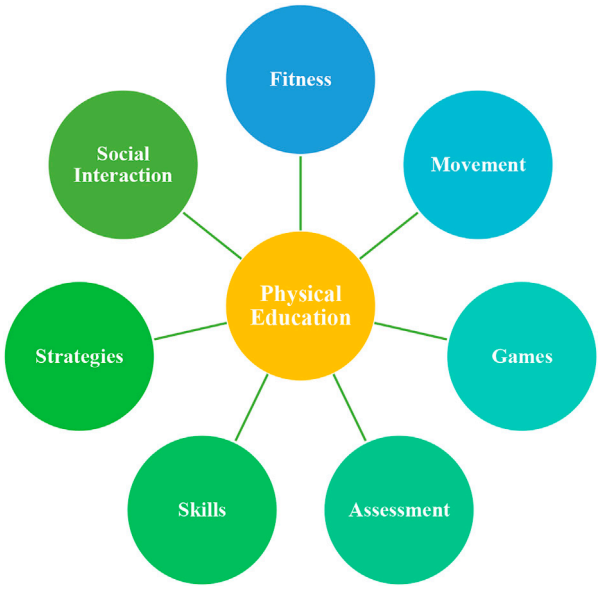


FIGURE 1
Components of physical education.

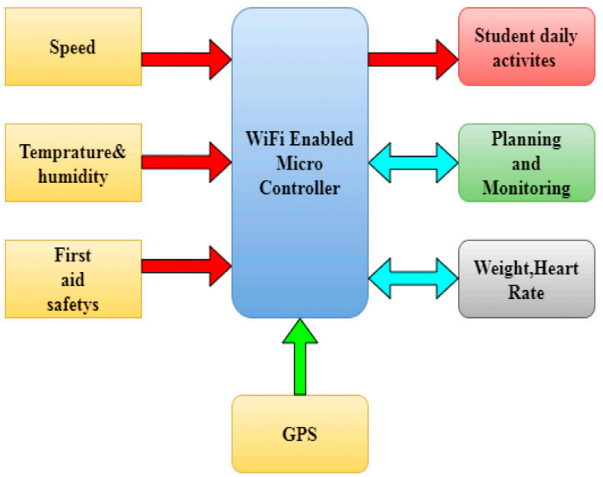


FIGURE 2
Emergency response system.

suggested. In Section 4, the experimental results are executed. Finally, Section 5 concludes the research article.

## 2 Literature review

Liu et al. (2020) focused on creating a computational regulation of behaviors using the Internet of Robotic Things (IoRT). Two major methodologies are used in this deep learning solution for robotic behavior management, deep reinforcement learning (DRL). Robot behavior control models the robot with the features required to react to its immediate environment *via* sensory-motor connections. To recognize robots' actions, DRL combines the principle of deep learning architecture with neural networks and reinforcement algorithms. Min (2021) discussed the field-programmable gate array (FPGA) for welfare organization management. The value of using a variety of methods to speed up main characteristics. Study methods are the new changes in deep learning networks based on FPGA in this study. Therefore, in the analysis of the direct and effective hardware acceleration of potential development researchers, this examination is intended to be useful. Lee and Lee (2021) suggested using artificial intelligence (AI) for physical education. Using AI in physical education (PE) and sports applications can enhance its possible use and improve the nature, visualization, and repetitiveness of PE. This study examines the concepts and use of PE based on AI-related research fields' philosophy and offers a concentrated, in-depth review of the PE technologies. To apply AI-based custom PE lessons, information provision, learner assessment, and learner therapy methods, AI facilitates educators' decision-making by reporting to learners on their status and providing different solutions to learners' problems in real-time. It supports educators efficiently in assessing and managing to learn.

Sung et al. (2020) introduced the Bidirectional Encoder Representations from Transformers (BERT) framework for categorizing ended responses into suitable categories with improved efficiency than conventional machine learning systems. In the processing of primary analysis, the satisfaction of deep learning in assigning many codes is innovative. The research has a simple method for analyzing qualitative data that does not fulfill mutual university. Telford et al. (2021) deliberated that the centerpiece of school physical education (PE) can be called physical education with ineffectual instruction. The lack of PE throughout the system of public primary schools has raised concerns. This analysis's objective was to assess the implementation, acceptability, and impact of PE teachers' provision in an integrated PEP approach to improve PE and PL opportunities for teachers in the classroom of a group of suburban elementary schools. Cao et al. (2020) initialized the topology-aware access control (TAAC) for the cyber-physical space access control system. It can potentially describe the control of cyber access, physical access control, and interaction access control, and for the policy compliance process, a risk evaluation approach is proposed. They suggested a role activation algorithm that would allow only legitimate and honest users to access items.

There are several challenges to existing methods to implement physical education and emergency response system. To come across the issues in this study, the PSERS-DL model has been suggested. The following section discusses the proposed model briefly. This article discusses the physical education and emergency response system using deep learning for improving student learning and enhancing physical training outcomes. Physical education supports students in achieving movement, safety knowledge, developing their physical abilities, and using various active events. Physical education (PE) allows students to maintain fitness and acquire positive social skills, and it builds the students' capacity and confidence to engage in a wide variety of physical activities. The study aims to analyze the degree of physical activity in community educational institutions. Data have been analyzed to determine whether physical education could enable young people to meet their health goals through prescribed physical activities accurately. The physical education components are shown in Figure 1.

Figure 1 shows the physical education components. The four major physical education objectives are nutrition, physical activity, athletic development, and social skills. Physical education goals include the understanding of the student body's growth and development of personality. The purpose of this article is to evaluate skill development progress across the integrated process. Social contact is cited as a significant factor in the importance of adolescence

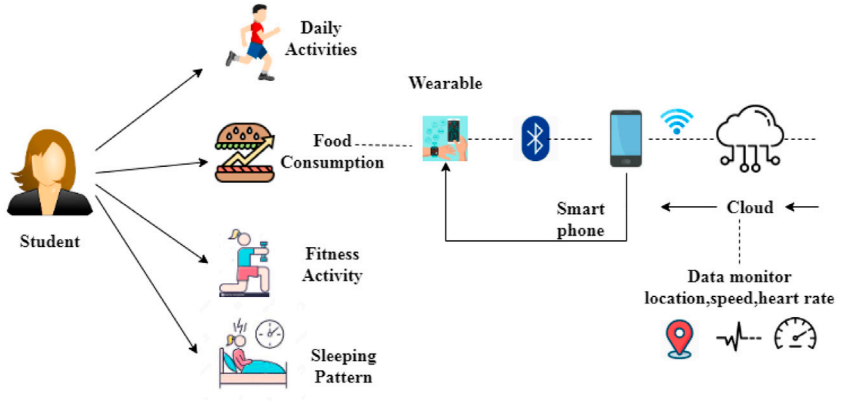


FIGURE 3
Fitness tracking process.

movement experience. Regular physical activity for students offers direct health benefits, effects on physical appearance and muscle growth, and a reduction in individuals' presence at high-risk failure. However, studies show that this condition is impractical and is rarely met in regular PE lessons. This study set a goal to determine students' physical activity during secondary school PE. The data have been considered for the recommended levels of physical activity to determine and help students become healthy.

# 3 Methodology

## 3.1 Emergency response system

The emergency response system design provides an understanding of essential emergency response parameters outlined in Figure 2. Monitoring athletes and all students in physical education play a significant part. Sensors can be used to produce and install an emergency response system properly, and a few sensors are interfaced to establish internet connectivity through a WiFi-enabled microcontroller. The sensors used in the configuration are the heartbeat sensor for ambient temperature and humidity object stabilization accelerometer and GPS module for situating the emergency reaction site. The number of moves and emergencies can be counted as droppings that generate the signal in the object's movement, such as planning, living, behavior, and tracking.

The standard magnitude vector estimated values in the region of the signal smart emergency response system are formalized in Eq. 1:

$$SMA = \frac{1}{Q}\left(\int_0^Q \Big/ Y(Q)dq + \int_0^Q X(Q)dq + \int_o^Q Z(Q)dq\right), \quad (1)$$

$$SVM = \sqrt{Y^2 + X^2 + Z^2}. \quad (2)$$

As shown in Eqs. 1 and 2, signal magnitude area $(SMA)$ and standard magnitude vector have been described. $X$, $Y$, and $Z$ are accelerations $Y(t)$, $X(t)$, and $Z(t)$, and sample signals for posture are obtained along the Y-axis, X-axis, or Z-axis.

## 3.2 Wearable sensor-based fitness process

Monitoring and evaluation (M&E) are two separate harmonizing, mutually enhancing methods based on wearable sensors. Generally, M&E is intended to track a strategy's effectiveness on the overall goals, priorities, objectives, and program operation progress. M&E often evaluates an activity's result significance and its performance, learning rate, efficiency, and sustainability on program effectiveness.

Figure 3 shows the fitness tracking process. Wearable systems include accelerometers, gyroscopes, sole sensors, and body-mounted barometric pressure sensors. To track their physiological and biochemical properties, different body sensors have been developed. The sensor is a microphone and is discreetly worn on the neck. Sound characteristics are extracted in real-time, and the camera records a video sequence for further study if a chewing action is classified. The sensors can sense variations in temperature, illumination, movement, vibration, or pressure of students. The combined use of wearable sensors and environmental sensors may provide useful information about the individual living under monitoring. Actigraphy instruments rely on an accelerometer to measure movement patterns (motion) and estimate sleep and wake conditions simply by assuming that motion means waking and sleeping. Tracking the eye movement helps the detection of gazing activities like reading and concentrating movements. The sensor network collecting and disseminating sensed data is a necessary component of wearable

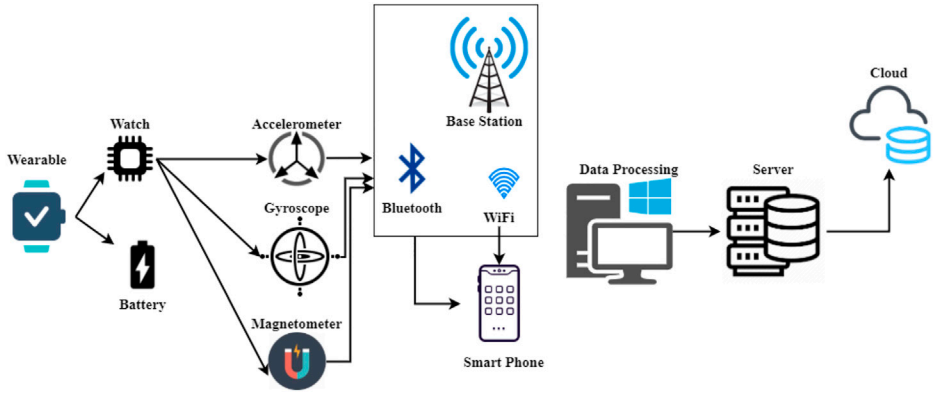


FIGURE 4
Wearable sensor framework.

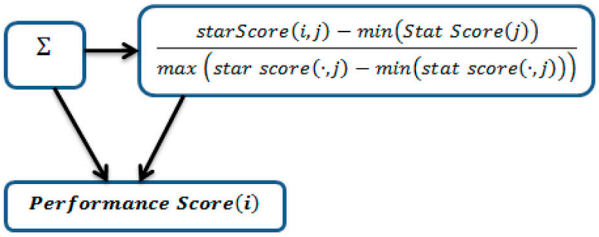


FIGURE 5
Performance score.

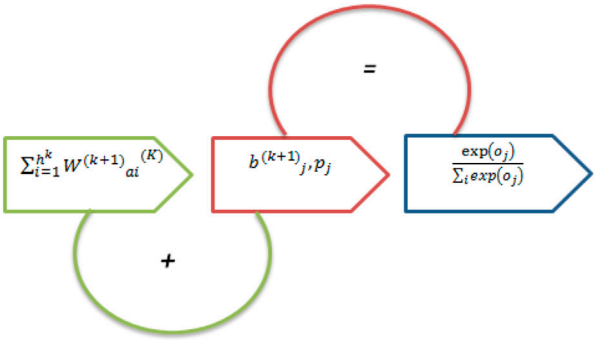


FIGURE 6
Softmax function.

computing. The lightweight application programming interface (API) is used for direct sensor connectivity with a cloud while the data collected, users, and sensors are served in a highly scalable way. Fitness data monitors are standard instruments used to assess physical involvement in class times and strengthen fitness principles related to well-being, such as aerobic ability and enhancing quantitative physical activity metrics inside and outside schools (Mustafa et al., 2022c). The understanding of wearable technology started with a wearable device, that is, a completely controllable device that can run without thinking or effort. It is a part of the user that this form can be seen in today's wearables, as they are considered "smart" since they are run with less human input into the controls because the consumer is free to take action from the fitness trackers.

## 3.3 Activity recognition wearable sensors

Student activity recognition, which has expertise in students' activities from raw sensor inputs, plays an important role in everyday life. It aims to understand students' conduct that enables computing systems to support users proactively based on their needs. Suppose a student carries out certain types of activities that belong to specified $A$ in Eq. 3:

$$A = \{A_i\}_{i=1}^{m}. \tag{3}$$

As explored in Eq. 3, student activity has been calculated. $A$ is a student activity, where $m$ refers to the number of forms of operation. There is an operation knowledge series of sensor reading in Eq. 4:

$$s = \{d_1, d_2, \ldots\ldots\ldots d_t, \ldots., d_n\}. \tag{4}$$

As inferred, in Eq. (4), sensor reading has been computed, where $dt$ indicates the time $t$ read sensor.

To predict the sequence of activities using sensors, a model $\mathcal{F}$ is constructed as shown in Eq. 5:

$$\hat{A} = \left\{\hat{A}_j\right\}_{j=1}^{n} = \mathcal{F}(s), \varepsilon \mathring{A}. \tag{5}$$

As calculated in Eq. 5, sensor-based activity predicts the sequence. However, the actual sequence of operation (ground truth) is as shown in Eq. 6:

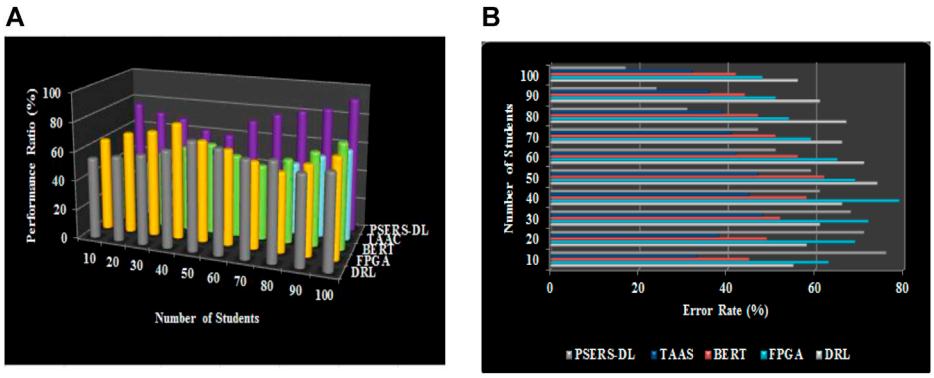


FIGURE 7
**(A)** Performance ratio. **(B)** Error rate.

$$A^* = \left\{A_j^*\right\}_{j=1}^{n}, \quad \hat{A}_j \varepsilon \text{Å}. \tag{6}$$

As deliberated in Eq. 6, the ground truth of sensor sequence operation has been obtained. In Eq. 6,$n$ indicates the sequence length, and n indicates the $m$ length.

The human activity recognition objective is to learn model $F$ by minimizing discrepancies between activity $\hat{A}$ and activity $A^*$—ground reality. A positive loss feature $L\,(F(s))$, Å to reflect their discrepancy is usually built. F does not normally take s as the input directly and normally assumes a projection function that projects a sensor reading data to $d$—dimensional vector, a projection function, all of which is $R_d$. The objective here is to minimize the $L(F\,(pour\,(di))$, $A\,(pour-))$ loss function.

The wearable device can be seen as an existing device in which a consumer's priority can see exercise as a routine instead of an activity. Figure 3 shows what a new wearable customer fitness process looks like concerning the individual.

The inertial measurement unit (IMU), GPS (global positioning system), magnetometer, gyroscope, and accelerometer sensors are often present in sports wearables configured. The inertial measurement unit can be used in various physical monitoring applications. In this study, there are differences in which sensors are compatible and which sensor technology can be adapted for sporting applications.

Figure 4 illustrates the wearable sensor framework. An IMU chip with a wearable sensor can monitor data and communicate *via* wireless technology. The preference for servers or phones with WiFi or Bluetooth depends on the customer, and the designer gets input. Sensors that regularly send and receive data will help to consume power. The advantage of integrated smartphone-based wearable technology is that it can optimize storage capacity (Mustafa et al., 2022d). Wearables are based on constant teachings and all data that wearable monitors can use. For PE training and learning, utilizing server or cloud services to store student data tracks live encryption and storage priority (Zhongjun et al., 2022).

Physical education has a concrete connection to physical activity for students. Activity data quantitatively represent a student-action state and are qualitatively evaluated by reports. It is possible to suppose that the phrases that relate to a student seem to have a polarity if students played well in physical education. In this context, two sentence-level annotation techniques have been proposed, and four physical annotation methods are performed throughout a season. In contrast, daily annotation is the second method focused on a student's success in physical education. Based on the average statistics for the whole season, the first approach evaluates the security and success rating of the $i^{th}$ students:

$$Per\,formance\,Score\,(i) = \sum \frac{starScore\,(i,j) - min\,(Stat\,Score\,(j))}{max\,(star\,score\,(\cdot,j) - min\,(stat\,score\,(\cdot,j)))}. \tag{7}$$

Figure 5 and Eq. 7 demonstrate the performance score, where $i$ is an index for the player and $j$ is a statistic index for the game. $S$ is the set of related performance appraisal game statistics. Statistics score $(i, j)$ is the standard $i^{th}$ player's score for the statistical $j^{th}$ game in Eq. 8:

$$StarScore\,(i,j) = \delta j\left(\frac{stat\,(i,j) - u\,(j)}{\sigma\,(j)}\right). \tag{8}$$

Equation 8 describes the statistical score of $(i,\ j)$ and the original statistic of the $j^{th}$ player game, and $u\,(j)$ is the mean and standard deviation of all the students' statistic for the $j^{th}$ season, respectively. In addition, $u\,(j)$ is an indicator of the relationships between the statistics on the j$^{th}$ game. All articles are available at the time of publishing and have annotated each sentence referring to a student who has regular records based on changes. If the direction of change suggests a performance improvement, then phrases referring to students published

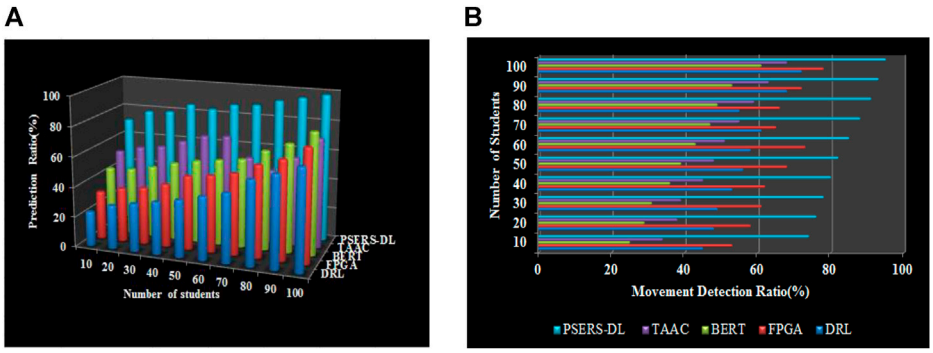


FIGURE 8
**(A)** Prediction ratio. **(B)** Movement detection ratio.

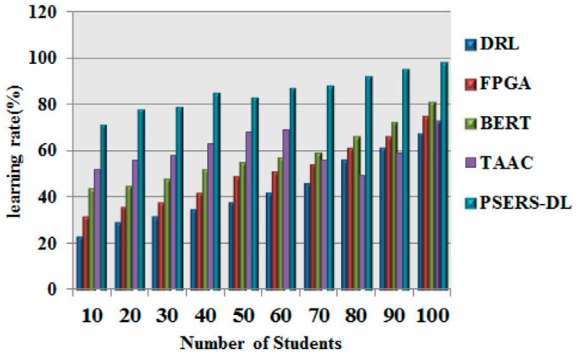


FIGURE 9
Learning rate.

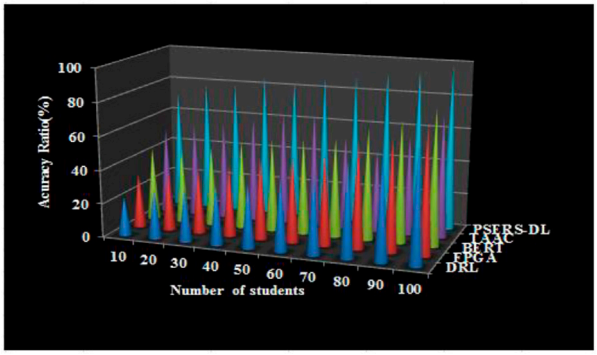


FIGURE 10
Accuracy ratio.

between the current game and the following game will be positive.

The basic architecture contains the sum of the input layer's weighted input values for each hidden unit in the first hidden layer. This weighted sum is transformed using the $h$-activation function, including linear, sigmoid, and hyperbolic tangent $(\tan h)$. The result of this is the hidden node.

$$h_j^{(1)} = \sum_{i=1}^{h^{k-1}} W_{ji}^{(k)} aj^{k-1} + b_j^k, a_j^k = g\left(h_j^{(k)}\right), \text{for k} = 2, \ldots\ldots\ldots, \text{H} \tag{9}$$

As expressed in Eq. 9, the output of the hidden node has been explored. Eq. 9 shows the $H$ is, respectively, the number of hidden $k-1^{th}$ and network layers of hidden nodes. Each output node, which corresponds to a class, uses the softmax function to take the weighted sum of the last hidden layer enabled output and converts it into a probability class $p_j$ for classification with less delay, and the task shows Eq. 10 as follows:

$$\sum_{i=1}^{h^k} W^{(k+1)} ai^{(K)} + b^{(k+1)} j, p_j = \frac{\exp\left(o_j\right)}{\sum_i exp\left(o_j\right)}. \tag{10}$$

Figure 6 signifies the softmax function. A deep neural network (DNN) is qualified for identification to increase the prediction error over the data, which is equivalent to reducing the cross-entropy optimization problem in Eq. 11:

$$cross - Entropy = -\sum_{i=1}^{n} \sum_{c=1}^{c} t_{ic} log\left(p_{ic}\right). \tag{11}$$

As found in Eq. 11, cross-entropy optimization has been explored, where $C$ indicates the number of training instances and total grades. In addition, the class label is 1 if it is $C$ and 0; otherwise, for the $i^{th}$ training case. Therefore, $p_{ic}$ is the forecast likelihood of class $c$ in the $i^{th}$ course. The proposed PSERS-DL model enhances the accuracy ratio of performance ratio, prediction ratio, increased efficiency ratio, less error rate, low delay time ratio, and high-security rate.

TABLE 1 Security ratio.

| Number of students | DRL | FPGA | BERT | TAAC | PSERS-DL |
|---|---|---|---|---|---|
| 10 | 24.2 | 30.2 | 33.6 | 43.7 | 75.4 |
| 20 | 28.6 | 38.8 | 37.8 | 35.8 | 77.5 |
| 30 | 28.4 | 40.6 | 40.5 | 45.7 | 79.7 |
| 40 | 34.9 | 25.8 | 45.9 | 49.7 | 65.9 |
| 50 | 37.4 | 33.4 | 48.7 | 50.9 | 72.3 |
| 60 | 45.5 | 43.8 | 50.5 | 55.8 | 75.8 |
| 70 | 49.8 | 47.5 | 55.7 | 58.6 | 79.3 |
| 80 | 54.4 | 50.6 | 59.9 | 60.8 | 81.9 |
| 90 | 56.3 | 55.3 | 60.3 | 63.5 | 85.5 |
| 100 | 58.8 | 59.5 | 65.8 | 65.7 | 95.5 |

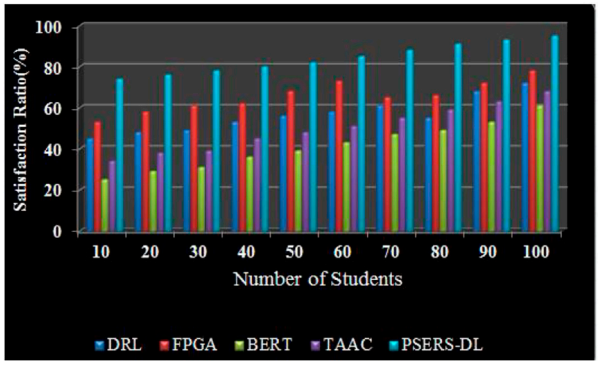


FIGURE 11
Satisfaction ratio.

## 4 Result and discussion

The physical education (PE) system's key goal is to educate individuals and the large community of participating students to achieve self-fulfillment. Deep learning uses integrated expertise to help students master challenging conditions in unfamiliar contexts. The proposed PSERS-DL models for preventing student injuries and monitoring physical activity. The experimental results have been performed, and the suggested PSERS-DL model is based on the performance metrics such as accuracy ratio, prediction ratio, efficiency ratio, security rate, and delay time ratio.

### 4.1 Performance ratio and error rate (%)

Fitness can involve student skills, attitudes, and academic performance, which are important elements for improving school performance. PE includes improved interest, concentration, and student performance. Physical training affects cognitive skills such as focus and enhances student habits which are essential components of increased student performance. Physical education develops students' concentration expression and improves memory, better heart health, lowers the risk of depression, bone health, and weight and improves grades. It makes us work successfully, appreciates recreational activities, and cope with emergencies. It can help us feel very healthy while learning to improve our physical health. Figure 7A shows the performance ratio.

Figure 7B shows error rate; physical education system strengthens student education and improves physical activities to care for the student's environment. These include recognizing the importance of using programs for the improvement of physical activity in the learning environment. Recognition of current opportunity inequalities and the need for equality of physical and physical activities.

TABLE 2 Behavior analysis ratio.

| Number of students | DRL | FPGA | BERT | TAAC | PSERS-DL |
|---|---|---|---|---|---|
| 20 | 28.6 | 28.5 | 38.8 | 37.8 | 77.5 |
| 40 | 34.9 | 34.7 | 25.8 | 45.9 | 65.9 |
| 60 | 45.5 | 49.8 | 43.8 | 50.5 | 75.8 |
| 80 | 54.4 | 55.3 | 50.6 | 59.9 | 81.9 |
| 100 | 58.8 | 69.7 | 59.5 | 65.8 | 90.7 |

### 4.2 Prediction ratio and movement detection ratio (%)

The deep learning (DL) models were used to calculate the accelerometer data's fitness values and determine the positioning location to predict physical activity (PA) data. These models showed a preference for the main wrist or shoulder, as the action is more stable in these positions. DL models using these positions were useful in predicting student PA accurately. The routine framework has been organized around physical activity, and high prediction is provided by physical education (PE). In this respect, PE's position on the school curriculum is generally justified by its commitment to health and fitness. However, the assumption seems to have some merit because PE is often highlighted as a major contributor to young people's everyday physical activity. DL is considered patterns in an acceleration signal instead of using the acceleration magnitude for the prediction. Research shows, however, that this criterion is very ambitious and that it is rarely encountered during PE lessons every day. Figure 8A shows the PSERS-DL curriculum prediction ratio.

Figure 8B shows the PSERS-DL curriculum movement detection ratio that students can learn a range of skills, activities of the movement, and qualities. It is important to

study whether exercises can be used as a lesson to practice different movements. This article aims to research students' different movement detection usage during the PSRES-DL period using new educational tools and emphasize numerous movement qualities.

## 4.3 Learning rate (%)

Students can build skills and use this knowledge to increase their skills in various circumstances. Students reach a health-enhancing fitness level and show physical activity and recognize that physical activity offers opportunities for pleasure, challenge, and self-expression. Students will show responsibility for their acts during their participation in the campaign and display responsible social behavior. Prove progress in fitness areas assessed by the department's deep learning system using the basic abilities, experience, manners, and vocabulary used in practical and fighting tasks. Figure 9 shows the physical education and emergency response system's learning rate using deep learning (PSERS-DL) to handle such situations effectively.

## 4.4 Accuracy ratio (%)

Physical training (PE) builds students' skills and confidence in various physical activities integral and school life. The PE program's accuracy allows all students to participate in a variety of physical activities and excel. The importance of sports accuracy will be known to those who have completed sports coaching courses. The students can choose and build user-friendly environments, exhibit sequence training, and incorporate learning styles and performance modifications based on good education values. Students demonstrate movement expertise, analyze physical training's success, develop and learn written lesson schemes, analyze fitness learning for students, assess it, and include the description and implementation of conceptual physical training for highly qualified employment, movement, sport, and physical development. Figure 10 shows the accuracy ratio.

## 4.5 Satisfaction ratio

The research was conducted to recognize students' satisfaction with physical education (PE). Students score the need for a high quality of good life; however, their school's contribution to healthy living is unsatisfactory. The PE training supports multiple physical exercises and gathers knowledge, values, and functions related to other educational concerns. The students were best satisfied with peer interaction among the four aspects of PE learning impact, teacher training, and facility. The students' satisfaction with PE ranged from average to satisfied. Figure 11 shows the student satisfaction ratio in PSERS-DL.

## 4.6 Security ratio (%)

Each student's and teacher's development is within their capacity and confidence. Ensure that traffic patterns are flowing around the equipment to prevent accidents. Guaranteeing the equipment is installed correctly, loaded, stretched, and used according to the system's wishes and that the operating devices are systematically started and finished. Table 1 shows the student security ratio is high in PSERS-DL.

## 4.7 Behavior analysis ratio

A summary of behavioral analysis shows that student data history and experiments in physical education settings are given in this article. To evaluate the effects of behavioral interventions in teachers' training settings based on the question. Table 2 provides descriptive data on the actions of students over several similar courses.

Considering the advantages reported by students in assessing training classes to analyze the relationship between student obligation assignment, motivation variables, and satisfaction with physical education classes, three different characteristics were offered: sports challenges, fitness activities, and aerobic activity. The movement's detection examines students' qualities on four levels: body, effort, space, and relations. Our findings show that exercises allow PE teachers and students to pay attention to various teaching qualities. In PE, the player engages in a complex sense of movement with physical exercise and other students.

The proposed PSERS-DL model enhances the accuracy ratio, performance ratio, movement detection analysis ratio, learning rate, efficiency ratio, security ratio, delay time ratio, and behavior analysis ratio when compared to deep reinforcement learning (DRL), field-programmable gate array (FPGA), Bidirectional Encoder Representations from Transformers (BERT) framework, and topology-aware access control (TAAC) methods.

# 5 Conclusion

This article discussed the emergency response system based on deep learning for student physical activity monitoring and improving student fitness. The provision of first aid protection steps is an emergency solution to reduce potential injury risks to students.

Therefore, in this article, PSERS-DL has been proposed to sports emergency management and handle physical education's critical situation. A global GPS allows surveillance systems to map the PE field in real-time so that the wounded student can automatically take safety action. Physical education programs worldwide are under strong pressure to prove that their practice prepares students for good active and long-term living. The experimental results show that the proposed PSERS-DL model enhances an accuracy ratio of 95.6%, a performance ratio of 97.6%, a movement detection analysis ratio of 96.3%, a learning rate of 95.2%, an efficiency ratio of 98.1%, a security ratio of 93.5%, a delay time ratio of 33.2%, and a behavior analysis ratio of 90.7% when compared to other existing approaches. This study can be used for physical education and emergency response system using deep learning and it can help to develop a better physical education environment.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

## Author contributions

The author confirms being the sole contributor to this work and has approved it for publication.

## Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# An empirical analysis of cultural inheritance and ICT role on learning practice in a working environment; A PLS-SEM analysis

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A review of the relevant research reveals that the concept of "professional growth" is understood to refer to an all-encompassing developmental process that occurs throughout a person's career as well as their entire life, and it is acknowledged as a phrase that is connected to other ideas. In addition, we can say that human attributes and circumstances are not the only factors that play a role in the process of professional development, but social and institutional experience also play a role in it. After that, this research is shown, which has personal dimensions for beliefs (B), co-workers (CW), culture inheritance (CI), customs (C), information and communications technology (ICT), and learning practice (LP). The research is formed to illustrate that promotion of professional growth in workplaces is connected to the mentioned variables. This study was based on the working experience of different backgrounds people. We tried to check how their attributes could influence their working practices and learning practices. A semi-structured questionnaire was adopted from existing literature and modified as per the study area. B > LP (β = 0.022; *p* 0.010), CI- > LP (β = 0.368; *p* 0.000), C- > LP (β = 0.210; *p* 0.000), and ICT- > LP (β = 0.410; *p* 0.000) were found to be significant using PLS-SEM direct path analysis.These results offer support to hypotheses H1, H3-H6 accepted and H2 rejected. As control variables, we looked at the respondents' age, education, and gender. Gender (β = 0.006; *p* 0.846) showed insignificant relationships with LP, whereas age (β = −0.103; *p* 0.001) and education (β = −0.072; *p* 0.034) showed significant relationships with the dependent variable. gender does not have any relationship with learning practices (LP), but age and education can be favorable control variables, and an aged and experienced person can have more impacts on LP and impacts on independent variables.

KEYWORDS

**ICT-information and communication technologies, practice in learning, working environment, belief, custom**

# 1 Introduction

Culture is something that should be valued by every individual because of the myriad ways in which it influences both day-to-day living and the workplace. Even though learning to function in new cultural contexts has been a struggle for adults for a very long time, relatively little is understood about the mechanisms that underlie this form of learning (Elliott. 2019). According to the findings of different research, situated cognition is the theoretical framework that is the most helpful for comprehending cultural learning (Oyserman and Sorensen., 2013). This way of culture has a direct influence on several different aspects of cultural study, including how a new culture is learned, how it might be taught, and how to link previous cultures if you move to a different cultural environment (Lave. 2021). To be more explicit, given that all of us normally originate from different cultural, religious, and social backgrounds, how we conduct business may or may not be influenced by this fact. Due to the challenges associated with promoting reflective beliefs during practical teaching, one may conclude that certain methods utilized in teacher education, such as eliciting implicit conceptions or beliefs, may not be the most effective choice (Winitzky & Kauchak, 1997). The support of one's coworkers has emerged as an essential component of the social support system provided at work, serving as a buffer against the constraints imposed by business (Hobfoll and Lerman, 1989). Organizations place a high value on the support and relationships that employees have with one another as a valuable resource for their work. As a consequence of this, the influence of support from coworkers as a kind of social support on the willingness to participate in group activities and educational pursuits is being researched as a direct result of the Conservation of Resources (COR) hypothesis (Dutta and Rangnekar, 2022). The dynamic relationship between technology, technological practice, and learning practices is an important phenomenon that needs to be explored. The role of information and communication technology (ICT) in learning practices is increasingly gaining importance in the working environment (Leach and Moon., 2000). Operationally, ICT has helped in many ways at work, and it may have an impact on our learning abilities as well. Pedagogically, it has enabled online, hybrid, and technology-enhanced learning as well as a host of other capabilities, from learning management systems to learning information systems (Hall and Higgins, 2005). ICT is now embedded in every aspect of working life. ICT is found to increase the value of learning practices (Bimrose et al., 2011; Szilárd et al., 2018). It has helped in the growth of research, expanding horizons for business mainly with limited accessibility. There are always two sides to the coin, and in this case, inaccessibility, economic disparity, and ineffective implementation of ICT have also created impediments to effectively adopting and diffusing integration of ICT (Ebrahim and Irani, 2005). This volume is a collection of interventions and collaborative practices across the world that showcase the multifaceted ways in which various institutions have been engaged in supporting teaching and learning with the use of technology and how it is equipping our future generation with the skills required to face a changing job market. Professional growth is viewed as an overall developmental process that occurs during one's career and lifespan and is understood as a phrase that overlaps with other related ideas, according to an analysis of the pertinent research (Pylväs et al., 2022). Furthermore, we contend that, in addition to individual characteristics and circumstances, social and institutional settings have a role in professional development. After that, this research is shown, which personal dimensions for belief (B), co-worker (CW), culture inheritance (CI), custom (C), information and communications technology (ICT), and learning practice (LP). The research is formed to illustrate that promotion of professional growth in workplaces is connected to the mentioned variables. Age, gender, and educational level are important demographic characteristics of a sample that might affect and improve the link between the independent and dependent variables (Mustafa, Qiao, et al., 2022a; Mustafa, Tengyue, Qiao, et al., 2022b; Mustafa, Tengyue, Jamil, et al., 2022c). Some research has been done that suggests environmental knowledge does not substantially impact females' intentions to use environmentally friendly items; however, it does have a large influence on males' intentions. The goals of this study were to 1) look at how culture is passed down and what role ICT plays in learning practices; 2) use a PLS-SEM approach to look at some attributes and how they affect learning practices. Education, age, and gender may all have an impact on DV. Based on our literature review, we developed the following hypothesis: (Figure 1)

H1: Culture Inheritance has a positive relationship with Learning Practice.

H2: Belief has a positive relationship with Learning Practice.

H3: Custom has a positive relationship with Learning Practice.

H4: Co-Worker influence has a positive relationship with Learning Practice.

H5: Information and Communications Technology has a positive relationship with Learning Practice.

# 2 Materials and methods

## 2.1 Data sources and data preparation

This study was founded on the work experiences of people from various backgrounds. We attempted to investigate how distinctive traits can influence their working and learning practices. A semi-structured questionnaire was adapted from

previously published material and tailored to the demands of the study (Sohail et al., 2022a; Sohail et al., 2022b). When developing the objectives of the study and collecting data from people, basic research ethics were considered, and participants in the study were given a full explanation of the study's goals (Rasool et al., 2017). Furthermore, the participants were informed that the information they supplied would be used solely for research purposes and that they were under no obligation to respond to the questions posed to them (McCusker and Gunaydin, 2015; Sohail et al., 2019; Sohail et al., 2021; Sohail et al., 2022c). The research's major indicators were determined as follows: beliefs (B), coworkers (CW), cultural inheritance (CI), customs (C), information and communications technology (ICT), and learning methods (LP). A total of 500 completed questionnaires were collected from the study region for this study, and a pre-test was undertaken to assess the reliability of the data and eliminate any discrepancies that may have arisen. This information was acquired from a variety of people who work for multinational corporations. The data was collected online via various social applications and email. WeChat was also employed. Following completion of data collection, the information was transmitted to PLS-SEM and SPSS 24 for further analysis. PLS-SEM is used to analyze data to check the relationship between variables because it is one of the most effective methods for predicting outcomes and because it is the method that is most commonly recommended for predicting and assessing explained variables to account for the greatest potential variance (Hair, Howard, and Nitzl 2020). use PLS-SEM to analyze data to check the relationship between variables because it is one of the most effective methods for predicting outcomes and because it is the method that is most frequently recommended for predicting and assessing explained variables to account for the greatest potential variance (Hair, Howard, and Nitzl 2020). PLS-SEM allows for the use of lower sample size while yielding conclusions of greater quality than other approaches. Aside from that, it can execute concurrent internal and external processing on all models, which is a highly helpful feature. It is also possible to investigate complex route models using this method of data collection (Hair and Sarstedt. 2021). Recent academic research (Mustafa, Qiao, et al., 2022a) reveals that the PLS-SEM technique's appeal in management science may be at least partially related to the method's prospective benefits. As a result, the PLS-SEM methodology looks to be the best option for this inquiry. A two-stage analysis is more successful than a single-stage analysis since the model compensates for non-linear interactions across accounts. To ensure the validity and reliability of the construct assessments, a route modeling technique based on PLS is tested not once but twice. First, convergent validity is investigated to see if it is dependable and valid. The structural model is next examined to see if it can be used to construct an inner model or establish a relationship between the latent components.

TABLE 1 Demographic characteristics.

| Characteristics | Range | Percentage(%) |
|---|---|---|
| Gender | Female | 45 |
| | Male | 55 |
| Age | 18–30 Years | 25 |
| | 31–40 Years | 38 |
| | 41–50 Years | 26 |
| | >50 Years | 11 |
| Education | High School | 10 |
| | Bachelor (BA) | 39 |
| | Master (M.A) | 45 |
| | Doctorate (Ph.D.) | 6 |

## 3 Results and discussion

This research is based on people's backgrounds and personal experiences of life and their impacts on their learning practices. It is important to know how these indicators can have on their working life. A total number of 500 completed questionnaires were collected to analyze the future relationship among DV, IV, and control variables. To better comprehend our study sample and its characteristics, we have collated the participant's age, gender, and education. Information about the demographics of our whole sample (500 people) is provided in Table 1.

According to prior research findings, scholars believe that some multivariate hypotheses should be tested before starting with a multivariate investigation (Mustafa, Qiao, et al., 2022a). When evaluating measurement models, it is critical to assess both the convergent and discriminant validity of the indicators and notions being used (Hair, Howard, and Nitzl 2020). We put the construct indicators through their paces by putting them through a series of tests to see if they provide an adequate evaluation of the research variables. We did this to determine whether they provide an appropriate evaluation of the study variables. We utilized Cronbach's alpha () in conjunction with item loading to determine whether or not the instrument in question was reliable. Both the average variance extracted (AVE) and the composite reliability (CR) are measures that are used to show the level of variance in indicators that are compensated for by the latent construct. The abbreviations for AVE and CR are AVE and CR, respectively. The abbreviations for these two separate measures are AVE and CR, respectively. The factor loadings on the linked structures are used as the basis for a study of the dependability of each item (Table 2; Figure 2). For an outside load to be considered significant for a component, it must be more than or equal to 0.6. Hair and colleagues (2020). Cronbach's alpha values for all constructs should be greater than or very close to the recommended cutoff of 0.7 to generate a greater sense of trust. This is because the cutoff was designed to assure dependability. According to Werts, Linn, and Joreskog (1974),

TABLE 2 Reliability and validity analysis.

| Variables | Items | Loadings (Value) | T (Value) | VIF (Value) | α (Value) | CR (Value) | AVE (Value) |
|---|---|---|---|---|---|---|---|
| Culture inheritance (CI) | CI1 | 0.725 | 18.779 | 1.548 | 0.737 | 0.831 | 0.552 |
| | CI2 | 0.714 | 18.093 | 1.532 | | | |
| | CI3 | 0.779 | 27.511 | 1.522 | | | |
| | CI4 | 0.753 | 24.520 | 1.263 | | | |
| Beliefs (B) | B1 | 0.699 | 16.159 | 1.257 | 0.679 | 0.807 | 0.513 |
| | B2 | 0.779 | 23.640 | 1.518 | | | |
| | B3 | 0.615 | 10.509 | 1.125 | | | |
| | B4 | 0.761 | 23.565 | 1.457 | | | |
| Customs (C) | C1 | 0.824 | 30.028 | 1.848 | 0.778 | 0.860 | 0.609 |
| | C2 | 0.852 | 41.569 | 2.098 | | | |
| | C3 | 0.612 | 10.205 | 1.158 | | | |
| | C4 | 0.810 | 27.773 | 1.862 | | | |
| Information and Communications Technology (ICT) | ICT1 | 0.846 | 44.489 | 2.174 | 0.879 | 0.916 | 0.733 |
| | ICT2 | 0.882 | 75.100 | 2.371 | | | |
| | ICT3 | 0.841 | 42.176 | 2.130 | | | |
| | ICT4 | 0.854 | 45.258 | 2.223 | | | |
| Co-Workers (CW) | CW1 | 0.813 | 27.832 | 1.664 | 0.833 | 0.889 | 0.669 |
| | CW2 | 0.691 | 14.913 | 1.429 | | | |
| | CW3 | 0.888 | 54.038 | 2.611 | | | |
| | CW4 | 0.865 | 40.595 | 2.627 | | | |
| Learning Practice (LP) | LP1 | 0.867 | 43.948 | 3.181 | 0.916 | 0.941 | 0.800 |
| | LP2 | 0.903 | 87.789 | 3.362 | | | |
| | LP3 | 0.878 | 78.449 | 2.955 | | | |
| | LP4 | 0.928 | 108.808 | 4.595 | | | |

this will help ensure the reliability of the results. In addition to Cronbach's alpha, the composite dependability (CR) of the constructs was examined. This procedure was employed instead of the traditional one (Werts, Linn, and Joreskog 1974). According to the commonly accepted criteria, a reliability level of 0.6–0.7 is deemed satisfactory, while a level of 0.8 or higher is considered goes greater than 0.95, on the other hand, are not always deemed positive because they may indicate redundancy (Hulin, Netemeyer, and Cudeck, 2001). These findings are supported further by the results' high high-reliability, which are all larger than 0.7. If a group of items is tightly related to one another, they are said to have a high Cronbach's alpha. This internal consistency metric is called after its namesake. It is taken into account as a measure of the scale's dependability. Because the measure has a "high" alpha value, it does not have to be unidimensional. Cronbach's Alpha (Cronbach's Alpha) for Beliefs (B) is 0.679, Co-Worker (CW) is 0.833, Culture Inheritance (CI) is 0.737, and Custom (C) is 0.778. Learning Practice (LP) has a score of 0.916, while Information and Communications Technology (ICT) has a value of 0.879. Table 1 shows that the AVE convergent validity estimations were either greater than or equal to 0.50. (Hair, Howard, and Nitzl 2020; Hair, Jr et al., 2021). From these results, it is clear that the dataset has enough information to be worth looking into further.

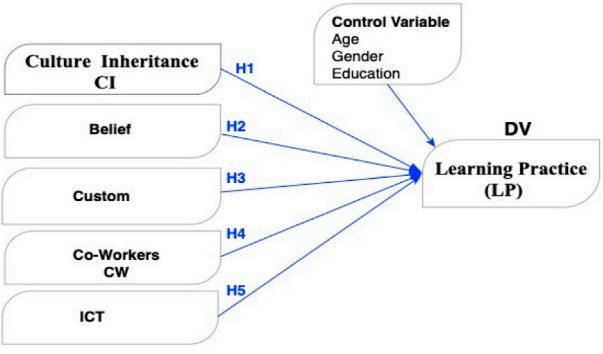


FIGURE 1
Hypothesis model.

The Fronell-Larcker criterion is one of the most often used approaches for identifying whether or not measurement models have discriminant validity. To satisfy this criterion, the square

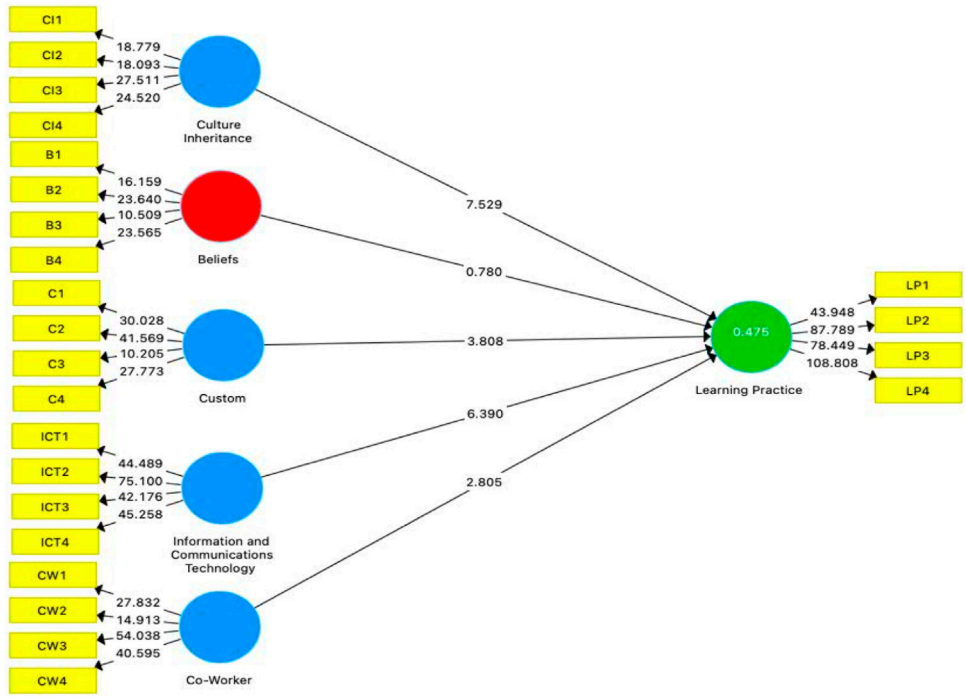


FIGURE 2
Measurement model, (Green and blue variables = Significant; Green and red variables = Insignificant).

root of the average variance retrieved by a construct must be greater than the correlation between the construct at issue and any other construct. The Fornell-Larcker criterion and heterotrait-monotrait (HTMT) ratios are used to assess the discriminant validity of the proposed model (Hair et al., 2020; Hair and Sarstedt, 2021). Table 3 clearly shows that the Fornell-Larcker criteria were used to verify the test's discriminant validity, as indicated by the variables having the highest significant correlation in each column (Fornell & Larcker, 1981). The HTMT ratio methodology is a revolutionary method proposed by Henseler, et al. (2015) as an innovative approach to determining whether or not discriminant validity exists. They maintained that, despite being effective in evaluating discriminant validity, the Fornell-Larcker criteria were unable to distinguish between the absence and presence of discriminant validity, even if the criteria were adequate for evaluating discriminant validity. This immediately necessitated the use of the HTMT within the framework of the technique for evaluating discriminant validity. The HTMT values for each of the several parameters investigated during this study are shown in Table 4, which summarizes the investigation's findings. For the experiment to be successful and meet the conditions, all of the variables' HTMT values must be less than 0.90. The HTMT values in this study are all less than 0.90, confirming the variables' discriminant validity. For the experiment to be successful and meet the conditions, all of the variables' HTMT values must be less than 0.90 (Henseler, Ringle, and Sarstedt, 2015).

The PLS-SEM evaluation procedure is divided into several stages, the second of which is the analysis of the structural model. When analyzing the structural path model, some of the factors that ought to be taken into consideration include the predictive relevance of the model, multicollinearity, the empirical importance of the route coefficients, and the degree of confidence. In addition to this, it is necessary to conduct a trustworthiness analysis of the structural path model. The structural model was examined in this study by making use of the guidelines that were supplied by Hair Jr et al., 2021) to comprehend the data. We put a model through its paces to study the direct impact that several different factors had on LP, and we did so by using the model. As a consequence of this, the outcomes of the PLS-SEM path analysis (shown in Figure 3) revealed an R2 value of 0.7, which demonstrated that our model is accurate (Table 5).

PLS-SEM was used to examine relationships between variables such as Belief (B), Co-Worker (CW), Culture Inheritance (CI), Custom (C), Information and Communications Technology (ICT), and Learning Practice (LP).To test the validity of the hypotheses that had been put forward previously, we began by examining the causal relationships that were already known to exist between the

TABLE 3 Fornell-Larcker criterion.

| Variables | SD | Mean | Beliefs | Co-worker | Culture inheritance | Custom | Information and communications technology | Learning practice |
|---|---|---|---|---|---|---|---|---|
| Beliefs | 0.057 | 0.023 | 0.716 | | | | | |
| Co-Worker | 0.054 | −0.135 | 0.401 | 0.818 | | | | |
| Culture Inheritance | 0.047 | 0.368 | 0.352 | 0.240 | 0.743 | | | |
| Custom | 0.047 | 0.211 | 0.572 | 0.363 | 0.337 | 0.780 | | |
| Information and Communications Technology | 0.063 | 0.406 | 0.396 | 0.641 | 0.335 | 0.361 | 0.856 | |
| Learning Practice | 0.042 | 0.485 | 0.390 | 0.286 | 0.547 | 0.451 | 0.518 | 0.894 |

TABLE 4 HTMT ratio.

| Variables | Beliefs | Co-worker | Culture inheritance | Custom | Information and communications technology | Learning practice |
|---|---|---|---|---|---|---|
| Beliefs | | | | | | |
| Co-Worker | 0.533 | | | | | |
| Culture Inheritance | 0.490 | 0.286 | | | | |
| Custom | 0.798 | 0.444 | 0.436 | | | |
| Information and Communications Technology | 0.510 | 0.754 | 0.397 | 0.436 | | |
| Learning Practice | 0.496 | 0.319 | 0.640 | 0.535 | 0.573 | |

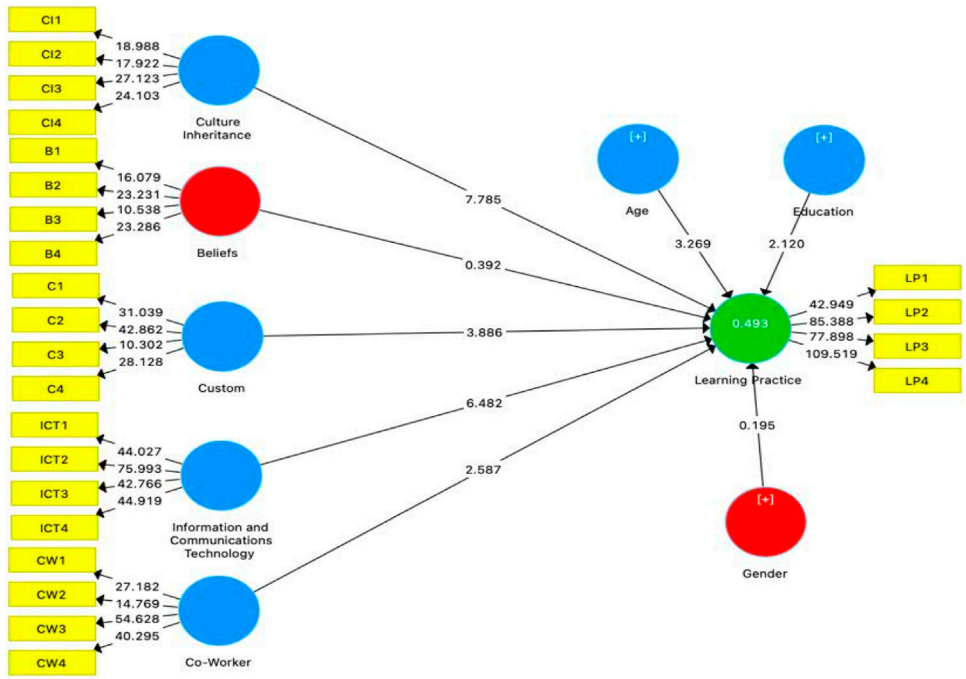


FIGURE 3
PLS-SEM Path Model (Green and blue variables = Significant; Green and red variables = Insignificant).

TABLE 5 Path analysis (PLS-SEM).

| PLS-SEM Paths | Beta (β) | SD | T (Value) | p (Value) | Hypothesis |
|---|---|---|---|---|---|
| B—> LP | 0.022 | 0.057 | 3.392 | 0.695 | Rejected |
| CW—> LP | −0.141 | 0.054 | 2.587 | 0.010 | Accepted |
| CI—> LP | 0.368 | 0.047 | 7.785 | 0.000 | Accepted |
| C—> LP | 0.210 | 0.054 | 3.886 | 0.000 | Accepted |
| ICT—> LP | 0.410 | 0.063 | 6.482 | 0.000 | Accepted |
| Control Variables | | | | | |
| Age—> LP | −0.103 | 0.031 | 3.269 | 0.001 | Significant |
| Gender—> LP | 0.006 | 0.033 | 0.195 | 0.846 | Insignificant |
| Education—> LP | −0.072 | 0.034 | 2.120 | 0.034 | Significant |
| $R^2$ | 0.493 | | | | |
| Adjusted $R^2$ | 0.485 | | | | |

Belief (B); Co-Worker (CW); Culture Inheritance (CI); Custom (C); Information and Communications Technology (ICT); Learning Practice (LP).

TABLE 6 Correlation among variable. Bold Values indicate moderate to high correlation among variables.

| Variables | Age | Beliefs | Co-worker | Culture inheritance | Custom | Education | Gender | Information and communications technology | Learning practice |
|---|---|---|---|---|---|---|---|---|---|
| Age | 1.000 | | | | | | | | |
| Beliefs | −0.095 | 1.000 | | | | | | | |
| Co-Worker | −0.004 | **0.401** | 1.000 | | | | | | |
| Culture Inheritance | 0.028 | **0.352** | 0.240 | 1.000 | | | | | |
| Custom | −0.041 | **0.572** | **0.363** | **0.337** | 1.000 | | | | |
| Education | 0.185 | −0.041 | 0.130 | 0.010 | −0.039 | 1.000 | | | |
| Gender | −0.218 | 0.004 | −0.106 | −0.051 | 0.034 | −0.219 | 1.000 | | |
| Information and Communications Technology | −0.014 | **0.396** | **0.641** | **0.335** | **0.361** | 0.159 | −0.075 | 1.000 | |
| Learning Practice | −0.123 | 0.390 | 0.286 | **0.547** | **0.451** | −0.051 | 0.017 | **0.518** | 1.000 |

different variables. Following that, we carried out a bootstrapping test using 5,000 replicates to evaluate the degree to which our findings were consistent with the hypothesis (Mustafa, Qiao, et al., 2022a). B > LP (β = 0.022; *p* 0.010), CI- > LP (β = 0.368; *p* 0.000), C- > LP (β = 0.210; *p* 0.000), and ICT- > LP (β = 0.410; *p* 0.000) were found to be significant using PLS-SEM direct path analysis.These results offer support to hypotheses H1, H3-H6 accepted and H2 rejected. As per the results of this model, we can say Co-Worker (CW); Culture Inheritance (CI); Custom (C); Information and Communications Technology (ICT); and have a strong association with Learning Practice (LP). We can say our learning particles can be effective with our personal beliefs, customs, ICT, and other related factors. We also looked at the respondents' age, education, and gender as control variables, and found that gender (β = 0.006; *p* 0.846) had insignificant relationships with LP, whereas age (β = −0.103; *p* 0.001) and education (β = −0.072; *p* 0.034) had significant relationships with the dependent variable. Gender has no effect on learning practices (LP), but age and education can be beneficial control variables, and an older and more experienced person can have a greater impact on LP and independent variables (Table 5 and Figure 3). Mathematical models can describe in detail the real relationships that exist between the parameters used to characterize water quality. This analysis not only offers a method for making forecasts but also offers a way to determine the nature of the relationship that exists between the variables. The multivariate parameters were subjected to a Pearson's correlation analysis, and the results show that there is a significant relationship between several of the variables (highlighted numbers). There is a positive association, ranging

from moderate to high, between all of the variables. The descriptive statistics and correlation coefficients of these selected variables are presented in Table 6, which may be seen below. Belief (B), Co-Worker (CW), Culture Inheritance (CI), Custom (C), Information and Communications Technology (ICT), Learning Practice (LP), Gender, Education, and Age (GEA), and Information and Communications Technology (ICT). The concept of correlation refers to a method that can be used to analyze the relationship between two or more variables. The correlation values range from plus one hundred to minus one hundred. The magnitude of the number, with one representing the highest possible value, is used to determine the strength of the link. In the current research, correlation values of selected variables are found to be significant among all variables, and there is a moderate to the high degree of correlation between the various variables. All of the variables were determined to be significant, and there was either a weak or moderately strong, positive or negative correlation between all of the variables that were selected (Table 6).

## 4 Conclusion

Professional growth is dependent on social and institutional contexts as well as personal attributes and circumstances. Following that, this research contains personal dimensions such as beliefs (B), co-workers (CW), culture inheritance (CI), customs (C), information and communications technology (ICT), and learning practice (LP). The research is formed to illustrate that promotion of professional growth in workplaces is connected to the mentioned variables. This study was based on the working experience of different backgrounds people. We tried to check how their attributes could influence their working practices and learning practices. A semi-structured questionnaire was adopted from existing literature and modified as per the study area. PLS-SEM direct path analysis revealed B > LP was insignificant, while CW > LP, CI > LP, C > LP, and ICT > LP are significant. These results offer support to hypotheses H1, H3-H6 accepted and H2 rejected. We have also looked at the levels of age, education, and gender of the respondents as control variables. Gender showed insignificant relationships with LP, and age and education showed significant relationships with the dependent variable. It means gender does not have any relationship with learning practices (LP), but age and education can be favorable control variables, and an aged and experienced person can have more impacts on LP and impacts on independent variables. However, the primary findings of this study can be applied not only in places where adaptations to climate change are currently insufficient but also in other places. The study will help get the right kinds of monitoring and public policies put in place to make sure integration and sustainability, and it will also help policymakers help farmers both in their everyday lives and in their farming work.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## Ethics Statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

FG; Data Collection ZM; Writing, HD; Supervising.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Lightweight noncommutative key exchange protocol for IoT environments

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Network communications are expanding rapidly in many fields, including telecommunications, the Internet of Things, space, consumer electronics, and the military, with different privacy and security issues at stake in each of these areas. The Internet of Things (IoT) has drawn increased attention from academic and industrial researchers over the last few decades. In this environment, keys are routinely exchanged through a public protocol to support the highly secure IoT domain and thwart security threats from unauthorized parties. The environment for IoT devices is subject to numerous limitations, including those related to processing, memory, and energy. These devices need to pass through a gateway or sink to connect to the network. Additionally, the environment must enable secure communication between gateways and IoT devices, even when the devices are disconnected from the rest of the network. In this paper, a lightweight key exchange protocol for IoT environments is presented, allowing the gateway and the IoT device to communicate over an open channel. Our proposed protocol improves security by utilizing noncommutative structures and polynomials over noncommutative rings. The underlying idea is to use the generalized decomposition problem associated with noncommutative rings. Furthermore, how the suggested protocol can achieve key certification and perfect onward secrecy is addressed. Results show this protocol is a strong candidate for key sharing and secure communication between IoT devices. We put our methodology into practice and the results of our experiments demonstrate enhancement of security levels. Finally, the performance analysis of the suggested protocol is compared with some other protocols, in terms of security, communication, and computing overhead.

KEYWORDS

**discrete log problem, public key exchange protocol, public key cryptography, noncommutative ring, polynomial, Internet of Things (IoT)**

# 1 Introduction

The Internet-of-Things (IoT) is an environment that enables interconnected devices and human beings to communicate and send one another information. The use of the IoT environment is growing and is increasingly prevalent in our lives. Many applications depend on functionalities that use information collected from IoT devices: monitoring patient health records, for example. Sometimes it is necessary to send large amounts of data over open wireless channels, such as heavy videos or large image files. In all these situations, the communication of data must be secured and authenticated.

In the IoT environment, the gateway/sink is the main object through which the rest of the environment's devices communicate. We thus require secure and authenticated communication between the IoT device and the gateway/sink. However, traditional key exchange protocols cannot be employed for this purpose due to several constraints. These constraints involve dependence on a trusted third party (TTP) and high processing requirements. It is also essential for IoT environments to be capable of operating even in disconnected mode, without access to a TTP.

The authentication and key exchange processes between two entities without a TTP requires a prior shared secret. Additionally, it is important to eradicate the chance of disclosure of that secret in the environment. We therefore look for more than one secret key, each of which is used for a different purpose. The most important requirement for the implementation of a protocol is to have Perfect Forward Secrecy (PFS). PFS is a feature of a key exchange protocol that ensures the secrecy of all previous session communications in the event of any leakage of a long-term private key. This situation can be controlled by using a different key for every session. If the cryptanalyst can somehow extract the session key, that key does not contain any information about further sessions. This is one of the motivations for our proposed key exchange protocol for the IoT environment. The digital certification of IoT devices depicting the authentication is another salient feature of the IoT environment, which our proposal also addresses.

There is a vast literature suggesting various new techniques, as well as case studies of new technologies and solutions (Ko et al., 2000; Sakalauskas and Burba, 2003; Cheikhrouhou et al., 2020; Zhongjun et al., 2022). In 2017, the National Institute of Standards and Technology (NIST) started an evaluation procedure of cryptographic techniques that can resist quantum attacks. Most of today's cryptosystems currently relying on integer factorization (Rivest et al., 1978) and discrete logarithms (ElGamal, 1985) will become obsolete because of the Shor algorithm (Shor, 1997). Given the quantum threats, there is an increasing trend toward developing new technologies known as quantum key distribution (QKD) (Bennett and Brassard, 1984; Center, 2021; Lizama-P´erez et al., 2021). Seven algorithms have been selected by NIST: four are public key cryptosystems and concern key establishment, and three are related to digital signature algorithms. That is why the active area of research is now noncommutative algebraic cryptography (Anshel et al., 1999; Ko et al., 2000; Paeng et al., 2001; Sakalauskas and Burba, 2003; Inam and Ali, 2016; Kanwal and Ali, 2016). The main focus of this area is to develop and analyze cryptographic protocols over noncommutative structures.

The use of noncommutative structures for public key exchange has been examined by several authors. Here we provide a brief overview of these protocols. In their proposals, Anshel et al. (1999) and Ko et al. (2000) suggested using braid groups as the underlying structure for achieving a good level of security. Thomas and Lal (2008) then proposed a public key cryptographic protocol whose security depends on the discrete log problem (DLP) of the inner automorphism. The main strength of this protocol is the difficulty of finding the conjugate element in a noncommutative group.

The use of a public key cryptographic model was highlighted by Shpilrain and Ushakov (2006), who introduced the difficulty of solving the symmetrical decomposition problem. Thomas and Lal (2008) then proposed a cryptosystem based on the symmetric decomposition problem and conjugacy search problems over a noncommutative structure. For their part, Anjaneyulu and Sanyasirao (2014) generated a common key or group key using the polynomial symmetric decomposition problem. Their proposal was based on the polynomial symmetric decomposition problem over noncommutative division semi-rings.

Furthermore, Meshram et al. (2017) proposed a new IND-CCA2 secure public-key cryptographic protocol. They used the integral coefficient ring polynomial concept with the Suzuki 2-group as the underlying work structure. Odoni et al. (1984) previously discussed the DLP for the ring of matrices. Similarly, the Diffie-Hellman protocol for different matrix rings was presented in Stickel (2005) and Alvarez et al. (2009). In 2004, Stickel (2005) proposed a public key exchange scheme using matrices in a particular subgroup. However, Sramka (2022) highlighted some weaknesses in the scheme, and Shpilrain (2008) provided a cryptanalysis of the scheme, suggesting that it would be more secure to work with a semigroup of all matrices over some finite ring as a platform for the scheme. He also provided a modified method for exchanging a shared secret key. However, Mullan (2012) successfully mounted a linear algebra attack against Shpilrain's modifications of Stickel's scheme.

A broad literature is available concerning key exchange protocols for IoT and their weaknesses (Mano et al., 2016; Khan and Salah, 2018; Mutlag et al., 2019; Lizama-Perez and López, 2021). The first public key exchange was proposed by Diffie and Hellman (1976). After that, there followed an extensive

list of public key exchange protocols, which can be found in the literature: for example, Menezes et al. (1996); Schneier (1996); Singh et al. (2017); and the references therein. Abdalla et al. (2005) proposed a three-party password-authenticated key exchange (3PAKE) protocol for wireless mobile communications. Lu and Cao (2007) modified the 3PAKE protocol, and Chung and Ku (2008) consequently indicated that these protocols were vulnerable to attack by impersonation.

Further, Guo et al. (2008) proved that Anjaneyulu and Sanyasirao (2014)'s improvement of the protocol of Chang et al. (2011) had no security against the replay attack. Chang et al. (2011) and Yoon and Yoo (2011) developed a protocol independent of a symmetrical type of algorithm. In this present study, an improved public key exchange protocol is proposed over the noncommutative ring for IoT devices. The main idea of our proposal is to take polynomials over a given noncommutative ring as useful for secure communication in the pre-and post-quantum age. It is also shown that the brute force attack leads to the solution of the generalized decomposition problem, rendering it infeasible. The rest of this manuscript is organized as follows:

Section 2 provides a brief overview of the security challenges and requirements of the IoT environment. Section 3 gives the basic definitions of related cryptographic problems over noncommutative structures. The proposed protocol is presented in Section 4. We also discuss security aspects of the proposed protocols. The guaranteed secrecy of the new session keys achieved by the perfect forward security method is described in Section 5. Section 6 describes a procedure to certify the public keys across inter-domain certificates. The experimental results and discussion of computational cost are covered in Section 7. Finally, the conclusion of the work is drawn in Section 8.

## 2 Security challenges of IoT environments

It is a highly challenging task to achieve proper levels of security in an IoT environment. These environments are vulnerable to potential attacks, such as user privacy and data integrity attacks. The physical failure of IoT devices and malicious invasions are other potential issues involved. The interconnected devices are usually resource-limited, with inadequate storage capability and energy, which is why IoT environments are sensitive to various threats. Thus, critical IoT data may be blocked and changed, with unrecoverable financial and security consequences. To protect the IoT against attacks, while keeping in mind the memory size and computation power of devices (Alohali and Vassialkis, 2015) in IoT environments, advanced protocols and algorithms need to be evolved. For robust security of the IoT environment, data integrity is also necessary, because a large amount of data has to be processed and managed, and therefore the security of data exposure is essential.


FIGURE 1
A simple hierarchical model for an IoT environment.

### 2.1 Security risks and secure design requirements for the IoT environment

The environment under consideration consists of a collection of wireless nodes (devices) having sensing elements. These devices, known as things, are structured into groups. There is a node called a gateway in each group responsible for connecting to the rest of the network. The gateway (GW) may connect with other gateways in the network, and all gateways may be connected to the main server. The data generated by different things are deposited on the main server. There are two main related risks. First, there is the risk of someone eavesdropping on the traffic of the data and of traffic analysis, which may result in the disruption of the whole network. To overcome this risk, secure communication is needed between the nodes. Second, there is always the risk of the physical destruction or imprisonment

of nodes. Given these risks, the following security requirements are essential:

- The things should be authenticated when they request to join the network.
- The gateways should forward data only from authenticated things.
- There should be complete privacy of communication between the things and the server.
- If possible, confidential information should not be put on any one individual thing.

Figure 1 shows a simple example of an IoT environment. Note that a thing may connect or leave the network at any time. Our proposal is based on the needs described above. The main aim is to guarantee the authentication of a thing without significant effect on the network and the provided facilities.

# 3 Background definitions

This section describes different problems involved in the security of noncommutative group-based cryptography. For instance, Diffie and Hellman (1976) and the Birman et al. (1998) used the conjugator search problem in braid groups to develop their approach. A new Diffie-Hellman-like protocol and ElGamal-like cryptosystem were proposed in Cao et al. (2007). These proposals are based on the symmetric decomposition and generalized symmetric decomposition problems over noncommutative groups. The details of these problems are given as follows.

## 3.1 Definition 1: Conjugator search problem (CSP)

Let $G$ be a noncommutative group. Given two elements $g, h \in G$, the problem of finding an element $k \in G$, where

$$h = k^{-1}gk$$

is known as the conjugator search problem.

## 3.2 Definition 2: Decomposition problem (DP)

Let $G$ be a noncommutative group and $S$ be the subset of $G$. Given two elements $g, h \in G$, the problem of finding two elements $k_1, k_2 \in S$, where

$$h = k_1 g k_2$$

is known as the decomposition problem (Cao et al., 2007).

Generally, for a noncommutative group, the two problems CSP and DP are considered difficult enough given the cryptographic assumptions. More specifically, the DP is intractable, meaning that no probabilistic polynomial-time algorithm is used to solve the DP with nonnegligible accuracy.

## 3.3 Definition 3: Symmetric decomposition problem (SDP)

Let $G$ be a noncommutative group and $m, n \in Z$. Given two elements $g, h \in G$, the problem of finding the element $k \in G$, where (Cao et al., 2007)

$$h = k^m g k^n$$

is known as the symmetric decomposition problem.

## 3.4 Definition 4: Generalized symmetric decomposition problem (GSDP)

Let $G$ be a noncommutative group, a subset $S$ of $G$ and $m, n \in Z$. Given two elements $g, h \in G$, the problem of finding the element $k \in S$, where (Cao et al., 2007)

$$h = k^m g k^n$$

is known as the generalized symmetric decomposition problem.

Given these problems, we now define the following cryptographic problem over a noncommutative group $G$.

## 3.5 Definition 5: Generalized decomposition problem (GDP)

Let $G$ be a noncommutative group, two subsets $S_1$ and $S_2$ of $G$ and $m, n \in Z$. Given two elements $g, h \in G$, the problem of finding two elements $k_1 \in S_1$ and $k_2 \in S_2$, where

$$h = k_1^m g k_2^n$$

is called the generalized decomposition problem.

Note that the GDP can be considered a special form of a constrained DP. If the size of sets $S_1$ and $S_2$ is taken to be sufficiently large, and assuming that extracting $k_1$ and $k_2$ from $k_1^m g k_2^n$ is impossible from the membership information of sets $S_1$ and $S_2$, then it is believed that the GDP is at least as hard as the DP. It follows that the GD assumption states that the GDP is intractable, which means there is no probabilistic polynomial-time algorithm that can solve the GDP with nonnegligible accuracy.

We now give a variant of the GDP over a noncommutative ring R and name it as the polynomial generalized decomposition problem (PGDP).

### 3.6 Definition 6: Polynomial generalized decomposition problem (PGDP)

Let $R$ be a noncommutative ring, $Z(R)$ be the center of $R$ and $Z(R)[X]$ be the polynomial ring over $Z(R)$. For any random elements $a_1, a_2 \in R$, consider the sets $S_{a_1} \in R$ and $S_{a_2} \in R$ defined as

$$S_{a_1} = \{P(a_1): P(X) \in Z(R)[X]\},$$
$$S_{a_2} = \{P(a_2): P(X) \in Z(R)[X]\}.$$

Let $m, n \in Z$. Given two elements $g, h \in R$, the problem of finding two elements $k_1 \in S_1$ and $k_2 \in S_2$, where

$$h = k_1^m g k_2^n$$

is known as the polynomial generalized decomposition problem.

So, the PGD (polynomial generalized decomposition) cryptographic assumption states that the PGDP over R is intractable, which means there is no probabilistic polynomial-time algorithm that can solve the PGDP with nonnegligible accuracy.

We are going to use the PGDP in our proposed key exchange protocols as described in the following section.

## 4 Proposed protocol for generation and distribution of keys

In order to increase security, we present a protocol that offers a novel authentication mechanism. It is more efficient and cost effective. The performance analysis of the suggested work is validated and compared with the current protocols in terms of security, communication, and computing overhead.

We now demonstrate the main structure of the proposed protocol for a group $g$ of IoT devices under a gateway $GW_g$. The nodes/devices are represented by $N_{i,g}$, $i = 1, 2, \cdots, n$. The gateway $GW_g$ manages key generation and distribution for the nodes by performing the following steps.

It selects a noncommutative ring $R$. Let $Z(R)$ be the center of $R$ and $Z(R)[X]$ be the polynomial ring over $Z(R)$. The elements $c \in R \backslash Z(R)$ and $a_1, a_2 \in R$ are the global parameters. For the $i$th node/device, the gateway executes the following steps:

- A random polynomial $P_{i,g}(X) \in Z(R)[X]$ such that $P_{i,g}(a_1) \neq 0$, $P_{i,g}(a_2) \neq 0$.
- Small numbers (for instance, less than 10 (Cao et al., 2007)) $r_{i,g}, s_{i,g} \in N$ are chosen.
- The gateway generates the key for each device as follows:

$$KN_{i,g} = \left(P_{i,g}(a_1)\right)^{r_{i,g}} c\left(P_{i,g}(a_2)\right)^{s_{i,g}} \quad (1)$$

.

- The $KN_{i,g}$ is sent to the $i$th device $N_{i,g}$.

The following steps would be executed for sharing a secret key between $i$th and $j$th node:

•$i$th node computes the shared secret key as follows:

$$W_i = \left(P_{i,g}(a_1)\right)^{r_{i,g}} KN_{j,g}\left(P_{i,g}(a_2)\right)^{s_{i,g}} = K_s. \quad (2)$$

- $j$th node finds the shared secret key as follows:

$$W_j = \left(P_{j,g}(a_1)\right)^{r_{j,g}} KN_{i,g}\left(P_{j,g}(a_2)\right)^{s_{j,g}} = K_s. \quad (3)$$

The correctness of the proposed protocol is shown in Theorem 1.

**Theorem 1:** Keeping in mind the specified notation, it follows that the shared secret keys obtained by both entities are the same, that is $W_i = W_j$.

Proof

First, consider the expression

$$W_i = \left(P_{i,g}(a_1)\right)^{r_{i,g}} KN_{j,g}\left(P_{i,g}(a_2)\right)^{s_{i,g}}$$

that becomes by using (1),

$$W_i = \left(P_{i,g}(a_1)\right)^{r_{i,g}} \left(P_{j,g}(a_1)\right)^{r_{j,g}} c\left(P_{j,g}(a_2)\right)^{s_{j,g}} \left(P_{i,g}(a_2)\right)^{s_{i,g}}. \quad (4)$$

Expression (3) gives

$$W_j = \left(P_{j,g}(a_1)\right)^{r_{j,g}} KN_{i,g}\left(P_{j,g}(a_2)\right)^{s_{j,g}}$$
$$= \left(P_{j,g}(a_1)\right)^{r_{j,g}} \left(P_{i,g}(a_1)\right)^{r_{i,g}} c\left(P_{i,g}(a_2)\right)^{s_{i,g}} \left(P_{i,g}(a_2)\right)^{s_{i,g}}. \quad (5)$$

Since the coefficients of the polynomials are from the center $Z(R)[X]$ of the ring $R$, they commute with every element $g$ of the ring. That is why, for any two polynomials $P(X), Q(X) \in Z(R)[X]$ and $\forall g \in R; \forall l, m \in N$, the following holds:

$$P(g)Q(g) = Q(g)P(g).$$

Using this property successively, we have

$$(P(g))^l (Q(g))^m = (Q(g))^m (P(g))^l, \quad (6)$$
$$\forall g \in R; \forall l, m \in N; \forall P(X), Q(X) \in Z(R)[X].$$

Given property (6), expressions (5) and (6) are the same.

It is obvious that for the proposed public key exchange protocol, the passive attack can be resisted with the PGD assumption over the noncommutative ring.

### 4.1 Device authentication

After getting the key by the gateway, the $i-th$ device $N_{i,g}$ announces its public key by the following:

- A random polynomial $P_i(X) \in Z(R)[X]$, such that $P_i(a_1) \neq 0$, $P_i(a_2) \neq 0$.

TABLE 1 The size of the set of polynomials of different degrees $\alpha$ and prime $p$ with the order of matrices $n = 2$.

| | α (degree of the polynomial) | $p$ (prime number) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2 | 3 | 5 | 7 | 11 | 13 |
| Proposed Protocol | 2 | 4 | 18 | 100 | 294 | 1210 | 2028 |
| Climent et al., 2012 | | 12 | 27 | 75 | 147 | 363 | 507 |
| Proposed Protocol | 3 | 8 | 500 | 2058 | 13310 | 26364 | 78608 |
| Climent et al., 2012 | | 16 | 36 | 100 | 196 | 484 | 676 |
| Proposed Protocol | 13 | 8192 | 3188646 | 4882812500 | 581334062442 | 345227121439310 | 3634501279107040 |
| Climent et al., 2012 | | 56 | 126 | 350 | 686 | 1694 | 2366 |
| Proposed Protocol | 20 | 1048576 | 6973568802 | 381469726562500 | 478753597785672000 | 6727499949325600000000 | 2280595652985700000000000 |
| Climent et al., 2012 | | 84 | 189 | 525 | 1029 | 2541 | 3549 |

- Small numbers (for instance, less than 10 [9]) $r_i, s_i \in N$ are chosen.
- The device generates the key $PN_{i,g}$ as follows:

$$PN_{i,g} = (P_i(a_1))^{r_i} KN_{i,g} (P_i(a_2))^{s_i} \tag{7}$$

If $j$th, the IoT device whose public key is

$$PN_{j,g} = \left(P_j(a_1)\right)^{r_j} KN_{j,g} \left(P_j(a_2)\right)^{s_j} \tag{8}$$

wants to communicate with the $i$th device, and before communication, $N_{i,g}$ wants to authenticate the device $N_{j,g}(j \neq i)$ of the same group, the device $N_{i,g}$ will have to validate the $N_{j,g}$ device, which is done by executing the following steps:

- The sender device $N_{j,g}$ sends

$$MN_{j,g} = \left(P_j(a_1)\right)^{r_j} PN_{i,g} \left(P_j(a_2)\right)^{s_j} \tag{9}$$

to the device $N_{i,g}$ for validation, where $P_j(a_1) \neq 0$, $P_j(a_2) \neq 0$, and $r_j, s_j \in N$.

- The device $N_{i,g}$ computes the following:

$$VN_{i,g} = (P_i(a_1))^{r_i} PN_{j,g} (P_i(a_2))^{s_i} \tag{10}$$

where $PN_{j,g}$ is the public key of device $N_{j,g}$.

If

$$VN_{i,g} = MN_{j,g}, \tag{11}$$

then device $N_{i,g}$ will validate the device $N_{j,g}$; otherwise, it rejects the request.

## 4.2 Choice of parameters

Suppose we take the ring of matrices of order 2 over $\mathbb{Z}_p$ where $p$ is any large prime as the noncommutative ring. Care must be taken in the choice of a large value of prime, approximately of the order of 60 decimal digits.

For a brute force attack, one has to check all the polynomials whose coefficients come from the set $Z(M_2(Z_p))$. The cardinality of the set of polynomials having degree $\alpha$ and coefficients from $Z(M_2(Z_p))$ is $(p-1)p^{\alpha}$. The feasibility of a brute force attack can be denied by taking $\alpha$ or prime p which is sufficiently large to be good enough for security. For example, with the choice of $\alpha = 20$ and $p$ of about 60 decimal digits prime, the set of polynomials to be considered is of the order of $10^{660}$. Although these parameters are not so high, the space for a brute force search can be made sufficiently large.

The values of $(p-1)p^{\alpha}$ for different values of α and p are shown in Table 1 and compared with the existing literature (Climent et al., 2012). We note that the number of possibilities of our proposal exceeds these drastically. The proposed protocol exhibits some kind of symmetry in the sense that the computation of public keys involves the same polynomial, which is multiplied with element c from both sides. This symmetry can be avoided by introducing two different polynomials for each user.

If the degrees of the two polynomials are $\alpha$ and $\beta$, respectively, then the total number of possible polynomials for one user is $(p-1)^2 p^{\alpha+\beta}$. The feasibility of a brute force attack could be avoided by taking $\alpha$, $\beta$, or a prime $p$ that is sufficiently large. For a prime $p$ of about 60 decimal digits (as in the case of the previous example), and $\alpha = 20$ and $\beta = 20$, the number of polynomials that an adversary has to consider is of the order of $10^{1320}$.

## 4.3 Security aspects of the proposed protocols

This section discusses the security analysis of the protocols proposed in Section 3. The security of the protocols depends on the solution of the generalized decomposition problem. For solving such a problem in a noncommutative ring, no polynomial-time algorithm is known. An adversary has to find the solution to the decomposition problems, which are expressed as the following system of equations:

$$M_A M_B = M_B M_A, \tag{12}$$
$$N_A N_B = N_B N_A, \tag{13}$$
$$M_A C N_A = K_A, \tag{14}$$
$$M_B C N_B = K_B. \tag{15}$$

The adversary also knows the elements $a_1, a_2 \in R$ and $c \in R \setminus Z(R)$. To break the protocol, the adversary has to find the elements $M_A, M_B, N_A$, and $N_B$. For this, the adversary tries to find out two polynomials $H_1(X), H_2(X) \in$ Z(R)[X] and numbers $l_1, l_2, m_1, m_2 \in N$ such that

$$(H_1(a_1))^{l_1} = M_A,$$
$$(H_1(a_2))^{l_2} = N_A,$$
$$(H_2(a_1))^{m_1} = M_B, \text{and}$$
$$(H_2(a_2))^{m_2} = N_B.$$

One can then guarantee conditions (12) and (13). We note that the size of the space of the polynomials over $Z(R)$ is a set of all possible random choices. Also, the adversary has to verify conditions (14) and (15). By ensuring the space of the polynomials over $Z(R)$ is large enough, the brute force attack becomes infeasible. To make brute force infeasible, it is suggested choosing a prime p of the order of 60 decimal digits and polynomials of degree 20. As discussed earlier, the space for brute force attacks can be made large enough with these choices. The order of the matrices n can be chosen so that $2^n - 1$ is a Mersenne prime. The choice of a Mersenne prime $n = 31$ is recommended (Stickel, 2005).

### 4.3.1 Man-in-the-middle attack

In this attack scenario, the adversary has a man-in-the-middle position. He can breach the security of the key exchange protocol by intercepting the communication between Alice (*i*th device) and Bob (*j*th). The attacker manipulates the public keys of both parties and blocks the transmission of actual messages on either side. The proposed protocol can be immunized against this type of attack in the following way.

The gateway can use hashes and encrypt the private keys $P_{i,g}$ of each device using the admin key, which are then saved into a devices hash table.

When the devices calculate their secret shared keys, the gateway calculates the same. The gateway then hashes the shared key and keeps it in the device hash table. Alice (*i*th device) and Bob (*j*th) then hash their shared keys and ask the gateway for verification. The gateway checks the hashed shared keys with the hash table. If the hash value of the shared key matches, then communication may be allowed. Otherwise, the shared key is assumed to have been intercepted and manipulated by the attacker.

For authentication of the gateway, the device authentication mechanism described in Section 4.1 can also be implemented between an IoT device and gateway. Each IoT device and gateway pair can have a unique pair of keys specifically for authentication. Further, IoT devices and the gateway are authenticated using encryption and a hash of the keys during a session.

### 4.3.2 Privileged insider attack

To prevent this type of attack, the passwords can be managed at the time of registration of the users in the following way.

Each user chooses a username and password and provides this information to the web browser. The passwords can be encrypted by the public key, and their hashes can be stored in a password management table. The users are authenticated by their usernames and passwords. It is hard to get passwords because they are encrypted by public keys. The protocol's security depends on the solution of Eqs 12–15 describing the generalized decomposition problem in a noncommutative ring. The insider finds it hard to guess a password.

### 4.3.3 Impersonation attack

It is difficult to detect an impersonation attack. In our case, if the attacker impersonates the authenticated user and launches a login request, it is not easy to extract the user id and password because they are encrypted, as discussed in the previous section. Inverting the hash function and decrypting it without knowing the key that generalizes the decomposition problem of the polynomials over the noncommutative ring is computationally hard. The user-impersonation attack is thus resisted by our proposed protocol.

# 5 Perfect forward secrecy (PFS)

Based on the already shared secret key $K_s$, Alice (*i*th device) and Bob (*j*th) may want to have a new secret key $K_t$. However, if there arises a situation in which $K_t$ is compromised by an adversary, then perfect forward secrecy (PFS) is a property of key exchange protocols that assure the secrecy of previously used keys in such leakage. Figure 2 depicts our PFS key exchange protocols that yield new session secret keys. As the private keys of Alice and Bob remain secret, the adversary may get access to $K_t$, but $K_s$ will not be found.

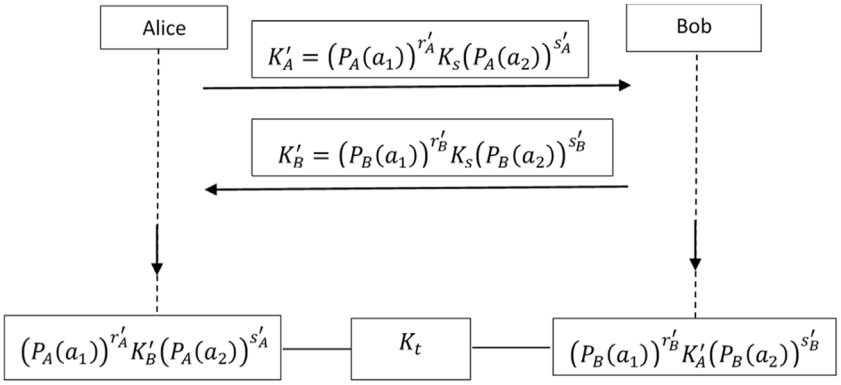


FIGURE 2
Perfect forward secrecy (PFS) in proposed noncommutative key exchange protocol.

Stickel (2005) proposed that the order of matrices $n = 31$ is a secured parameter, and the parameter $q$ (the order of finite field $F_q$) was not specified. But Shpilrain (2008) remarked in his paper that $q = 2q' \, for \, q' \in [2, 31]$. Shpilrain's attack revealed the shared key without knowledge of any private exponents, whereas Sramka's (2022) attack concentrated on computing the private exponents $l, m, r, and \, s$ of Stickel's scheme.

Shpilrain modified Stickel's scheme to prevent his linear algebra attack, suggesting that the publicly announced elements $M, N, W$ need not be invertible matrices in $M_n(R)$, for some finite ring R. But no specification about ring $R$ was made. Further, he suggested the use of polynomials in the form $\sum c_i X^i, \; for \, c_i \in R$, where $R$ is a finite commutative ring, and then used the fact that all powers $Mi$ of a matrix $M$ commute in the expression of the form $\sum c_i X^i$. This is a generalization of Stickel's scheme, in which Alice and Bob choose polynomials instead of exponents of the public noninvertible matrices $M$ and $N$.

Mullan (2012) called Shpilrain's modification the polynomial version of Stickel's scheme. He offered a cryptanalysis of Shpilrain's polynomial variant of Stickel's scheme to discover the shared key. Cao et al. (2007) proposed a new scheme for devising a public key cryptosystem based on noncommutative rings. The main idea of their proposal was that for a noncommutative ring, the set of polynomials can be considered the underlying work structure. The Diffie-Helman-like key exchange protocol and consequently ElGamal-like cryptosystems were constructed using polynomials over the noncommutative ring. The authors also showed how to extend their method to noncommutative groups (or semi-groups). The main difference between Shpilrain's polynomial version of the Stickel scheme and the key exchange protocol proposed by Cao et al. (2007) was in the use of the underlying structures. Shpilrain's proposal was for commutative structures, whereas Cao et al. (2007) proposed the use of noncommutative structures.

The protocol proposed by Cao et al. (2007) deals with the polynomials having coefficients from the set of positive integers. In our proposal, polynomials with coefficients from the center of the respective underlying noncommutative structure are used. The advantage of using the coefficients from the center over integer coefficients is that these coefficients depend on the nature of the noncommutative structure used as a platform. That is why determining the values of coefficients is difficult when choosing a complex platform.

A random choice of the polynomial $P(X) \in Z(R)[X]$ and $a_1, a_2 \in R$, such that $P(a_1) \neq 0 \, and \, P(a_2) \neq 0$ is the essential idea. An attacker has no way of determining a polynomial such that $P(a_1)(\neq 0) \in S_{a_1}$ and $P(a_2)(\neq 0) \in S_{a_2}$, even with unlimited computational power. Keeping in mind the huge size of the set of polynomials, as discussed in previous sections, and consequently the huge number of elements of sets $S_{a_1}$ and $S_{a_2}$, there is an insignificant probability of tracing the private key by an attacker. That is why, even with infinite computing power, the protocol is sound.

The proposed protocol meets the different kinds of requirements of lightweight mechanisms. As it is based on polynomials, it requires fewer bytes for manipulation over the network. Also, the computations involved in key exchange and authentication are fast and space efficient, which makes the protocol suitable for implementation in a lightweight scenario. The protocol can also resist various attacks. Table 2 summarizes the overall strengths of the proposal.

TABLE 2 Comparison of security in some existing protocols.

| | Protocols | | | | |
|---|---|---|---|---|---|
| Security aspects | Proposed | Poomagal et al., 2020 | Wang et al., 2008 | Strangio, 2005 | Zhangxiang et al.; Hu et al., 2022 |
| Authentication | Yes | Yes | Yes | Yes | No |
| Perfect Forward Security | Yes | Yes | Yes | Yes | No |
| Impersonation Attack | Yes | Yes | Yes | No | No |
| Man-in-Middle Attack | Yes | No | No | No | Yes |

TABLE 3 Certification Authority's public database.

| User | Public key | Certified key |
|---|---|---|
| Certification Authority | $K_{ca} = (P_{ca}(a_1))^{r_{ca}} c(P_{ca}(a_2))^{s_{ca}}$ | — |
| *i*th device | $K_i = (P_i(a_1))^{r_i} c(P_i(a_2))^{s_i}$ | $(CK)_i = (P_i(a_1))^{r_i} K_{ca}(P_i(a_2))^{s_i}$ |
| *j*th device | $K_j = (P_j(a_1))^{r_j} c(P_j(a_2))^{s_j}$ | $(CK)_j = (P_j(a_1))^{r_j} K_{ca}(P_j(a_2))^{s_j}$ |

## 6 Certified keys

A vital characteristic of public keys is authentication by a certification authority (CA). The keys of the proposed key exchange protocol can be certified using the CA's private key $(P_{ca}, r_{ca}, s_{ca})$, as described in Table 3.

After getting their public certified keys from the web service, *i*th and *j*th device find the shared secret key as $(P_i(a_1))^{r_i}(CK)_j(P_i(a_2))^{s_i}$ and $(P_j(a_1))^{r_j}(CK)_i(P_j(a_2))^{s_j}$, respectively.

## 7 Experimental results and performance analysis

For the implementation of our protocol, Python 3.6.9 with cryptography library Pycrpto 2.6.1 is used. The Mininet platform (Hu et al., 2022) is used for creating the networking environment. The communication cost of a protocol is affected by different attributes. By analyzing these attributes, the effects of the implementation of the protocol can be studied. The following are some parameters to be studied in this regard:

### 7.1 Passes overhead

The number of messages exchanged in the execution of the protocol is known as the number of passes. A key exchange protocol with a significant number of passes is considered more costly. The proposed protocol costs three passes in distributing and sharing keys, with the choice of parameters suggested in Section 4.2. Practically, the *i*th and *j*th nodes can generate their shared key simultaneously and need only one communication pass from either node without any further communications.

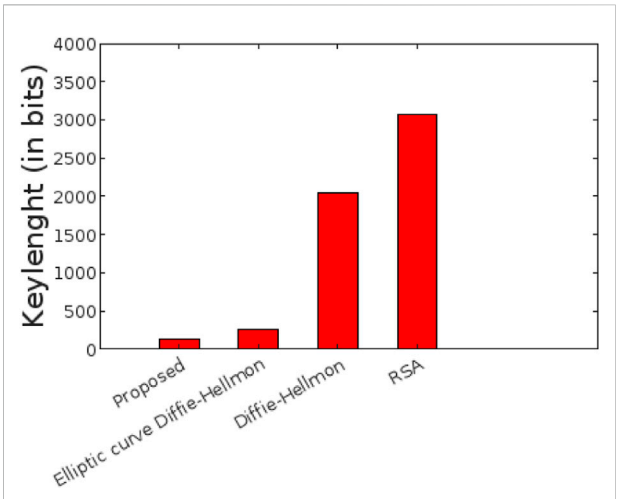


FIGURE 3
Key length comparison.

### 7.2 Communication cost

The total number of transmitted bits for optimized performance is known as communication overhead or communication cost. A protocol with a low communication overhead is considered more efficient. We take the key length of our key exchange protocol to be

TABLE 4 Comparison of cost.

| | Protocols | | | |
|---|---|---|---|---|
| Parameters | Proposed | Poomagal et al., 2020 | Wang et al., 2008 | Strangio, 2005 |
| Total number of operations | $9t_{sm}+10t_e+1t_h$ | $3t_{sm}+1t_e$ | $3.5t_{sm}+1t_{fi}+2t_h$ | $5t_{sm}+2t_h$ |
| computational cost (in seconds) | 0.192348 | 0.20845 | 0.228967 | 0.316015 |

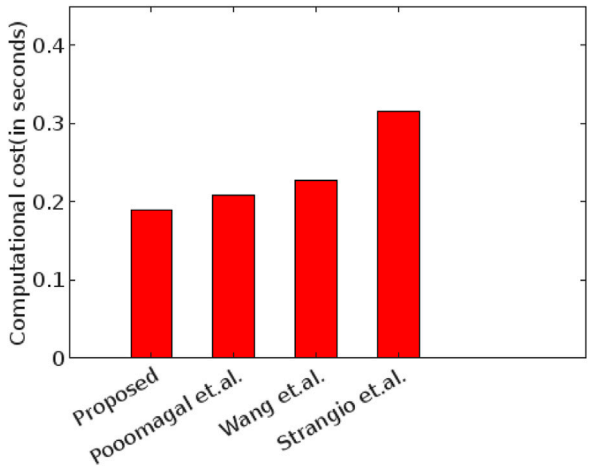


FIGURE 4
Comparison of computational cost.

128-bits, whereas the equivalent key lengths of the state-of-the-art protocols of RSA, Diffie-Hellman, and elliptic curve Diffie-Hellman are 3072-bits, 2048-bits, and 256-bits, respectively. Our proposed protocol performs better than these protocols because it uses polynomials over the noncommutative ring. When compared to the exponential operations used in RSA and Deffie-Hellman, and the elliptic curve operations used in elliptic curve based protocols, operations based on polynomials use less processing space and power. Figure 3 shows the comparison of the key lengths of the protocols.

## 7.3 Computational time

The total time consumed by the protocol is known as computation time. Some of the attributes of the computational cost are as follows:

For the execution of an algorithm, it is preferred that the total number of arithmetical operations is as low as possible, so as to enhance efficiency and reduce the computational cost. With the increase in the number of operations, the energy and running time of the algorithm may be compromised. The calculation of the computational time of the proposed protocol is based on the ring scalar multiplication, hash operation, and exponentiation operation. The calculated result is then compared with some recent protocols.

With the choice of parameters suggested in Section 4.2, the scalar multiplication involved in our proposed protocol requires 0.003432 s, the hash needs 0.00025 s, and the modular exponentiation operation takes 0.016121 s. The gateway performs six scalar multiplications and eight exponentiations, while three scalar multiplications, two exponentiation operations, and a hash function calculation are involved in the calculation of the key at each IoT device end. Therefore, 0.14956 and 0.042788 s are required for calculations on the gateway and each device, respectively. The total time cost is 0.192348.

The time for simple addition and multiplication operations can be neglected because it is negligible compared to other operations. Table 4; Figure 4 show the comprehensive result of the total computation time for all the operations of our protocols and other protocols. Notations $t_e$, $t_{sm}$, $t_{fi}$, and $t_h$ represent the computation time required for exponentiation, scalar multiplication, field inversion, and hash function, respectively. The protocol in Poomagal et al. (2020), Wang et al. (2008), and Strangio (2005) takes more time than the proposed algorithm. It also performs better than some existing protocols, as depicted in Table 4.

# 8 Conclusion

A lightweight, efficient, and secure key exchange protocol for secret communication in IoT environments is presented. The related features of key exchange protocol, such as PFS and key certification, are addressed in the proposal. The security aspects of the new protocol are discussed in detail. For the scheme's implementation, the values of related parameters are suggested. It is shown that the proposed protocol enables secure communication between IoT devices in the future regime. Further, an ElGamal-like cryptosystem can also be constructed based on the proposed protocol.

# Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

## Author contributions

SK designed the model and the computational framework and analysed the data. SI and RA assisted with the measurements and wrote the paper with input from all authors. OC and AK contributed to the interpretation of the experimental results. AK provided critical feedback and helped shape the overall structure of the revised manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Health risks associated with radon concentrations in carbonate and evaporite sequences of the uranium-rich district Karak, Pakistan

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The present research was carried out to investigate the behavior of radon ($^{222}$Rn) concentrations over the carbonate and evaporite sequences and to assess the related health hazards. A total of 50 points from three different stratigraphic units, namely, the Bahadurkhel Salt, Jatta Gypsum, and the Kohat Formation of the Eocene age, were analyzed for radon concentrations in the district of Karak, Khyber Pakhtunkhwa, Pakistan. Measurements for radon levels were made by using RAD7 of Durridge, United States. The highest average $^{222}$Rn concentration (16.5 Bq/L) was found in the limestone unit of the Kohat Formation of the Eocene age. However, the lowest radon levels were observed in the salt-bearing strata of the Bahadurkhel Salt of the Eocene age. The study revealed that the average radon concentration in all the lithologies varied in the order of *RnLimestone* > *RnSalt* > *RnGypsum*. The findings of the current research suggest that the study area is safe from radon-related health hazards.

KEYWORDS

**radon, gypsum, salt, limestone, Eocene, Karak**

## Introduction

$^{222}$Rn, an invisible radioactive gas with a half-life of 3.82 days, is naturally occurring in all types of soils in measurable quantities (Goodwin et al., 2009). $^{222}$Rn is a $^{238}$U chain progeny decaying to $^{218}$Po and discharging a potentially harmful alpha particle. Radon and its progenies like $^{218}$Po, $^{214}$Po, and $^{214}$Bi have been pointed out to be the major sources of public exposure from natural radioactivity, contributing to almost 50% of the worldwide mean effective dose to the community (UNSCEAR, 2000; Somlai et al., 2007). Over 90% of the total radiation dose received due to radon exposure is

contributed by two of the alpha-emitting daughters of $^{222}$Rn, i.e., $^{218}$Po and $^{214}$Po (Gillmore et al., 2001). After inhalation or ingestion, radon decays and releases energy, causing lung and stomach cancer (Khattak et al., 2011). Exposure to elevated radon concentrations *via* inhalation for a long time is the second major cause of lung cancer, with smoking being the first cause (The World Health Organization, 2005; Matiullah and Muhammad, 2017). This phenomenon of radon makes it a human health menace. The presence of radon, on the other hand, in the rocks, soil, and alluvial material can serve as a tool for exploring geological features and predicting earthquakes.

Radon emanates from rocks and easily migrates and enters the groundwater bodies that fracture (Arabi et al., 2016; Khan et al., 2022). Although radon can occur in almost all rock and soil types, the concentration differs with different sites and geological materials (Singh et al., 1999). The source and distribution of radon is mainly controlled by the geology (Appleton and Miles, 2005; Appleton and Miles, 2010). Particular rock types (not all) and unconsolidated deposits have relatively high radon emanation, for example, granites, phosphatic rocks with uranium enrichment, and organic shales. The chemical composition of the rocks and soils and the distribution of alluvium and till deposits are controlled by the geology of the region from which radon is being released. According to Gundersen et al. (1992) and Schumann (1993), different rocks and soils act as sources for radon gas. Amongst the most likely rock types that are causing radon emissions are carbonaceous shales, glauconitic sandstones, fluvial deposits, carbonate rocks (karst topography), chalk, phosphorites, tillites, granites, metamorphosed rocks with granitic composition, bauxite, different types of coal deposits, graphite schists, silica-rich volcanic rocks, fractured or faulted rocks, and some types of contact metamorphic rocks. The different rocks, e.g., quartzose sandstone, non-organic shales and siltstones, and silica-deficient igneous and metamorphic rocks, are least likely to cause radon emanations. Localized uranium deposition as hydrothermal vein deposits in igneous and metamorphic rocks and roll-front deposits in sedimentary rocks can cause exceptions to radon discharge (Gundersen, 1991).

The most important fundamental influence on soil $^{222}$Rn potential is the concentration of radionuclides in the rocks. In most cases, a high soil gas $^{222}$Rn concentration is developed over the rocks with high $^{226}$Ra concentrations (Schumann and Gundersen, 1996; Khan et al., 2022). Not only is the $^{238}$U or $^{226}$Ra concentration of a soil controlled by the type of bedrock but also the gas permeability of a soil, which determines the migration distance, depends on the bedrock. By comparing the average $^{238}$U concentration of rocks and soils indicate that enrichment of radionuclides can take place in soils due to weathering processes. This is particularly true for limestones; even if these rocks are poor in $^{226}$Ra, high $^{226}$Ra concentrations are observed within their soils (Wiegand, 2001). Limestones were intensely chemically weathered during the tropic conditions of the Tertiary period, absorbing a large fraction of the mobilized $^{226}$Ra by the thin layer of clay minerals, which is usually developed above limestone. The overall concentration of $^{238}$U in sediments from the limestone catchment is low (2.8–3.6 ppm). High radon emissions can occur on limestone because of the higher permeability and high specific surface area of these uranium minerals, allowing the efficient release of radon (Ball et al., 1991). Additionally, elevated migration rates are prompted by the high fracture and joint permeability of the limestone and the permeability of the overlying soils.

The term evaporite is generally used for rocks that are formed as a result of the process called evaporation. These rocks are also called crystalline rocks because they are formed by the linking or bonding of crystals with each other. The most common types of evaporites are salt (NaCl) and gypsum ($CaSO_4.2H_2O$). These rocks are made up of crystals of minerals that do not have uranium in them, so they are considered to be less radon-prone rocks (Baloch et al., 2012). If any intrusion occurs, it may increase the probability of radon emanation in evaporites, such as granitic intrusion (Scheib et al., 2013).

The transport of gases is influenced by the main component of soil regarded as diffusivity (Ball et al., 1991; Ehsan et al., 2018). The interstitial pore spaces of soil are the sites from which radon gas can emanate. A controlled measurement of radon can be carried out from the bedrock or soil as it diffuses to the surface before decaying. The two main constituents required to predict the radon hazard potential of an area include the soil radon concentration and soil gas permeability (Neznal et al., 2004). The elevated levels of radon gas identified in indoor air make it a dangerous agent for human health.

Different research practices have been carried out to assess the impacts of environmental issues on human health. According to the United Nations' sustainable development goals, environmental conditions have direct and indirect impacts on human wellbeing. It is claimed that better opportunities for human wellbeing are produced by better ecological conditions, thus creating positive associations between good quality environmental conditions and human wellbeing (Sohail et al., 2019; Bhandari, 2022; Sohail et al., 2022). The present study is aimed to measure the soil gas radon concentration over three different lithological units, i.e., salt, gypsum, and limestone, with the active method of using an electronic RAD7 radon monitor to establish a database for soil gas radon levels and associated health risks as the literature survey shows that no attempt has been made in the area in this regard.

## Geological setting

The study area lies in the southern Kohat Plateau. The geology of the area has been studied in great detail by many workers (Meissner et al., 1974; Ahmad, 2003). In general, the

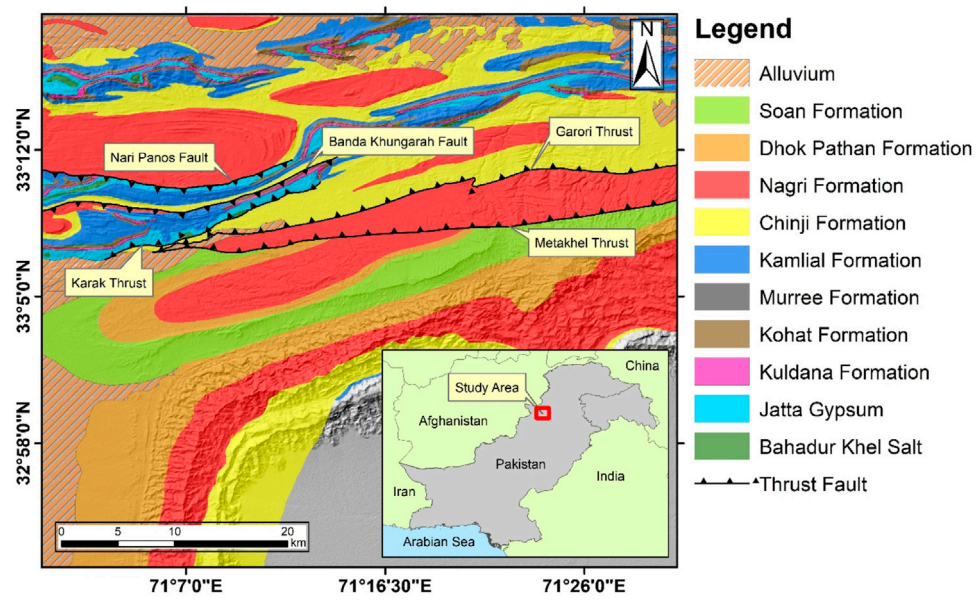


FIGURE 1
Geological map of the study area (redrawn after Meissner et al. (1974).

rocks are characterized by multiple deformations resulting in superimposed folding and repeated faulting and thrusting. The stratigraphic units of the study area comprise the Bahadurkhel Salt (salt with intercalations of shale) and Jatta Gypsum (gypsum and clay intercalations) of the Eocene age, being the oldest exposed rocks in the study area. The salt and gypsum units are overlain by the Kuldana (red clay) and Kohat formations (limestone and shale) of the Eocene age, respectively (Figure 1). The complete rock series of the Siwalik Group (Miocene–Pleistocene age), comprising the Kamlial Formation (sandstone, siltstone and conglomeratic lenses), the Chinji Formation (shale and sandstone), the Nagri Formation (massive sandstone and shale), the Dhok Pathan Formation (friable sandstone), and the Soan Formation (pebbles, sandstone, and shale), in turn overlies the Eocene sequence in the area (Meissner et al., 1974). Karak District consists of huge deposits of evaporites, hydrocarbons, coal, and uranium (District Profile Karak, 2009).

During late Miocene, the Kohat Plateau had been subjected to the southward progression in deformation. The boundary in the northern part of the plateau is marked by the Main Boundary Thrust (MBT). This thrust brings the older rocks of the Kohat Range of Mesozoic age over the younger rocks of the Tertiary age of the Kohat Plateau (Yeats and Hussain, 1987). Toward the south, the Kohat Plateau is bounded by the Bannu Basin, while the south-eastern boundary is marked by the Surghar Range. The left lateral Kurram Fault is juxtaposing the Mesozoic age rocks with the Tertiary age rocks toward the west (Ahmad, 2003).

The area is tectonically disturbed and consists of major thrust faults: the Karak Thrust, Methakhel Thrust, Garori Thrust, Banda Khungarah Fault, and Nari Panos Fault. Along the Karak Thrust, Jatta Gypsum is thrown over the Chinji Formation, while the Garori and Methakhel thrusts emplace the Nagri Formation on top of the Chinji Formation, and similarly, both Banda Khungarah and Nari Panos faults are back-thrust and bring the older Eocene rocks on top of the Pliocene age rocks in the area (Khan, 2013; Khattak et al., 2014; Khattak et al., 2016; Khan et al., 2022) (Figure 1).

## Materials and methods

Radon measurements can be made in the field or samples can be taken and measured in laboratories where background contributions can be reduced by shielding the detector (e.g., by using lead) from ambient gamma radiation. Continuous and time-integrating measurements are generally made *in situ*, while instantaneous measurements can be made in the laboratory or *in situ*. In this study, the grab-sampling mode of Durridge RAD7 was used during the measurements of *in situ* radon. For collection of soil samples, a depth of 60 cm was attained at every measuring station.

A stainless steel soil gas probe supplied by Durridge Company (United States) was used to measure radon activities in soil gas. A 60 cm deep and 2 cm wide hole was made by inserting the probe with a hollow tube through the

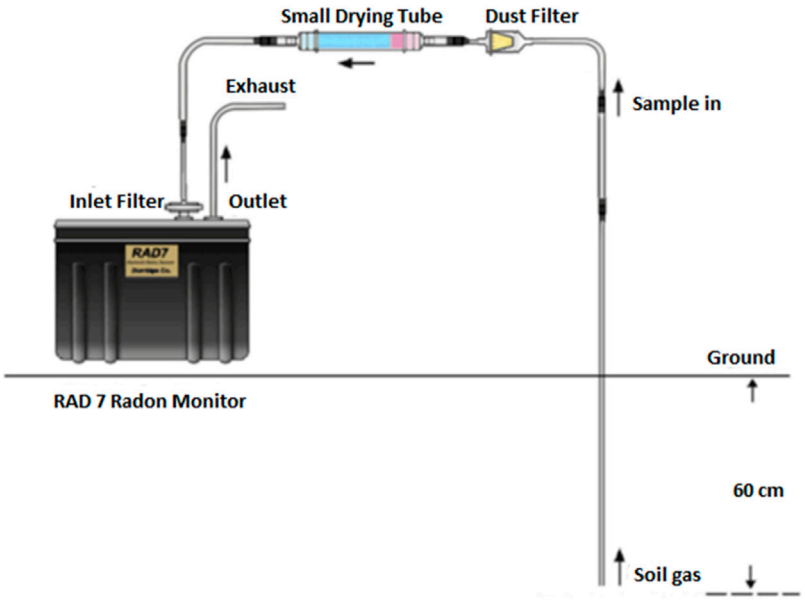


FIGURE 2
Measurement procedure for radon in soil (Liu et al., 2016).

soil with the help of a hammer (Figure 2). Sometimes the depth of the hole was less than 50 cm due to poor development of soil above the parent rock or the pebbly nature of the soil that did not allow the rod to reach 60 cm depth. The probe was connected to RAD7 by pushing the plug-in hose connector into the probe to prevent any water entry into the detector. After the water trap, the air passed through a drierite desiccant tube (calcium sulfate, $CaSO_4$), then to a filter, and finally to the RAD7 system. Before the counting process started, the hole was properly sealed in order to prevent the mixing of soil air with air from the atmosphere. Air was then drawn up the tube into RAD7 and circulated in a closed circuit for a period of 5–10 min, and then, four 5-min cycles are counted. A printout summary with the bar chart for the counted cycles (four), the average concentration of radon, and a collective spectrum is produced by RAD7 at the end. A total of 30 min is taken by the process of measurement in the grab method. Correction factors for radon decay must be applied if the measurements are made after an hour of sample collection. But during this study, all the measurements were taken at the location, which is why no correction factors have been applied (Khan et al., 2022).

Durridge calibrates all instruments to a set of four "master" instruments with a calibration precision of about 1%. The master instruments have been calibrated by way of inter-comparison with secondary standard radon chambers designed by the U.S. EPA. The estimated accuracy of the master instrument is to be within 4%, based on inter-comparison results. It is estimated that the overall calibration accuracy of RAD7 is better than 5%.

# Results

## Evaporites

The evaporitic sequence of the study area consists of Bahadurkhel Salt and Jatta Gypsum of the Eocene age. The concentration of radon in Bahadurkhel Salt varies from 0.15 to 7.6 Bq/L with an average of (1.8 Bq/L) for 10 measuring points, and Jatta Gypsum yielded radon levels in the range of 0.2–3.4 Bq/L; the average concentration of radon for Jatta Gypsum for 20 sampling points is revealed (1.6 Bq/L (Figures 3, 4). The number of sampling points along Bahadurkhel Salt was limited to 10 because of the extent of the formation in the study area. The results of the present study clearly indicate that Bahadurkhel Salt has higher values of radon concentrations than Jatta Gypsum.

## Limestone

The limestone present in the study area belongs to the Kohat Formation of the Eocene age. The Kohat Formation comprises bioclastic limestone in the lower parts and grades into massive limestone toward the top. Throughout the

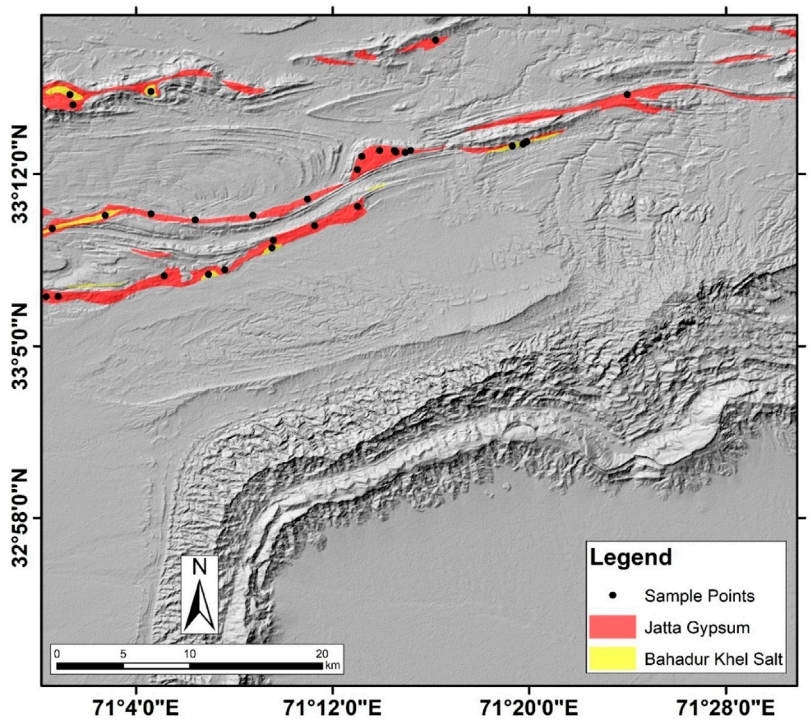


FIGURE 3
Sample locations of radon levels in the evaporite sequence of the study area.

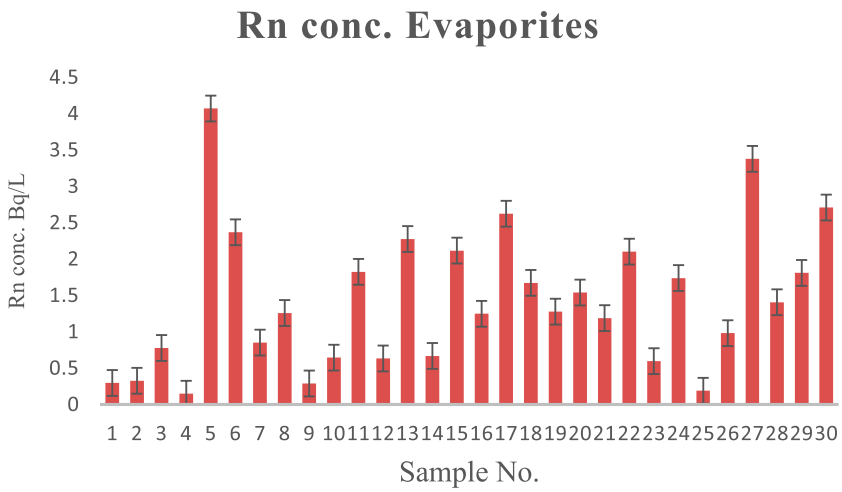


FIGURE 4
Radon concentration in the evaporite sequence of Karak District.

limestone unit, variable radon concentrations were observed. The highest concentration of radon was measured in the lower unit of the formation. A total of 20 radon measurements were made along the Kohat Formation (Figure 5), and a wide range of radon concentrations was observed. The radon concentrations varied between a wide range of

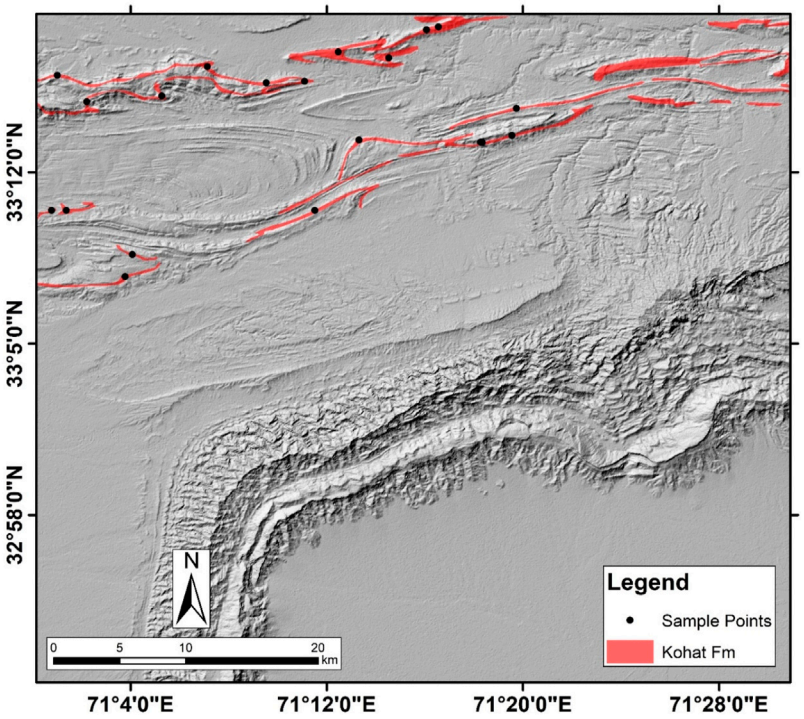


FIGURE 5
Location for radon measurement in the limestone unit of the study area.

0.44–16.5 Bq/L and an average concentration of 3.3 Bq/L (Figure 6).

## Discussion

Radon is mainly responsible for such public exposure to natural radiation (Cinelli et al., 2015). Different factors might be responsible for the soil-radon activity: 1) the parent radionuclide concentration in different rocks; 2) the volume-to-surface ratio of the soil and sub-soil clasts (the low-volume ratio to surface area causes low efficacy in the radon escape from the rock matrix); 3) the sub-surface rocks' average bulk permeability and permeability type (secondary or primary); and 4) due to variance in the deep gas flux, the changes in the transport mechanism driven by advection (Singh et al., 2002).

Low radon levels, as expected, were observed in the areas where salt and gypsum occur, clearly indicating that these lithological units are made up of mineral crystals poor in uranium mineralization, so they are considered to be less radon-prone rocks (Baloch et al., 2012). If any intrusion occurs, it may increase the probability of radon concentrations in evaporites, such as granitic intrusion (Scheib et al., 2013). It can also be inferred that the salt-bearing Bahadurkhel Formation is yielding much concentrations of radon in comparison to the gypsum-dominated Jatta because secondary porosity is more common in salt, creating more intense pores for facilitating invasion.

Radon is considered to have originated from uranium-rich bedrocks (Esan et al., 2020). Elevated radon concentrations in limestone can be attributed to the generally fairly high concentration of uranium in the carbonates as compared to evaporites. The high surface area of uranium and the high permeability of the bedrock can result in the high concentrations of radon (Scheib et al., 2013). Uranium has a uniform distribution within the limestones, which is usually <10 ppm, and is often associated with the finely disintegrated organic matter of bioclastic limestones. This high surface area of uranium in limestones compared to granites allows the effective release of $^{222}$Rn into the air and water (Appleton and Ball, 1995). But the migration of radon is likely to be restricted by the carbonate cements by greatly reducing both the permeability and porosity of the matrix (Scheib et al., 2013).

Due to ubiquitous aeration of the soil, the radon concentration is variable from the soil to the atmosphere (Clavensjö and Åkerblom, 1994). The overall concentration of radon in all the three lithologies at different sampling locations in the studied area ranges between 0.15 and 16.5 Bq/L. Nevertheless, the variation in the average radon levels in all the three lithologies

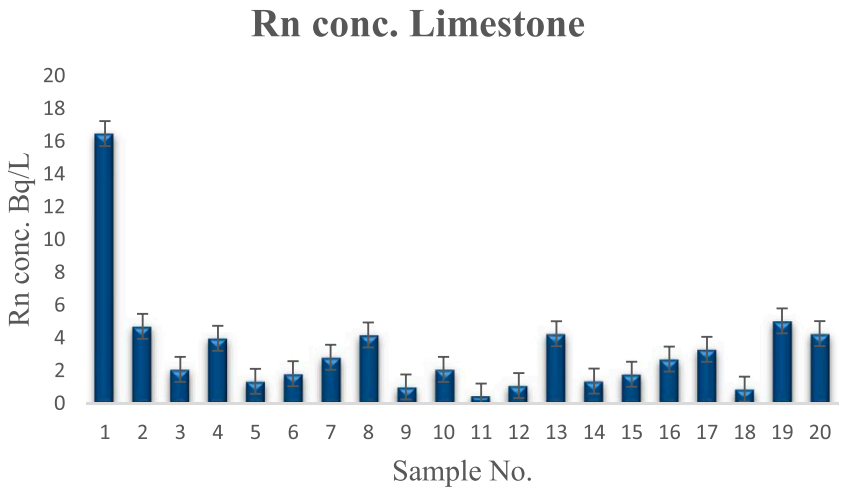


FIGURE 6
Radon concentration in the limestone unit of the Kohat Formation.

TABLE 1 Comparison of radon concentrations in salt, gypsum, and limestone under investigation with those in other countries.

| S.No | Technique | Lithology | Rn concentration Bq/l | Country | Reference |
|---|---|---|---|---|---|
| 1 | Pylon AB-5 | Salt | 0.07 | Romania | Calin and Calin, (2010) |
| 2 | SSNTD | Salt | 0.04 | Pakistan | Baloch et al. (2012) |
| 3 | RAD7 | Salt | 0.03 | Pakistan | Baloch et al. (2012) |
| 4 | RAD7 | Gypsum | 5.74 | India | Mittal et al. (2016) |
| 5 | Lucas cell | Limestone | 41.59 | Portugal | Pereira et al. (1999) |
| 6 | SSNTD | Limestone | 6.25 | England | Scheib et al. (2013) |
| 7 | Pylon AB-5 | Limestone | 57.98 | Scotland | Scheib et al. (2009) |
| 8 | RAD7 | Salt | 1.83 | Pakistan | This study |
| 9 | RAD7 | Gypsum | 1.61 | Pakistan | This study |
| 10 | RAD7 | Limestone | 3.27 | Pakistan | This study |

fluctuates between 1.8 Bq/L, 1.6 Bq/L, and 3.3 Bq/L for Bahadurkhel Salt, Jatta Gypsum, and Kohat Formation, respectively.

In Table 1 a comparison of the soil gas radon concentration in the salt, gypsum, and limestone lithologies from different countries and the present investigation by using passive and active techniques has been presented. The yielded results show that the radon concentrations determined in the salt lithology of both Romania and Pakistan are lower than the reported values in the present investigation. However, the radon concentrations observed in the gypsum and limestone lithologies in India, Portugal, England, and Scotland are higher than the reported values in this study.

Descriptive statistics of the soil gas radon concentrations obtained in the study area are presented in Table 2. Soil gas radon concentration values obtained across all the sampling locations ranged between 0.15 Bq/L and 16.5 Bq/L with a mean of 1.8 Bq/L. However, in the soil overlying the three lithologies, the concentration values varied from 0.15 to 7.6 Bq/L, 0.2 to 3.4 Bq/L, and 0.44 to 16.5 Bq/L with mean values of 1.8 Bq/L, 1.6 Bq/L, and 3.3 Bq/L for salt, gypsum, and limestone, respectively. The distributions of the soil gas radon concentration throughout the study area and across the three lithologies of the study area are positively skewed. A skewness value of 3.87 was obtained for the measured soil gas radon concentration across the study area, whereas across the three lithologies, skewness values of 1.99, 0.35, and 3.27 were obtained for salt, gypsum, and limestone, respectively.

TABLE 2 Statistical data summary.

**Data summary**

| Lithology | N | Min | Q1 | Median | Q3 | Max | Mean | SD |
|---|---|---|---|---|---|---|---|---|
| Limestone | 20 | 0.44 | 1.355 | 2.385 | 4.19 | 16.5 | 3.3 | 3.4142 |
| Evaporites | 30 | 0.15 | 0.6475 | 1.27 | 2.03 | 4.07 | 1.4 | 0.9723 |

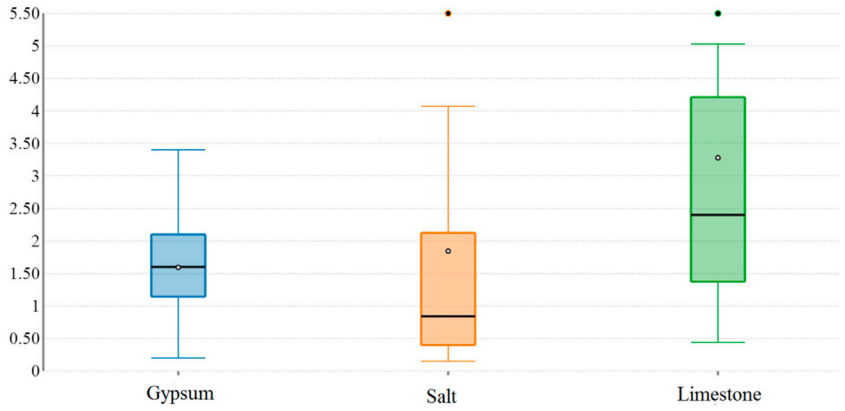


FIGURE 7
Displaying box and whisker plot of the Rn concentration.

The data have been analyzed using the box and whisker plot, as shown in Figure 7. The limestone box plot shows the four major quartiles, of which Q4 is the major quartile. The median lies on the value of 2.385. One value is found as an outlier in the data on sample 1. The evaporites show a narrow range of values as compared to the limestone, with a median value of 1.27 and major coverage by the Q4 values. One outlier was also found in this analysis for salt lithology.

On the basis of the intercomparison among these plots, it is clearly revealed that the highest variations of values are found in the limestone, whereas evaporites have lesser variations.

The radon concentrations over the carbonate and evaporite sequence of the study area indicate that the health hazards related to radon and its progenies are within safe limits. Radiological health hazards such as the presence of $CO_2$, $SO_2$, CO, and other radioactive elements posing health concerns are not considered in this study. Proper regulatory measures such as ventilation and regular dosimetry of inhabitants must be adopted in order to minimize the health hazards related to radon and its progenies and other radioactive pollutants. It is also recommended that extensive research should be carried out in the quarries and mines where the gypsum and salt are extracted because the dust in these quarries and mine atmosphere normally contains radioactive aerosols that can adhere to the lungs and respiratory tract and can damage the bronchial tissues and cause lung cancer (Qureshi et al., 2000).

## Conclusion

- The present study revealed that the radon concentration in the observed lithologies varies in the order of: RnLimestone > RnSalt > Rn Gypsum. The radon concentration in limestone is about two times greater than that of salt and gypsum.
- The soil gas radon concentration in the study area exhibits wide variation, ranging between 0.15 and 16.5 Bq/L, in comparison with salt, limestone, and gypsum.
- The elevated radon potential of the limestone in comparison to the evaporite sequence in the study area can be related to the high joint and fracture permeability of the limestone and to the amount of uranium present in carbonates.
- The area under study is fairly safe from the health hazards related to radon gas and its progenies. Other radioactive pollutants and gaseous elements posing health risks may be present in the area and need to be monitored and minimized.

- The present findings will act as baseline data for further investigation in the region regarding radon levels in soil gas, particularly in the carbonate and evaporite sequences.

## Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Spatial distribution and risk identification of arsenic contamination in water and soil through GIS-based interpolation techniques in Jianghan Plain, Central China

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Arsenic is considered a poison because of its seriously toxic effects on the human body; elevated concentrations of arsenic in drinking water have been reported in different parts of the world. Investigating the arsenic distributions in soil, surface water (SW), and groundwater (GW) is an interesting topic of research, along with probing its correlations with local factors of the ecosystem and other hydrogeochemical parameters. This study mainly aims to investigate the impacts of various factors on elevated arsenic concentrations in water and soil. The following factors are assessed for their relationship to the propagation of arsenic in Jianghan Plain, which is the study area: population density, pumping rate, rain, land use, surface elevation, water level, and heavy metal contamination. The arsenic contamination potential prediction map and categories were developed using GIS-based techniques, such as ordinary kriging and quantile methods. Then, the "raster calculator" tool was applied to verify the impacts of the abovementioned factors on arsenic concentration. Eighty-four single-factor, bi-factor, and multi-factor models were established to investigate the effective combinations among the factors. Land use and pumping rate were identified from the soil through an equal frequency tool, whereas water population density and pumping rate were obtained with high matching percentages. The arsenic concentrations varied in the ranges of 0.0001–0.1582 mg/L in GW, 0.0003–0.05926 mg/L in SW, and 1.820–46.620 mg/kg in soil sediment. The single factors showed the best equal frequency of arsenic concentration in water for population density (68.62%) and in soil for land use (65.57%) and pumping (63.66%). Statistical calculations with percentage frequency factors also depicted a positive trend. Arsenic was reported to have high correlations with Fe in GW ($r^2$ = 0.4193), with EC in SW ($r^2$ = 0.4817), and with Cu in soil ($r^2$ = 0.623). It is observed that the alkaline behaviors of water bodies are associated with arsenic mobility. Elevated arsenic values were observed in grids along surface flows with high anthropogenic activities and urbanization. Additionally, low concentrations

of Fe depicted reduced activities in aquifer systems. Filtering drinking water as well as controlling the suspected sources and factors affecting concentrations of arsenic in the three phases are options for reducing the health risks of the local populations.

KEYWORDS

**Arsenic, Geographic Information System (GIS), groundwater, Jianghan Plain, soil, surface water**

# 1 Introduction

Natural and anthropogenic factors are potential sources of propagation and elevation of various pollutants in water (Singh et al., 2020) and soil (Akhtar et al., 2021). Globally, the water quality has declined rapidly, particularly in developing countries, owing to natural and anthropogenic processes (Muhammad. and Zhonghua, 2014; Akhter et al., 2021). The geochemical characteristics of groundwater (GW) are a result of the combined action of different factors. GW quality is linked to the local geological environment and hydro-meteorological conditions of an area, its GW recharge, flow and discharge, and human activities (Zhou et al., 2013). Arsenic and other pollutants have been reported to have high concentrations in soil in agricultural land in the last three decades (Gong et al., 2020).

Owing to rapid urbanization and industrialization, China is now facing great challenges with regard to heavy metal contamination, including Arsenic pollution in water and soil (China Environmental Monitoring Center 1990; Zhang et al., 2009; Cao et al., 2022). High arsenic concentrations have been reported in GW worldwide, including Bangladesh, India, Cambodia, Vietnam, Argentina, the United States, Chile, Pakistan, and China (Smedley and Kinniburgh 2002; Fendorf et al., 2010; Muhammad et al., 2016), and the most serious waterborne endemic arsenic poisonings were reported in Bangladesh, India, and China. Two major geoenvironmental factors favor the arsenic enrichment of GW: inland or enclosed basins with arid or semi-arid climates and strongly reducing alluvial aquifers. Both factors are associated with geologically young sediments in flat and low-lying areas where the GW flows are sluggish (Smedley and Kinniburgh, 2002; Muhammad et al., 2015). Consequently, high concentrations of arsenic are observed in regions near surface water (SW) bodies, such as rivers and lakes, in China (Wei et al., 2022).

The first case of arsenic poisoning in Jianghan Plain was reported from Shahu village in 2005. In May 2006, the Center for Endemic Disease Control of Xiantao and Hubei Province investigated 19 towns in Xiantao to assess the distribution of endemic arsenic poisoning, where about 60% of the 2538 $km^2$ farmlands have fertile alluvial–lacustrine sediments deposited by rivers and lakes. The popular local crops are rice, rapeseed, cotton, and vegetables, and about 24% of the land is in the form of ponds for aquaculture (Duan et al., 2015). Investigations showed that 863 wells in 12 towns (179 villages) had arsenic levels exceeding the National Drinking Water Standard of 10 μg/L (Gan et al., 2014). Moreover, arsenic concentrations in some wells were 50 times higher than the standard. Such elevated arsenic levels in the GW, SW, and soil of Jianghan Plain deteriorate the drinking water, food supplies, and wetland ecosystems (Wang et al., 2021).

The distribution and accumulation mechanisms of high arsenic levels in the GW, SW, and soil in Jianghan Plain are still unknown, and the sources of arsenic are not well understood. Differences in the climate, geological background, and anthropogenic activities affect the investigation of high arsenic levels in the GW in Jianghan Plain compared to that in northern China (Yu et al., 2022). Jianghan Plain is composed of Quaternary sediments deposited by the Yangtze River from the Himalayan Mountains. Accordingly, the occurrence of arsenic in the alluvial aquifer may be related to similar cases of arsenic contamination in Bangladesh, Pakistan, India, Cambodia, and Vietnam (Deng et al., 2009; Muhammad et al., 2016).

The present work is a comprehensive study in the Jianghan Plain of China, which investigates various factors (GW level, population density, heavy metal contamination, pumping rate, land use, rain, and elevation) related to GW, SW, and soil contamination to assess the impacts of elevated arsenic concentrations. This study aims to identify the most influential factors for enhanced arsenic concentrations in water and soil in the Jianghan Plain of China through GIS applications and statistical methods. The findings of this work are expected to be useful for mitigating and controlling arsenic distribution as well as protecting the health of the local communities.

# 2 Study area

## 2.1 Location, climate, geology, and hydrogeology

Jianghan Plain is an alluvial plain formed by the Yangtze and Han rivers located in the Middle Reaches of the Yangtze River, which includes the central and southern regions of Hubei Province (Figure 1). The study area has a subtropical monsoonal climate, and the annual temperature ranges between 15 and 17 °C. The general climate is regarded to be

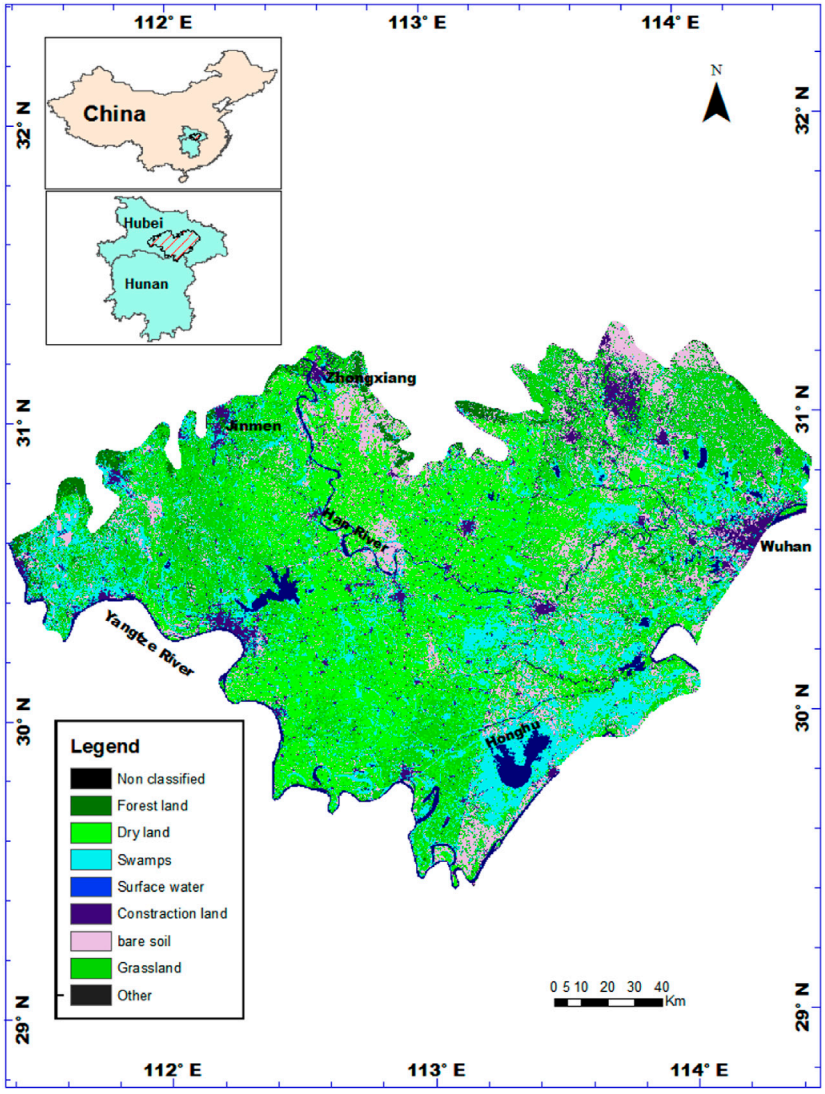


FIGURE 1
Location of the selected study area in Hubei province (Jianghan Plain).

warm and humid, with a high intensity of precipitation at Jianghan Plain. The average annual precipitation in the region is 1269 mm, and about 30%–50% of the precipitation occurs in summer. The value of the average annual evaporation is estimated to be 1200 mm. The nonfrost season is 200–290 days (Duan et al., 2015).

Jianghan Plain is famous for its large farming areas of fish and rice in central China and has low and flat topographic characteristics owing to plenty of SW resources. The major area of the plain is between the Yangtze and Han rivers, so alluvial sediments constitute a large part of the plain (Li et al., 2009). The thickness of the layer of alluvial sediments varies by region; the average depth of this layer is 100–200 m at the center and 20–100 m in the outlying areas. Additionally, the local topography and hydrogeological characteristics are highly favorable for GW recharge. However, the surface elevation (SE) varies between 20 and 40 m (Gan et al., 2014).

## 2.2 Regional hydrogeological conditions

The lithology of Jianghan Plain is mainly Quaternary deposits. The hilly areas primarily consist of aquitard, while the center consists of unconsolidated water-bearing sediment layers. The shallower unconsolidated sediments (10–35 m thick) are mainly made of clayey silt, sandy silt, sandy clay, and interlaced clay lenses. The soil texture in the depth direction is mainly composed of sand and gravel. These

aquitard and unconsolidated layers constitute a complete hydrogeological unit in this plain. The Quaternary unconsolidated sediments form porous media, while Pliocene clasolite forms the porous-fissure media for GW. The hydrogeological conditions differ owing to the varying aquifer distributions and water-bearing formations (Zhao et al., 2007; Muhammad et al., 2015).

The aquifer system can be subdivided into unconfined and confined aquifers based on the burial conditions. An unconfined aquifer is distributed in the shallower areas of the flat plain; its main composition includes clayey silt, sandy silt, sandy clay, and interlaced clay lenses from the Holocene and upper Pleistocene of the Quaternary. The thickness of the aquifer is 3–10 m, with a recharge rate of 43–302 $m^3$/dm. The depth of the GW level is about 0.5–2.0 m (Gan et al., 2014; Duan et al., 2015). Jianghan Plain has two kinds of confined aquifers: confined aquifers in the Quaternary sediments as well as porous-fissured media of the Pliocene and lower Pleistocene sediments. The former is mainly distributed in the lower plain and anterior borders of the hilly areas, which consist of sand and sandy gravel. The thickness varies greatly at different regions, from about 100 m at the thickest and 30–50 m on average. The overlain clay is 5–25 m thick, creating the aquifuge. The hydraulic head is 16–40 m at sea level, and the recharge rate varies from 60 to 454 $m^3$/dm. Confined aquifers in porous-fissured media of the Pliocene and lower Pleistocene sediments occur in the hilly areas; such aquifers are composed of sandy gravel, sandstone, conglomerate, and mudstone, with a recharge rate of 26–156 $m^3$/dm. The hydraulic head is much higher than that of the formerly confined aquifer and may be higher than ground level during the monsoon period. The results of sediment boring core samples collected in the central region of Jianghan Plain (112°59′E, 30°02′N) indicate that the main heavy minerals of the upper sediments (0–100 m) are enriched with Fe and Mn, such as epidote, hornblende, pyroxene, garnet, hematite, limonite, ilmenite, magnetite, and iron-stained rock debris (Kang et al., 2009). The highest Mn concentration observed in the Jianghan Plain sediments was 914 mg/kg (Tang et al., 2020). In addition, many organic materials have been reported in the sediments (Zheng et al., 2004).

# 3 Data collection and methodology

## 3.1 Groundwater, surface water, and soil sampling

For a recent project, 300 samples of GW (from hand-pumped and motor-pumped wells), 125 samples of SW (from rivers and lakes), and 75 samples of soil from Changde, Yiyang, Yueyang, Changsha, and Jingzhou were collected. The sampling points covered the entire study area. The samplings were conducted from 2016 to 2018. Four 50-mL high-density polyethylene bottles were used for each water sample that was filtered onsite (using 0.45-μm membrane filters). The GW samples were collected after 5–10 min of pumping until the physical parameters were stable. For the total dissolved As analysis, hydrochloric acid was used to acidify one bottle wrapped with tinfoil; a second bottle was acidified using ultrapure $HNO_3$ (pH ≤ 2) for chemical analysis of the dissolved ions and trace elements, and the remaining two bottles were used as is for analysis of anions and H/O isotopes. All samples were stored at 4 °C immediately after collection till the analyses were conducted. The soil samples were collected from a depth of 20 cm from a boring core and capped with polytetrafluoroethylene lids, following which they were stored at 4 °C in an opaque anerobic box.

## 3.2 Analytical methods for the waters

The temperature, dissolved oxygen (DO), pH, and electrical conductivity (EC) were measured at the sampling sites using a portable device (HQ40D Field Case, cat. No: 58258-00, HACH, Colorado, United States). The portable gel-filled ORP probe (MTC10103, HACH) was used to measure the activity of electrons. The total concentrations of dissolved ions (Mg and Fe) were determined using an inductively coupled plasma atomic emission spectrometer (ICP-AES) (Thermo Electron ICP-OES spectrometer IRIS Intrepid II XSP, United States). Inductively coupled plasma mass spectrometry (ICP-MS) (Perkin Elmer, ELAN 9000/DRC-e) was used to examine the trace elements. Verifications of the major elements analyzed by ICP-AES and ICP-MS were found to have accuracies within 4% and 5%, respectively. Anions ($NO_3^-$ and $SO_4^{2-}$) were measured using an ion chromatograph (Dionex 2500, United States), with an analytical precision within 5%. The total organic carbon analyzer (multi N/C 3100, Germany) was used to measure dissolved organic carbon (DOC), whose detected value was 0.004 mg/L with a precision of ±8%. The total amounts of GW and SW were measured using a hydride generation atomic fluorescence spectrometer (HG-AFS, 930, Titan, China).

## 3.3 Soil analysis method

To measure the mineralogical compositions of the soil samples, an automated powder X-ray diffractometer (Cu–Kα radiation with a graphite monochromator; X'Pert PRO DY2198, PANalytical) was used with a detection limit of 2%. The chemical components were determined by X-ray fluorescence spectroscopy (XFS; Spectro Xepos HE XRF Spectrometer), and the remaining chemical analyses were conducted at the State Key Laboratory of Biogeology and Environmental Geology and State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China.

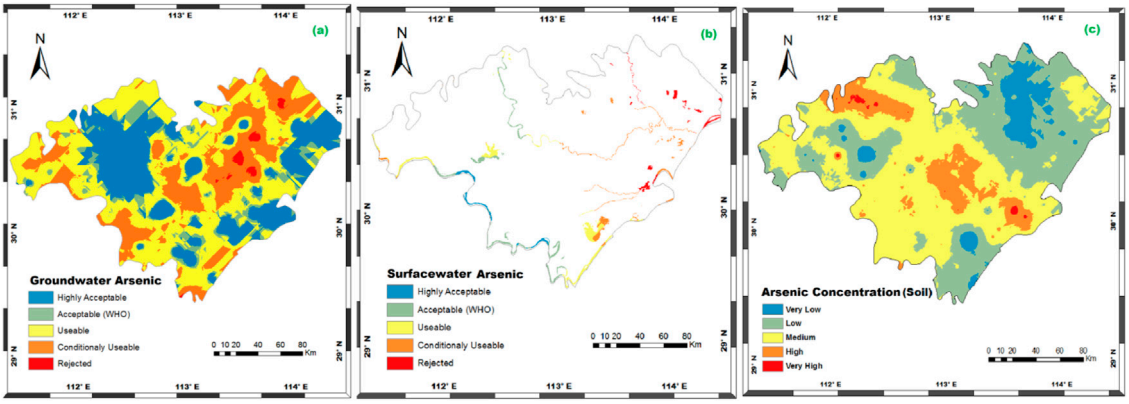


FIGURE 2
Arsenic distributions in the **(A)** groundwater (GW), **(B)** surface water (SW), and **(C)** soil in Jianghan Plain.

## 3.4 GIS model development

The topographical map of the study area (1:50,000) was used to create a thematic map containing comprehensive information about the boundaries and land use, as shown in Figure 1. The simple kriging method was used with the ArcGIS10.3 Geostatistical Analyst toolbar to develop arsenic distribution zones in the GW, SW, and soil. To design the distribution map, the 2016 arsenic concentrations were categorized into five levels using the quantile method, as shown in Figure 2. The quantile method estimates the data of different factors, such as rain (Ringard et al., 2017), contamination parameters, and elevation. Then, six different factors were tested to examine their influences on the arsenic concentration levels in the GW, SW, and soil.

The simple kriging method was used to create the GW level, pumping rate, population density, heavy metal contamination, and rain zones for the study area. The rainfall data of 90 meteorological stations (for the year 2016) were downloaded from the Hydrology and Water Resources Survey website of Hunan Province. A heavy metal concentration distribution map was developed based on the data available in a report titled "the ecological geochemical assessment report of Dongting Lake in Hunan Province" published by the Geological Research Institute of Hunan Province (Fang et al., 2021). Landsat 8 images were used to create the supervised land use classifications for the study area in the Environment for Visualizing Images (ENVI) software environment developed by L3Harris Geospatial, United States. Seven major categories (woodland, dryland, paddy field, SW, construction area, bare land, and green land) were used to understand the real local land use. The SE often controls water flow and affects the probability of water infiltration. The ASTER digital elevation model (DEM) was used to create a contour map of the study area using 3D analyst tools in ArcGIS.

The final maps of the factors were classified into five groups according to the quantile method using the reclassify tool included in the spatial analysis toolset. The "raster calculator" tool was then used to evaluate the factors affecting the intensities of arsenic distribution in the water and soil. All digitalized maps of the employed factors were converted to shape files and layers in ArcGIS. Raster calculator is designed to execute single-line algebraic expressions, while simple and complex algebraic maps are employed using the button-like calculator tool interface. Eighty-four different models were developed using the raster calculator; these models were built by combining different factors to determine the most effective combination. Single-factor and multifactor models were carefully established by assigning coefficients 1 to 6 as the rank because each model contains unique values. Then, the quantile method included in the reclassify tool was repeated for each model to categorize the results into the five groups. The "equal to frequency" tool was used to evaluate the models based on cell-by-cell matching with the arsenic concentration model to select the best frequency match models. Additionally, the "band collection statistic" tool was applied to compute the frequency range to obtain statistical results from a multivariate analysis of a set of raster bands. Finally, the frequency range was counted for the matched and unmatched cases.

# 4 Results and discussion

## 4.1 Arsenic levels in soil, surface water, and groundwater

Chemical analyses of the GW samples showed arsenic concentrations in the range of 0.0001–0.1582 mg/L. Figure 2A shows the spatial arsenic distribution in GW and indicates the mix in the entire study area; however, the east–west and

northwest areas contained low levels while the central region in the northeast showed the most elevated levels of As (according to WHO and Chinese standards). Elevated arsenic in the GW has been observed in the northwest region of China (He et al., 2020). A study of shallow GW in Jianghan showed arsenic concentrations in the range of 0.02–0.13 mg/L. Gan et al. (2014) conducted a study to investigate arsenic levels in GW and reported that 87% of the samples exceeded the WHO and Chinese standards, with values ranging from 0.01 to 2.330 mg/L. Additionally, statistical tools showed a standard deviation of 0.0159, while Zhou et al. (2013) calculated a standard deviation of 0.02 in another study in the Jianghan Plain.

SW samples were collected from the rivers and lakes of Jianghan Plain, and chemical analysis showed both low (0.0003 mg/L) and high (0.5926 mg/L) concentrations of As. The major sources of SW pollution in China are untreated municipal, industrial, and agricultural effluents. The map developed for SW arsenic concentration depicted spatial variations; the eastern part of the study area showed elevated concentrations over 0.02 mg/L, whereas the water quality in the Yangtze River and lakes (Honghu and Changhu) were observed to be satisfactory (within the range of WHO and Chinese prescribed standards). Shao et al. (2006) observed that domestic sewage was the main cause of polluted lakes in China, while Gao and Mucci (2003) identified agricultural activities as the cause of watershed pollution. Previously, researchers have identified that the water quality of many SW resources in the form of lakes, rivers, and open water bodies in China are not good (Zhang, 2022). Figures 2A,B show similar arsenic concentrations for SW and GW, except along the southeast boundary. This significant resemblance in the spatial arsenic distribution was used to identify the SW impact on GW at Jianghan Plain. The higher concentrations of various pollutants in unsealed wells may be linked to anthropogenic pollution, oxidization in shallow aquifers, and interactions of the SW and GW (Gan et al., 2014; Yu et al., 2022).

Chemical analysis results of the soil samples showed significant variations in concentration between 1.820 and 46.620 mg/kg. Increasing human activities are regarded as the major causes of different air and soil pollutants, such as fossil-fuel combustion, agriculture, and industrialization. The observed values were much higher than the range measured in the present study. A suggested baseline of As concentration in soil is 5–10 mg/kg (Smedley and Kinniburgh, 2000), but Wang and Shpeyzer (2000) measured As range between 2.5 and 33.5 mg/kg in Chinese soil, where mountain soil (16 mg/kg) had a comparatively higher value than siallitic soil (4 mg/kg). Various types of soil in China were examined, where regosol and mountain soils had higher arsenic concentrations than unsaturated siallitic soils (He and Charlet, 2013). Contaminated soils affect the natural resources and human health, so this problem had garnered attention from researchers (Zhang et al., 2015). Elevated atmospheric arsenic levels slightly increased the soil content of arsenic (Gan et al., 2014; Yu et al., 2022) as China consumed an estimated 3.92 billion tons of coal in 2020 (Mengshu et al., 2021). Zhong et al. (2014) identified high As content in soil from agricultural activities, industrial SW flow (Guo et al., 2012), and urbanization (Zhao et al., 2007) in Jianghan Plain.

Relationships between arsenic distribution can be examined under three categories: spatial variance of the arsenic distribution has significant relationships in some parts of the study area. Inhomogeneities between the SW, GW, and soil may be attributed to variations in the compositions of the sediments, hydrogeological parameters, anthropogenic activities, and other factors. The interactions may have clear and complex pollutant transport concepts among the soil, SW, and aquifer interfaces. Comparing SW (Figure 2B) and soil (Figure 2C), a weak affiliation was detected in the eastern areas, whereas the western region showed the best correlation for low arsenic values. Owing to the direct interactions of the SW and soil particles, contaminant particle exchange is convenient between these phases. Normally, solid wastes and effluents are deposited in the soil or SW resources globally. Over 80% of China's rivers have different levels of contamination (Deng et al., 2022), which directly impact the soil and sediments as well as indirectly impact the local GW systems. In addition, local anthropogenic factors affect the soil compositions in different parts of China.

The relationship between arsenic in water and soil showed a strong association in the central and some western parts, while several other wide regions showed negative relationships, the actual reasons being water level (WL) and recharge intensity, which are major interaction mechanisms. In Figure 3, the population classes show significant relationships with SW and GW, and the arsenic contamination levels in soil generally tend to increase with population density. In the fourth group, where the population density is in the range of 1051–5000, high arsenic values were observed in the soil (14.6717 mg/kg) and GW (0.207 mg/L), whereas the SW had a value of 0.0203 mg/L in the most populated area. The statistical analysis showed increasing pumping rates with elevated arsenic concentrations in the three media. Pumping rates over 0.7251 $m^3/s$ highly affected the soil and GW qualities, but the highest arsenic concentration of 0.0243 mg/L was observed when the pumping rate was between 0.5251 and 0.7250 $m^3/s$. GW exploitation factors can also modify the recharge patterns, and rapid recharge is associated with soil and GW contamination in Jianghan Plain.

Among the five groups of WLs, high impacts of arsenic were observed for WLs that were 81–100 m from the surface in soil (16.2550 mg/kg), SW (0.0210 mg/L), and GW (0.0212 mg/L) (Figures 3, 4). The arsenic level in soil was affected by the WL

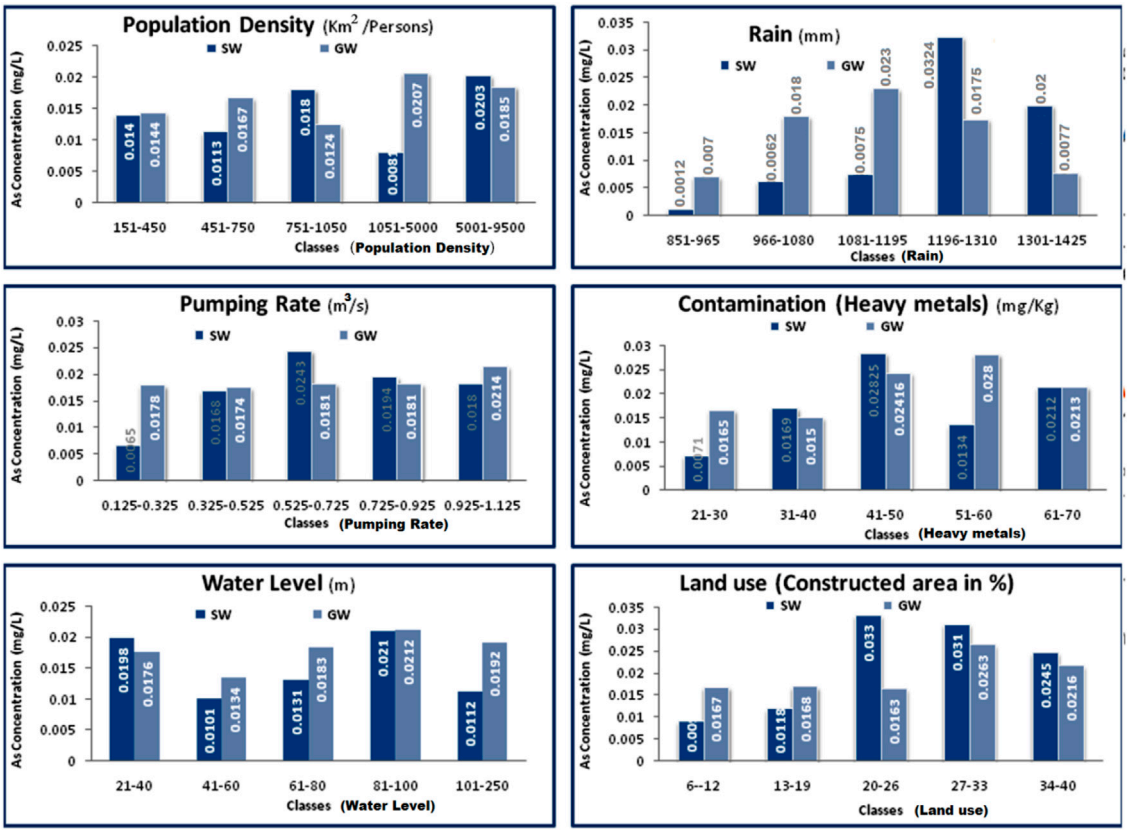


FIGURE 3
Factor classifications and average arsenic concentration of each class in water.

depth, but both water media showed values in a mixed range. The highest correlation was observed between heavy metal contamination and GW quality. Figures 3, 4 show the heavy metal contamination to be in the range of 41–60 mg/kg, with the arsenic content in soil, GW, and SW having values of 14.83 mg/kg, 0.0280 mg/L, and 0.02825 mg/L, respectively. The arsenic concentrations in the five SE groups had mixed values; however, an elevation of over 81 m impacts GW (value range <0.0217 mg/L) and SW (value range <0.0210 mg/L) significantly. The main reason for this may be the soil structure composition may as well as GW flow.

Figure 4 shows the percentages of two land-use factors, which indicate that more land use activities enhance arsenic levels in the soil. The constructed and green land areas had low or high impact on different classes, but low effects were detected in the low percentage range for these classes. Counties with constructed areas over 20% show gradually increasing arsenic concentrations in the soil (<15.3700 mg/kg) and GW (<0.0163 mg/L), while arsenic levels between 0.0245 and 0.0330 mg/L are observed in SW. Green land with coverage over 45% and large-scale agriculture activities were observed to have major levels of contaminants in the soil and SW, which indirectly affected the GW quality. Thus, it can be concluded that arsenic is present in all three examined media in Jianghan Plain. Naturally, these media have interaction systems that transport pollutants from one medium to another based on various parameters. However, other factors can also enhance arsenic mobility, which pose risks for local communities.

## 4.2 Results of GIS-based factor analysis models

### 4.2.1 Arsenic level in soil

Eighty-four single-factor and multifactor models were developed and verified by their correlations with the arsenic model based on the equal frequency tool in GIS. The highest equal frequency multifactor model was used to develop gradually lower factor models; the single-, two-, and three-factor models with the highest equal frequencies are presented in Table 1. The results of these models and their correlations with elevated arsenic in soil are presented in this section. It is extremely important to explore the impacts of local factors that elevate arsenic values, their causes, and their relationships. The soil arsenic distribution model was compared with the single-

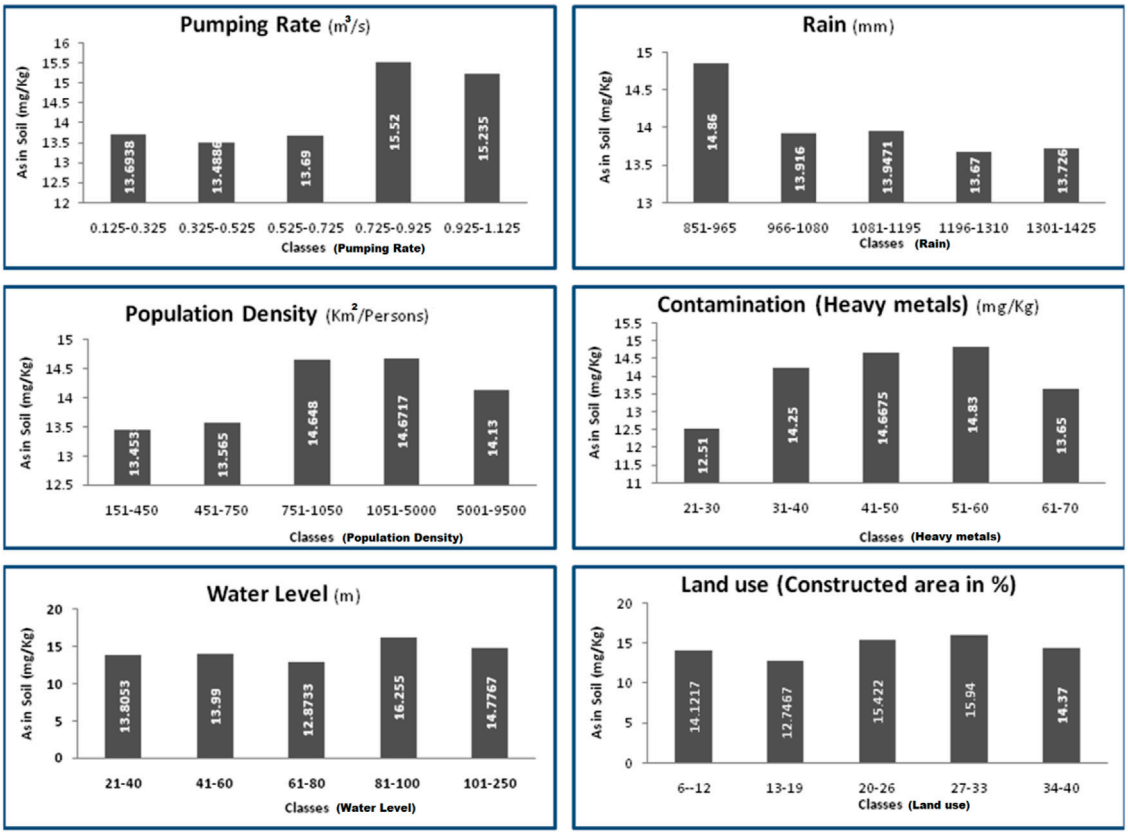


FIGURE 4
Factor classifications and average arsenic concentration of each class in soil.

factor and multifactor models. Table 1 presents the seven single models for equal frequencies of land use (Model_152) and pumping rate (Model_154), whose equal frequencies are 65.57% and 63.66%, respectively. In contrast, the lowest similar frequency was seen for rainfall as the factor (Model_156; 18.1%).

The results of the GW pumping and land use models show high equal frequencies with the soil arsenic concentration in Jianghan Plain. The highest and lowest equal frequency values among the developed models were for Model-149 (1LU*2Pump) and Model-156 (Rain), whose values are 68.74% and 18.1% similar with that of arsenic, respectively (Table 1). These model results indicate that the local anthropological activities have negative impacts on the soil, which are transmitted to the GW system over time. The best frequency matching maps are displayed in Figure 3. The raster calculator tool in GIS was used to develop the multifactor models, and ranking techniques were applied to verify the highest and lowest impact factors. For example, the single-factor and multifactor raster models and arsenic concentration were reclassified and assigned similar color schemes to indicate the same frequency. Table 1 shows the best model results and the most effective factors, which are the pumping rate and land use.

### 4.2.2 Arsenic concentrations in the waters

This study investigated the relationships of seven major factors with high arsenic concentration and distribution in aquifer and soil in Jianghan Plain. The stress intensities of each factor were evaluated for water and soil. Thus, the permissible levels of arsenic in drinking water in China are 0.05 mg/L (50 ppb) for GW and SW as well as 40 mg/kg for soil, which are safe for human health. The following sections present the results of the developed models for each factor, arsenic concentration correlations with the single-factor and multifactor models, and effects of various factors on the arsenic concentrations to explore the causes of high arsenic concentrations and their relationships with the examined factors.

Here, the arsenic concentration distributions were compared using similar frequency values for a single factor, two factors, and multiple factors included in the raster models. The highest similarity frequency factors were then used to develop

TABLE 1 Model frequencies of factor correlations with arsenic concentrations in the water and soil.

| Surface water and groundwater (W) | | | Soil | | |
|---|---|---|---|---|---|
| **Model no.** | **Factor and rank** | **Equal frequency %** | **Model no.** | **Factor and rank** | **Equal frequency %** |
| Model_51 | W*WL | 60.12 | Model_151 | Soil*WL | 27.33 |
| Model_52 | W*LU | 63.34 | Model_152 | Soil*LU | 65.57 |
| Model_53 | W*Pop | 68.62 | Model_153 | Soil*Pop | 54.22 |
| Model_54 | W*Pump | 65.77 | Model_154 | Soil*Pump | 63.66 |
| Model_55 | W*SE | 58.03 | Model_155 | Soil*SE | 61.94 |
| Model_56 | W*Rain | 20.25 | Model_156 | Soil*Rain | 18.1 |
| Model_57 | W*Cont | 60.41 | Model_157 | Soil*Cont | 62.47 |
| Model_49 | W*(1Pump+2Pop) | 64.81 | Model_149 | Soil*(1LU+2Cont) | 68.74 |
| Model_50 | W*(2Pump+1Pop) | 63.34 | Model_150 | Soil*(2LU+1Cont) | 65.12 |
| Model_43 | W*(3Pump+2LU+1Pop) | 67.63 | Model_143 | Soil*(3Pump+2LU+1Cont) | 60.51 |
| Model_44 | W*(3Pump+1LU+2Pop) | 66.21 | Model_144 | Soil*(3Pump+1LU+2Cont) | 63.21 |
| Model_45 | W*(2Pump+3LU+1Pop) | 64.55 | Model_145 | Soil*(2Pump+3LU+1Cont) | 61.65 |
| Model_46 | W*(2Pump+1LU+3Pop) | 56.61 | Model_146 | Soil*(2Pump+1LU+3Cont) | 61.59 |
| Model_47 | W*(1Pump+3LU+2Pop) | 66.36 | Model_147 | Soil*(1Pump+3LU+2Cont) | 65.24 |
| Model_48 | W*(1Pump+2LU+3Pop) | 65.15 | Model_148 | Soil*(1Pump+2LU+3Cont) | 64.34 |

multiple models. The results of the estimated frequency values according to the models are displayed in Table 1. Table 1 shows that the best frequency percentage decreases with increasing number of factors. Among the single-factor models, the population density (Model 53 with 68.62%) and pumping rate (Model 54 with 65.77%) had values higher than the remaining single-factor and multifactor model frequencies. The model results showed that close matching frequencies for the population density and WL greatly affect the arsenic concentrations in Jianghan Plain. Furthermore, among the single models, population density showed the highest matching frequency with arsenic, while rainfall (Model 56 with 20.25%) showed the lowest matching frequency. Therefore, the anthropological activities in the study area were unsafe for the local GW system and negatively impacted its water resources. However, the single-factor model frequencies were lower than those of the multifactor models.

The multifactor raster models were developed using the raster calculator tool and ranking technique. The results in Table 1 also exhibit the relationships between the combined factors and arsenic concentrations. The best matching frequencies among the multifactor models were observed for W*(3Pump+2LU+1Pop) (Model 43 with an equal frequency of 67.63%) and W*(1Pump+2LU+3Pop) (Model 48 with an equal frequency of 65.15%). Close matching frequency percentages were observed among the two-factor models (65.49%) and three-factor models (63.61%), while the four- and five-factor model values ranged from 10.9% to 55.66%. The most effective factors were population density and pumping rate, which had the two highest matching frequencies among all models. These results were also confirmed by the frequency maps of the four best models shown in Figure 6. Analysis with the equal frequency tool explored the various factors contributing to decreasing water quality in Jianghan Plain. These results can help identify the impacts of single factors as well as different combinations of factors. Human activities based on water demand that impact WL through pumping were diagnosed as the major factors that enriched arsenic levels in the water resources.

## 4.3 High equal frequency factor relationships and their impacts on the three media

### 4.3.1 High equal frequency factors in soil

First Factor F1: This section describes the land use and arsenic concentration impact on soil; the general factors with regard to anthropogenic activities include different waste materials and pollutants directly in soil. The seven major land use classes are presented in Figure 7A. The land use map (Figure 5A) exhibits high values for green land, dryland, SW, and urbanization (domestic and commercial areas), followed by agricultural land use and industrial activities. Almost 13.7% of the study area comprises urban settlements and other constructions, as shown in Figure 7A. Human activities are regarded as important,

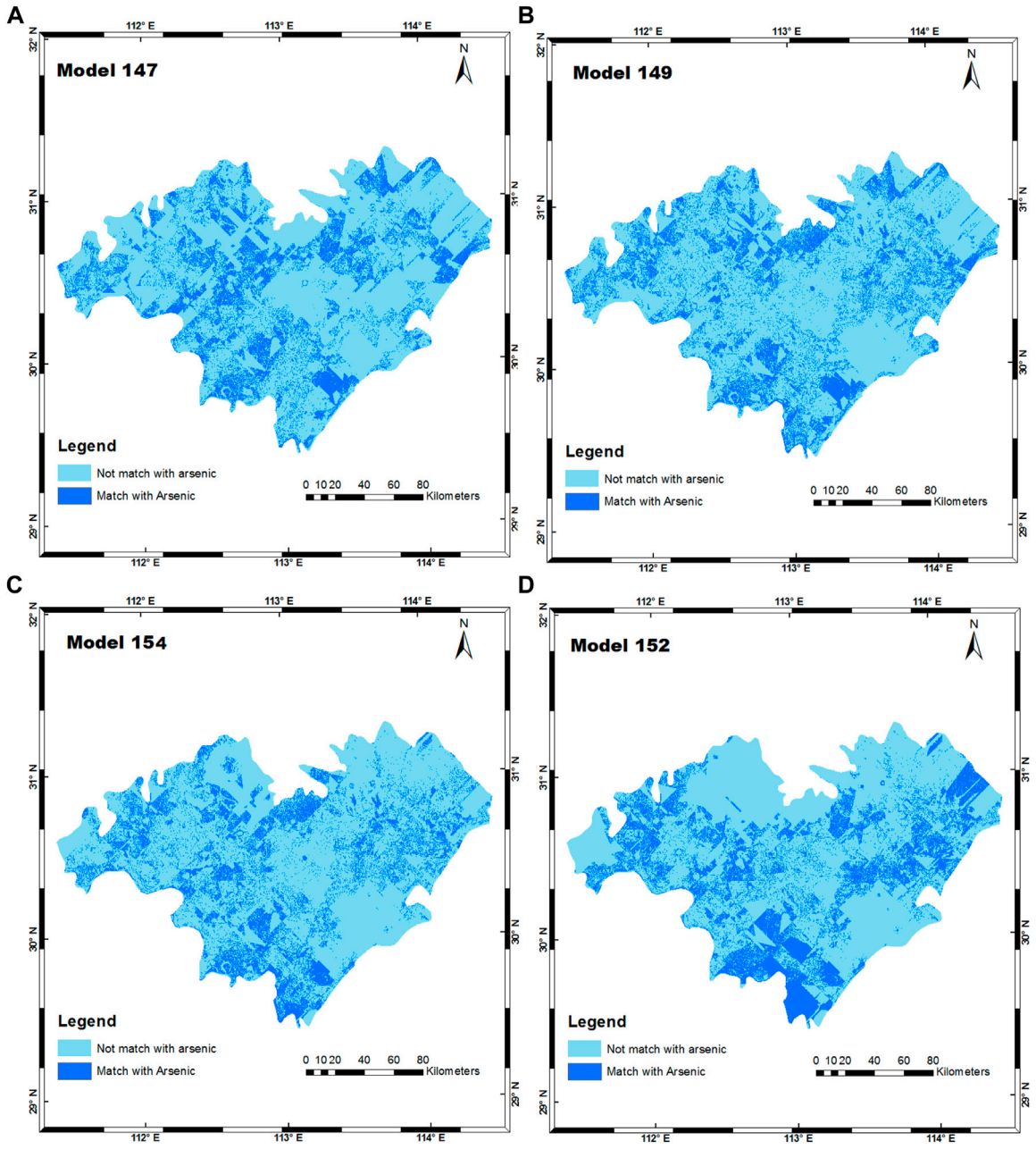


FIGURE 5
The best matching frequencies maps models for soil arsenic concentration among the multifactor models were observed for Soil*(1Pump+3LU+2Cont) in panel **(A)**, soil*(1LU+2Cont) in panel **(B)**, soil*Pump in panel **(C)** and soil*LU in panel **(D)** with an equal frequency of 65.24%, 68.74%, 63.66% and 65.57% (Table 1), respectively.

which result in elevating the levels of different pollutants in the topsoil of Jianghan Plain. Industrialization, rapid population growth, and agricultural activities affect the soil quality in Jianghan Plain, China (Gan et al., 2014). Increasing amounts of agrochemical use and rapid industrialization have subjected the soil to stresses owing to increasing pollution (Zhong et al., 2014).

The calculated correlation value ($r^2 = 0.543$) between human activities and arsenic levels shows a close relationship in Jianghan Plain. The two major land use factors are construction and green land area, as shown in Table 2 which generally show high land use intensity affecting arsenic concentrations in soil. Counties with construction areas below 19% show average arsenic concentrations between 12.7467 and 14.1217 mg/kg, while the

TABLE 2 Statistical data representations of the hydro and geochemical data and correlations with arsenic concentrations in the GW, SW, and soil.

| Elements | Min | Max | Avg. | Correlation with As ($r^2$) |
|---|---|---|---|---|
| Groundwater | | | | |
| As (mg/L) | 0.0001 | 0.1582 | 0.0139 | |
| pH | 6.3000 | 9.6000 | 7.2270 | 0.3850 |
| EC | 223.0000 | 2440.0000 | 886.4767 | 0.2807 |
| Ba (mg/L) | 0.0010 | 3.5030 | 0.3497 | 0.1309 |
| Ca (mg/L) | 3.0460 | 246.4000 | 93.3220 | 0.1250 |
| Cu (mg/L) | 0.0001 | 0.0164 | 0.0018 | −0.0167 |
| Fe (mg/L) | 0.0001 | 32.9032 | 0.7827 | 0.4193 |
| K(mg/L) | 0.0011 | 19.4600 | 5.1287 | 0.0918 |
| Mg (mg/L) | 0.0017 | 90.7919 | 16.2626 | 0.0815 |
| Mn (mg/L) | 0.0019 | 73.4126 | 5.7844 | 0.2820 |
| Na(mg/L) | 0.0012 | 204.8000 | 22.8379 | −0.1295 |
| Ni (mg/L) | 0.0004 | 0.0374 | 0.0098 | 0.4186 |
| Pb (mg/L) | 0.0029 | 26.1900 | 1.0828 | 0.1854 |
| Zn (mg/L) | 0.0002 | 0.5028 | 0.0513 | −0.0480 |
| F (mg/L) | 0.0166 | 12.2100 | 0.4302 | −0.0337 |
| Cl (mg/L) | 4.0175 | 225.1000 | 25.8907 | 0.1713 |
| $NO_3$ (mg/L) | 0.0903 | 378.9743 | 32.6929 | 0.0581 |
| $SO_4^{2-}$ (mg/L) | 0.1137 | 642.1270 | 34.4588 | 0.0617 |
| Surface water | | | | |
| As (mg/L) | 0.0003 | 0.5926 | 0.0231 | |
| pH | 5.3000 | 9.9000 | 8.0397 | 0.1091 |
| EC | 0.8170 | 2340.0000 | 388.2374 | 0.4817 |
| Ba (mg/L) | 0.0020 | 0.2448 | 0.0876 | −0.1049 |
| Ca (mg/L) | 0.0001 | 109.4000 | 40.0576 | 0.1512 |
| Cu (mg/L) | 0.0001 | 0.0194 | 0.0037 | −0.1378 |
| Fe (mg/L) | 0.0001 | 0.5431 | 0.0202 | 0.0922 |
| K (mg/L) | 0.0002 | 28.7330 | 3.8669 | −0.0886 |
| Mg (mg/L) | 0.0002 | 35.2300 | 9.1149 | 0.3467 |
| Mn (mg/L) | 0.0002 | 14.5657 | 2.4915 | 0.1457 |
| Na (mg/L) | 0.0001 | 70.5900 | 11.2844 | 0.1622 |
| Ni (mg/L) | 0.0001 | 4.4660 | 0.5965 | 0.4545 |
| Pb (mg/L) | 0.0001 | 7.5240 | 0.6267 | 0.0338 |
| Zn (mg/L) | 0.0008 | 1.3369 | 0.1586 | 0.1945 |
| F (mg/L) | 0.1131 | 9.6375 | 0.9451 | −0.0218 |
| Cl (mg/L) | 7.4735 | 3318.4000 | 105.3815 | 0.0393 |
| $NO_3$ (mg/L) | 0.4550 | 338.5557 | 23.0079 | −0.1661 |
| $SO_4^{2-}$ (mg/L) | 0.1131 | 231.5000 | 33.6499 | 0.4667 |
| Soil | | | | |
| As (mg/kg) | 1.820 | 46.620 | 12.811 | |
| Ca (mg/kg) | 7.898 | 815.700 | 137.809 | 0.048 |
| Mg (mg/kg) | 3.080 | 141.679 | 43.064 | 0.577 |
| K (mg/kg) | 7.340 | 153.800 | 21.387 | −0.084 |
| Na (mg/kg) | 10.070 | 148.953 | 73.905 | 0.421 |
| Fe (mg/kg) | 3.320 | 230.600 | 41.488 | 0.096 |
| Cd (mg/kg) | 4.000 | 35.000 | 0.162 | 0.350 |
| Cr (mg/kg) | 9.050 | 120.400 | 15.046 | −0.212 |
| Cu (mg/kg) | 11.190 | 30.210 | 19.868 | 0.623 |
| Mn (mg/kg) | 320.000 | 1081.110 | 588.856 | 0.522 |
| Sr (mg/kg) | 78.700 | 240.000 | 107.450 | −0.160 |
| Zn (mg/kg) | 16.000 | 331.800 | 73.131 | 0.379 |
| $SO_4^{2-}$ (mg/kg) | 2.760 | 101.340 | 32.650 | 0.213 |

highest arsenic level was observed in the fourth class (27–33%), with a value of 15.9400 mg/kg. Green land areas that are linked to agricultural activities, as shown in Figure 4, showed that areas with over 57% agricultural land had the highest arsenic concentration of 16.0240%. Over time, land use generally affects soil composition, which can also affect the arsenic concentration in the aquifer; this result indicates that each category of land use contributes differently to the increasing arsenic contamination in the study area (Figure 4). Thus, soil characteristics are affected by various land use activities in the Jianghan Plain. The hydrogeological characteristics of Jianghan Plain are hence strongly associated with high-arsenic GW systems (Yu et al., 2022).

First Factor F2: In Jianghan Plain, GW is the principal source of drinking water, and the demands vary with season and number of activities. Among the seven factors, pumping rate was identified through GIS modeling as the major source of increased arsenic contamination in the soil. The excessive pumping of GW to satisfy the increasing public demands can rapidly decline the water table levels, thereby affecting soil and GW quality adversely. The chemistry of soil, SW, and GW is affected by the changing recharge patterns. Many researchers have agreed that indiscriminate pumping may have facilitated the spread of arsenic within the GW layer (Harvey et al., 2005; Rosencranz et al., 2021). The estimated total GW exploitation for the purposes of different counties were noted to be between 0.1251 and 1.1250 $m^3$/s. Ravenscroft et al. showed that the operational age of a well and the period of pumping are linked to GW quality and can elevate its arsenic concentration (Cuthbert et al., 2002). At the same time, the Honghu and Dangyang counties having high pumping rates of over 1.1 $m^3$/s showed low GW exploitation compared to other areas (Figure 7D). The soil arsenic distribution map shows a close relationship to GW exploitation, and the central and southern parts show elevated arsenic levels (Figure 2C), with similar areas having high pumping intensities (Figure 7D). The vulnerability of water supply wells to natural and anthropogenic contaminants depends on the pumping stress levels of the GW system (Van Geen et al., 2002).

Regarding the relationship between arsenic concentration and pumping quantity, the total GW exploitation can be divided into five classes to verify soil arsenic concentration variation with increasing pumping quantity. The statistical results show a general trend of positive correlations between the two factors ($r^2$ = +0.4532). Elevated arsenic values of 15.5200 mg/kg in soil were observed within the 0.7251–0.9250 $m^3$/s class, while the lowest arsenic concentration of 13.4886 mg/kg was noted in the second class where the pumping rate limit was between 0.3251 and 0.5250 $m^3$/s. A previous study of Jianghan Plain reported that the average arsenic measured in sediments was 14.5 mg/kg (Gan et al., 2014). Therefore, infiltration of high-arsenic-induced water and increasing discharge rate into aquifers indicate the possible risks of arsenic contamination in GW.

### 4.3.2 High equal frequency factors in water bodies

First Factor F1: Population density was estimated based on each county's collected data available in the China Statistical Yearbook (2014). The population strength was between 294 $km^2$/persons to 9422 $km^2$ as displayed in the population distribution results in Table 2. According to the National Bureau of Statistics, the annual national population growth rate was 0.49% between 2012 and 2013 and 0.35% for Hubei Province over the past 3 years. The population distribution map (Figure 7C) also showed wide spatial dispersion in the study area. The central area had medium density compared to the other parts of Jianghan Plain. Additionally, high spatial distribution was noted for the eastern areas in CaiDian, Wuhan, and AnLu counties, while counties in the western areas such as YiLing and XiLing showed the highest population intensities. Less than 500 $km^2$/persons population density was observed in the southwest region along the Yangtze River. However, medium-population densities were located in the central parts of the study area (Figure 7C). The population pressures could result in increased solid waste production, urban nonpoint runoff, and declining water quality. In the case study of Dongting basin, the population distribution showed a low relationship with arsenic concentration.

The statistical results based on each county's average arsenic concentration and population density in the study area had significant impacts on the average arsenic levels. The population density in the study area significantly impacted the average arsenic level of each county, with a calculated correlation coefficient of +0.532. This implies that the pollution risk due to inhabitant ratio is high in the study area. However, the average arsenic concentrations in the counties were divided into five classes, where the lowest population class (151–450 $km^2$/persons) showed an arsenic concentration of 0.0144 mg/L in the GW, which is 0.0140 mg/L under the limit permissible by Chinese standards but higher than that prescribed by the WHO. The average arsenic concentrations observed in Jianghan Plain were within the limits imposed by the Chinese standard (0.05 mg/L) but over that prescribed by the WHO (0.01 mg/L) (Table 2). The highest average arsenic concentration (0.0207 mg/L) was measured in the region where the population density was between 1051 and 5000 $km^2$/persons, and the results indicated that human activities impacted GW resources. It has been reported that the GW resources in highly populated areas have elevated arsenic concentrations (Van Geen et al., 2002), and similar results were observed in Jianghan Plain. In recent decades, rapid population growth in the Jianghan Plain has degraded the local water resources (Yu et al., 2022). A high correlation was observed between arsenic concentration and dense population in large areas of Dhaka (Sarker, 2022). China accounts for only 7% of total landmass of the Earth but feeds about 25% of the global population. Therefore, water scarcity and quality are significant issues for the large population (Impending Water Crisis in China, Nina Brooks).

Table 2 depicts that the arsenic concentration in SW resources are significantly high, where the 0.5251–0.7250 $m^3$/s class shows an average concentration of 0.0243 mg/L. However, a low average value was observed in the first class (0.0065 mg/L). Mixed correlations between arsenic range and population strength were observed with regard to the classes. Therefore, it can be concluded that the broad range of human activities influence the pollution concentrations in SW resources. A comprehensive study was conducted to explore the population under arsenic risk, which showed that highly populated areas in China with a greater percentage of inhabitants are affected by arsenic toxicity (Xu et al., 2022).

First Factor F2: The pumping rate distribution in Jianghan Plain is shown in Figure 6A. It is observed that mixed pumping rate distribution can be seen over the entire area; however, Honghu and Dangyang counties show high GW exploitation of over 1.1 $m^3$/s and Jingshan, Yiling, and Shishou counties have exploitation rates below 0.2 $m^3$/s. The results in Table 2 present the average arsenic concentrations; high values are observed for the middle pumping rate class of 0.5251–0.7250 $m^3$/s (0.0243 mg/L in SW and GW) and fifth class of 0.9251–1.1250 $m^3$/s (0.214 mg/L). The general trends observed in the SW and GW are that the arsenic concentrations increased with increasing pumping quantity in the Jianghan Plain. Comparing Figure 7B, Figure 2A, it is seen that many parts of the study area have close relationships between the pumping rates and arsenic concentration levels in the GW.

Similarly, the pumping rate and SW show strong correlations in almost all parts of the study area except for the eastern region. Owing to the major farming activities in southern China, large amounts of unpolluted water need to be pumped for irrigation purposes each year in Jianghan Plain, which affects the GW quality. Gan et al. (2014) observed that the SW quality was degraded by various anthropogenic factors, such as industry, agriculture, and high population

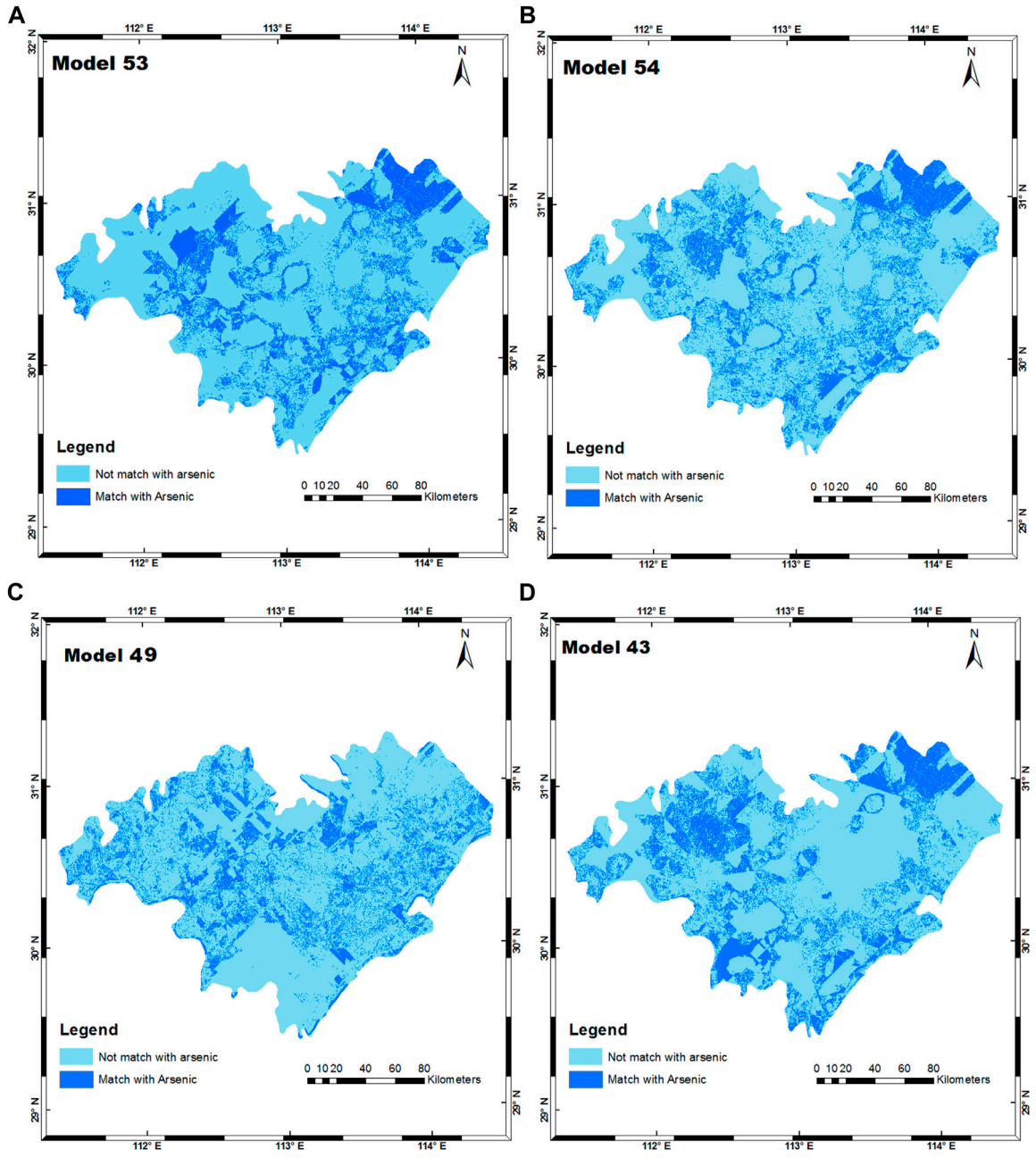


FIGURE 6
Final equal frequency maps of the best models for GW and SW arsenic concentrations: **(A)** W*Pop, **(B)** W*Pump, **(C)** W*(1Pump+2Pop), and **(D)** W*(3Pump+2LU+1Pop).

growth rate. The lowest water quality observed in shallow aquifers was attributed to SW, urban water and sanitation systems, high urban density, poor solid waste disposal, and agricultural activities, while the high arsenic levels in deep aquifers was related to the high pumping rates for different sectors, such as the urban and industrial sectors (Farooqi et al., 2003). Various studies on different water supply sources have concluded that deep aquifers can be protected against arsenic percolation by shallow pumping (Hossain and Piantanakulchai, 2013; Akhtar et al., 2015). Our findings show that GW overexploitation results in higher arsenic concentrations owing to contaminated recharge, while the high arsenic concentrations in deep GW may be from high pumping rates over the years.

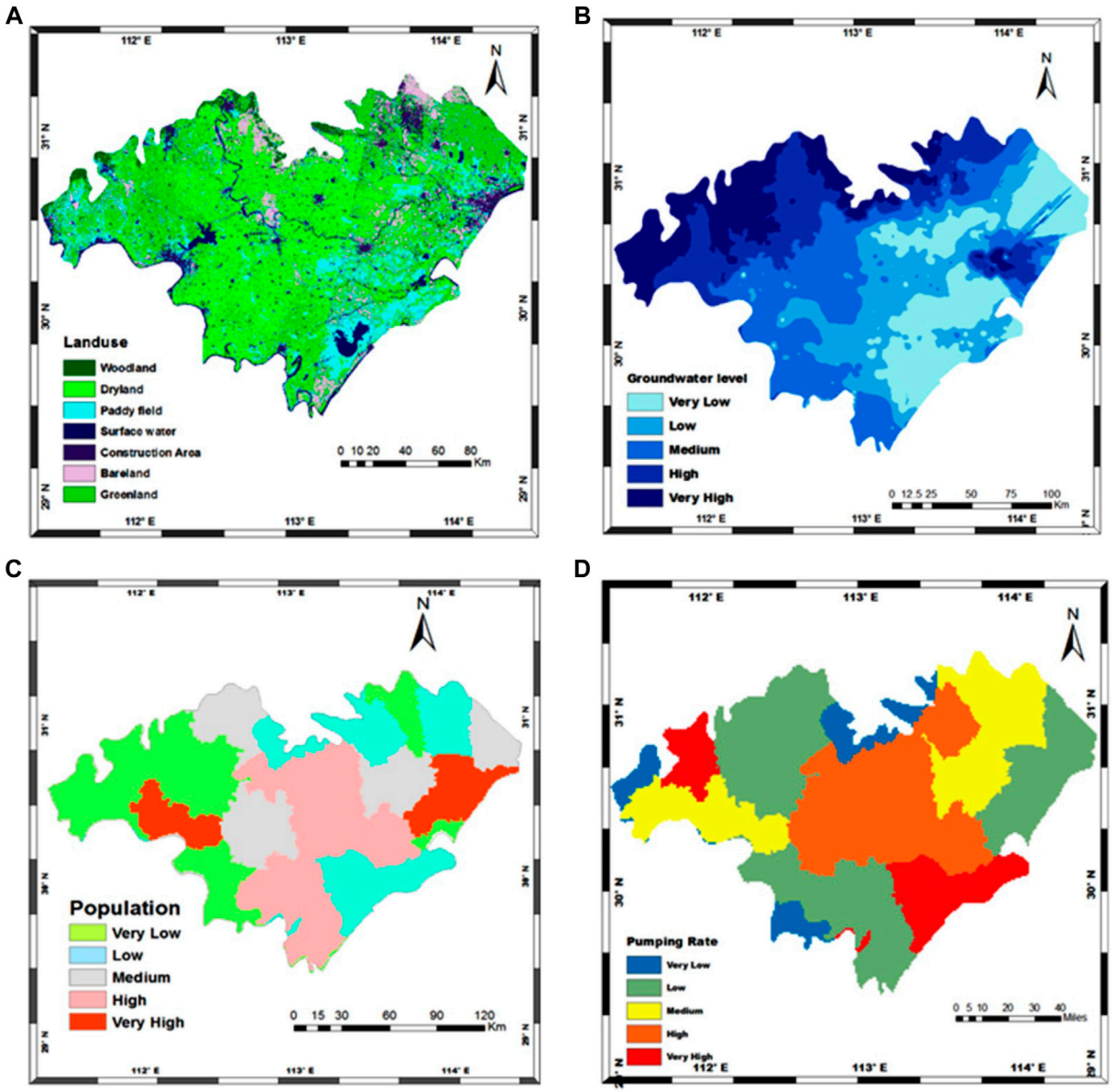


FIGURE 7
**(A)** Land use, **(B)** GW table, **(C)** population density, and **(D)** pumping rate for Jianghan Plain.

## 4.4 Arsenic spatial variation along surface water resources

This section explains the changes in arsenic concentration in SW resources and spatial variations in arsenic levels in urban and semi-urban areas. Figure 8 shows the gridded map of the study area, and each grid covers an area of 400 km$^2$. The SW flows north from the east–west part, so we were interested in investigating the spatial changes in arsenic levels to determine the relationships among SW, GW, and soil. Grids having SW were numbered, and graphs were developed based on the average arsenic value in each grid area. The average As values vary in different grids, and their concentration may be affected by different factors. Figure 9 shows that the average As values in SW, GW, and soil are less than those of other parts (from grids 1 to 6). In the first six grids, the arsenic ranges in GW (0.0027–0.008 mg/L) and SW (0.012–0.034 mg/L) depict good water quality, while the other grids show higher values. The As values indicate that grids with high anthropogenic activities show elevated values and that the upstream regions contain low arsenic concentrations compared to the downstream. Honghu and Dongting lakes are located in the southern part, and the water

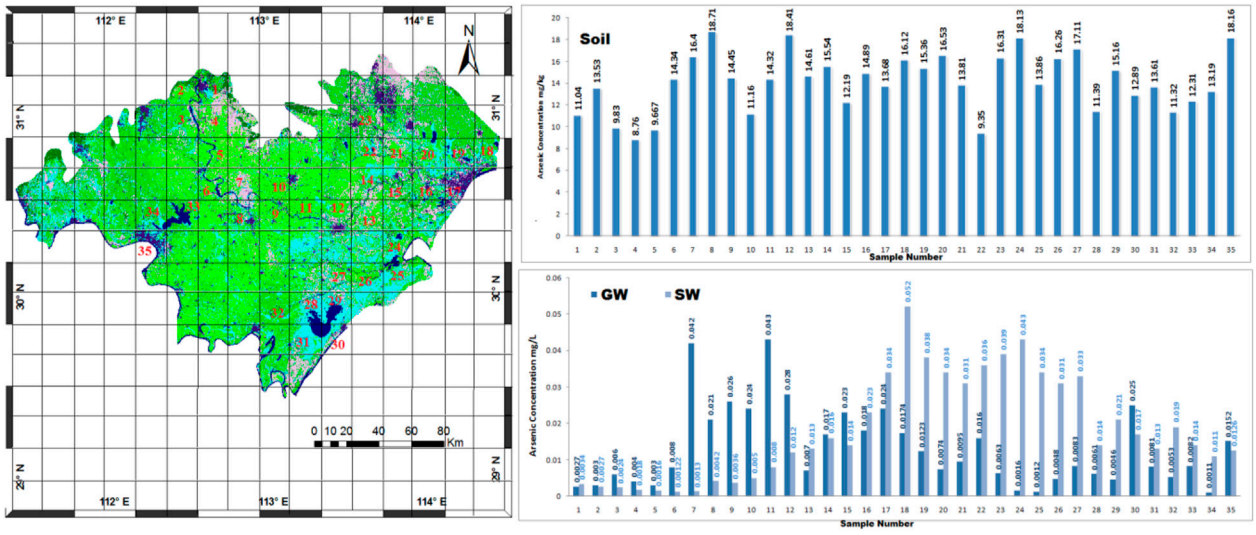


FIGURE 8
Spatial variations in arsenic concentrations in the GW, SW, and soil in Jianghan Plain.

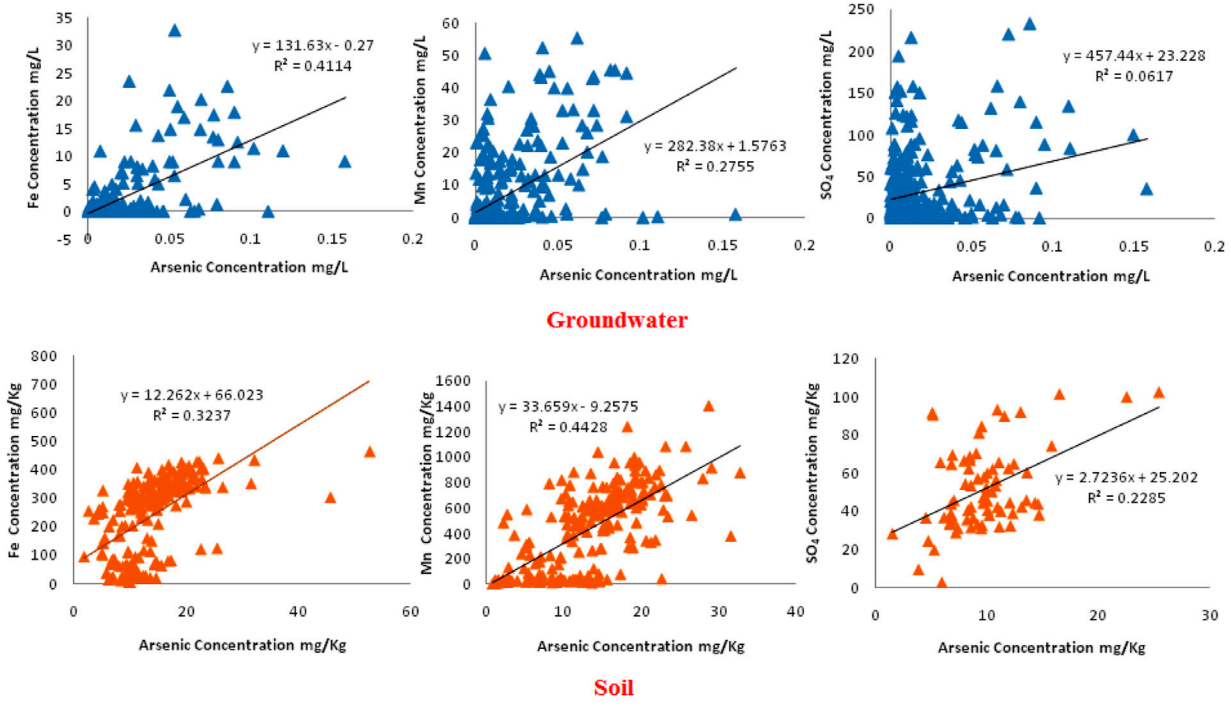


FIGURE 9
Arsenic correlations with elements in the GW and soil.

quality of Honghu lake is much better than that of Dongting lake because the latter is located near Wuhan, Zhengxiang, Shayang, Qianjiang, Xiantao, Hanchuan, Honghu, and Jingzhou, which are major cities in the study area. Comparisons of the arsenic situations in major cities and rural areas showed significant differences. The most elevated average arsenic value in soil

was observed near Xiantao (18.71 mg/kg) in grid 12, and the second highest value (18.41 mg/kg) was noted in grid 8 at Qianjiang city. A similar trend was observed for arsenic in soil near highly populated regions, such as Wuhan, Shayang, and Jingzhou, whose average values were 13.68, 14.34, and 18.16 mg/kg, respectively. However, semi-urban and rural areas showed comparatively lower arsenic risk. Elevated arsenic concentration in the SW was found near Wuhan city (0.52 mg/L), while poor quality GW was detected between Shayang and Xiantao (grids 6–12) with values in the range of 0.43–0.21 mg/L. These results clearly show that anthropogenic activities are major sources of pollution in the study area, which may be from the high population, pumping rate, waste management, or other factors.

The GIS model results are closely matched in Table 1 and Figure 9. Previous studies did not indicate clear arsenic sources in the Jianghan Plain, so it was expected that geogenic and anthropogenic causes were responsible for the elevated arsenic levels. Variations in the climate, geological characteristics, and anthropogenic activities were investigated for the elevated arsenic levels in GW in the Jianghan Plain (Gan et al., 2014). The GW system and topsoil chemistry depend on different hydrogeological parameters and factors that affect their movement and pollutant flow direction. Previous studies have observed that anthropogenic factors, such as sewage discharge, industrial wastewater discharge, and agricultural fertilizer leaching, are major sources of sediment contamination (Akhtar et al., 2014; Wang et al., 2022). Heavy metals naturally sink to the bottom of the lake and river sediments and eventually become a part of the GW system (Segura et al., 2006; Yu et al., 2008).

## 4.5 Arsenic correlation with hydrogeochemical parameters

Table 2 presents the statistical analysis results of hydrogeochemical data and their correlations with the arsenic concentrations in soil, SW, and GW from Jianghan Plain. The highest values of arsenic were measured in soil (46.62 mg/kg) and GW (0.1582 mg/L), which were over the WHO and Chinese standards, while a value of 0.0231 mg/L was detected in the SW, which is the below Chinese standard (>0.05 mg/L). The overall average arsenic concentrations detected in the three media were within the range of both standards. The chemical analysis results of trace elements (Cr, Fe, Cu, Co, Mg, F, Cu, Mn, and Pb) and their correlations with arsenic are presented (Table 2). High relationship between arsenic in soil and Cu ($r^2$ = 0.6228), SW and pH ($r^2$ = 0.48173), and GW and Fe ($r^2$ = 0.4114) were observed. At the same time, the other hydrogeochemical parameters showed significant variations in the concentration and correlation values.

The pH values varied from acidic to alkaline in the GW, with values in the range of 6.3–9.6 and an average value of 7.227. A similar trend was observed for the SW, where the average value (7.974) indicated a general alkaline behavior. Often, high pH values indicate the presence of anions, which encourage reduction processes to control arsenic mobility (Source: USGS). High arsenic levels were detected in waters where the pH values were over 8. Lower pH (<8) values may be attributed to arsenic desorption due to surface oxidation (Smedley and Kinniburgh, 2006). Elevated Pb concentrations were detected in the GW (average value: 1.0828 mg/L) and SW (average value: 0.6267), which show relationships with pH. Owing to the redox-sensitive element, pH conditions can enhance Pb mobility (Mapoma and Xie, 2014). Arsenic correlation with Fe ($r^2$ = 0.3237) in soil indicates that arsenic has low association with minerals (Xie et al., 2008). The correlations of Fe with arsenic were computed to be 0.4114 and 0.0922108 for GW and SW, respectively. Significant correlations were observed between arsenic and Ca, Na, Cd, Cu, Mn, and Zn based on the geochemical analyses of collected soil samples and from statistical calculations. The correlations of other geochemical parameters were higher than those of iron, indicating that As had no strong associations with iron-based minerals. The relationship between arsenic and $SO_4$ is consistent with the reduction dissolution of iron oxides/oxyhydroxides, as has been shown in other case studies (Welch et al., 2000; McArthur et al., 2004). Under oxidizing conditions, the correlation between Fe and As is common. Interestingly, high concentrations of $SO_4$ (GW: max = 194.063 mg/L; SW: max = 81.85 mg/L) indicated the slow occurrence of reduction processes in the system for the production of sulfide mineral precipitates (Xie et al., 2008). The arsenic correlations with $SO_4$ in the three media showed significant trends.

The low concentration of average Fe value is linked to the reduction of the primary source of GW arsenic rather than the Fe/$SO_4$ cycle in Jianghan Plain. Fe and alkalinity correlations with GW and SW show the strong impact of redox processes on the elevated arsenic concentrations. Many studies have shown that the elevated Fe concentrations could be due to the reduction process in water (Cummings et al., 1999). Suboxic to anoxic conditions of the chemical reactions and correlations of $NO_3$ and $SO_4$ with arsenic do not support the reduction mechanism of dissolution of Fe in soil. Therefore, Fe concentration levels in the sediments and GW are used to predict arsenic mobility and sources.

Nominal arsenic concentration correlations with iron ($r^2$ = 0.4114) and Mn ($r^2$ = 0.2755) were detected in GW, while low correlations were observed with Fe ($r^2$ = 0.0922108) and Mn ($r^2$ = 0.14568) in SW. The positive correlation between Fe and As indicates reductive dissolution of arsenic links with Fe oxides under reductive conditions. Reductive dissolution of As correlated with Fe oxides/hydroxides is regarded as a major process controlling arsenic mobility in the GW (Nickson

et al., 2000; Smedley and Kinniburgh, 2006). It was observed that Fe and Mn oxides/hydroxides under reducing conditions are supported mechanisms for arsenic release in Jianghan Plain (Gan et al., 2014). The values of $r^2$ for arsenic in SW and GW also show the low mobility of arsenic. Thus, a combination of mechanisms such as reductive dissolution and pH-dependent desorption influence the mineralization of As in the aquifer systems of Jianghan Plain.

Gan et al. (2014) investigated the arsenic concentrations in GW at Jianghan Plain and concluded that the hydrochemical and hydrogeological characteristics have significant similarities with other high-arsenic GW areas, such as Bangladesh; Bihar and West Bengal in India; and Pakistan (Muhammad et al., 2016; Lanjwani et al., 2022). The statistical results of the hydrogeochemical data and their relationships helped identify that geogenic, hydrogeological, and anthropogenic factors were involved in the elevated levels and mobility of arsenic in Jianghan Plain. However, oxidation/reduction mechanisms were also observed; therefore, other factors are important for investigating the real causes of increased arsenic levels in the study area.

## 5 Conclusion

The present study is concerned with arsenic concentrations in the soil, SW, and GW as well as their relationships with seven factors in Jianghan Plain. The arsenic levels were identified in three media of the water cycle; however, the concentrations changed with the locations. Thus, direct GW use is not recommended for drinking because the shallow water is highly contaminated. Among the single-, two-, and three-factor models, the major factors related to elevated arsenic levels in GW and SW were population density and pumping rate, while land use and GW pumping rate induced higher arsenic levels in soil. In addition, arsenic concentrations along the SW flow were investigated. Arsenic values in GW, SW, and soil were elevated near main cities and areas with high anthropogenic activities.

The average pH value (below 8 in SW and GW) indicates a slow reduction process, and an As–Fe correlation of $r^2$ = 0.419343 in GW depicts the association of soil with mineralization. The relationship between arsenic and $SO_4$ is consistent with the reduction dissolution of iron oxides/oxyhydroxides; arsenic relationship with other hydrochemical parameters shows that geogenic sources are slightly linked to increased arsenic concentrations in GW; however, the hydrogeochemical data depict a positive relationship.

For drinking and domestic use, treated water or alternative water sources are considered to be good options. Therefore, the local water resource managers and planners should develop strategies for Jianghan Plain to control the high arsenic concentrations in potable water. The concerned departments, such as environmental, urban planning, industrial, and water management, can solve the GW, SW, and soil contamination problems by sharing information, improving future planning, as well as introducing and implementing suitable pollution control laws.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

## Author contributions

All authors listed have made substantial, direct, and intellectual contributions to the work and approved it for publication.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher’s note

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# Evaluation of the factors affecting arsenic distribution using geospatial analysis techniques in Dongting Plain, China

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Due to high toxicity, arsenic is regarded as a major global environmental pollutant. The present study is investigated the potential factors influencing to elevate concentration of arsenic in groundwater, surface water, and soil of the Dongting basin. The arsenic contamination potential prediction map and categories were developed using various GIS techniques such as Ordinary Kriging and the Quantile method. Then the "Raster calculator" tool was applied to verify the impact of the factors on arsenic. Eighty-four single-factor, bi-factor, and multi-factor models were established to investigate effective combinations among factors of each phase. Additionally, statistical tests were computed to evaluate arsenic between classes and factors. The arsenic value varies in groundwater from 0.0001 to 0.1582 mg/l, while in surface water between 0.0001–0.0287 mg/l and soil sediments range from 1.8–45.69 mg/kg. JunShan and GongAn groundwater resources have been identified as posing a high risk to human health. The single factors showed the best match frequency of arsenic with a population density of 66.86% in water and land use depicted match frequency of arsenic 73.19% in soil. The statistical calculations with percentage frequency factors also depicted positive trends. The correlation of the factors with arsenic in soil and water showed slow oxidation and reduction in the groundwater system. Treated portable water could be the best option to reduce the health risk of the local community.

KEYWORDS

**GIS, remote sensing, geostatistical analyst, arsenic, Dongting plain**

## 1 Introduction

Contaminated natural sources are a constant threat to the healthy survival of the living organisms (Chormare and Kumar, 2022), but due to human activities and natural factors, the natural composition of the soil, surface water, and groundwater has been changed (Malik Muhammad and Zhonghua, 2014). Groundwater arsenic is known as a high-

toxicity environmental pollutant globally due to its carcinogenic and non-carcinogenic health effects on living organisms (human and animal) health (Zhang et al., 2015a; Waqas et al., 2017) and skin cancer (Lamm et al., 2007). Last few decades, heavy metal pollutants in water and soil have seriously affected China's ecological environment (Wu et al., 2014). Elevated value of arsenic in groundwater has been observed in many countries, especially Bangladesh, Cambodia, Chile, China, India, Pakistan, Vietnam, and the United States (Polizzotto et al., 2008; Fendorf et al., 2010; Muhammad et al., 2016). A high arsenic ratio was reported in China's continental lithosphere (CCL) and natural water (Che et al., 2020). However, Bangladesh, Pakistan, and China are facing serious issues related to waterborne endemic arsenic poison (Zhang et al., 2015b; Muhammad et al., 2016). Between 2008 and 2009, five major arsenic contamination incidents were reported from providences: Guizhou, Hunan, Guangxi, Yunnan, and Henan (Wu et al., 2014). In recent decade, environmentalists have focused their research on pollution issues in the Dongting basin (Chen et al., 2018). Exacerbated human activities, reclaimed agriculture, and deforestation have dominated its catchment and adjacent area of the Dongting basin (Du et al., 2001). Different researchers conducted studies and concluded that the Dongting area contained a high arsenic and other heavy metals in water resources (Yao et al., 2009; Qian et al., 2005). China is facing high pressure on its natural resources due to urbanization and industrialization, which has many challenges related to arsenic pollution (Zhang et al., 2009; Li et al., 2021). During a national survey, it was found that 2.7% of collected soil showed elevated concentration of arsenic (http://www.mep.gov.cn/gkml/hbb/qt/201404/W020140417558995804588.pdf). Song investigated 109 regions of China and found a 9.48 mg/kg average arsenic value in soil (Song et al., 2013). During a survey of 45 counties in nine provinces of China, nineteen contained elevated arsenic in portable water higher than WHO permissible limit (0.01 mg/l) and China Standard (0.05 mg/l) (He and Charlet, 2013). It was observed that 0.01–0.05 mg/l arsenic value was exposed in the local community (He et al., 2020). The present research is a comprehensive study of arsenic distribution in water and soil in the Dongting basin of China, including various factors such as groundwater level, population density, heavy metal contamination, pumping rate, land use, rain, and surface elevation. The influence of these factors to high arsenic in the area was investigated. Remote sensing techniques, GIS applications and statistical methods are new ways to find out what controls the amount of arsenic in three different media.

# 2 Location, climate, and hydrogeology of Dongting plain

Dongting Lake Plain is located in the northeast of Hunan Province, in the south of the two lake plains (also known as the Hubei basin), and in the north, it is connected with the Jianghan Plain in Hubei Province. It is mainly composed of the sediment imported from the Yangtze River through the four ports of Songzi, Taiping, Ouchi, and Tiaoxuan, and the sediment from the Xiangjiang, Zijiang, Yuanjiang, and Lishui rivers. It covers an area of 10,000 $km^2$ with an altitude of 34.5 m and a total capacity of 17.8 BCM. The whole plain covers a total area of 18,780 $km^2$, of which 15,200 $km^2$ are part of Hunan Province, accounting for 81% of the total area; 3,580 $km^2$ are part of Hubei Province, accounting for 19%. Most of the main lakes and depressions are on the southern margin. Dongting Lake produces fish, water chestnuts, lotus, reeds, etc. It is an ideal base for grain, cotton, hemp, aquatic products, and silk. The lake area is mostly surrounded by lakes to form polder fields. China's commodity grain base and important freshwater fish areas the output has reached the forefront of the country.

# 3 Data collection and methodology

## 3.1 Sampling

Total 300 groundwater samples were collected from Donating Plain while 125 samples and 75 samples were collected from surface water (Rivers and Lakes) and soil, respectively. The groundwater depth is shallow in the study area, generally 0.5–3.5 m deep. The samples were collected after more than 10 min of pumping until the physical parameters [temperature, electrical conductivity (EC), and pH] were stable. Four 50 ml HDPE bottles were used for each sample point and filtered on site (using 0.45 m membrane filters). For the total dissolved analysis, HCL was used to acidify the bottle and wrap it with tinfoil. The second bottle was acidified (PH2 using ultra-pure $HNO_3$) for chemical analysis of dissolved ions and trace elements, and the remaining two bottles were not acidified for the analysis of anions and H/O isotopes. All samples were immediately stored at 4°C until the analyses were completed. Our study area is seriously affected by arsenic contamination of groundwater, so investigating arsenic levels in the soil is important to develop their relationship. Soil samples were collected at 20 cm in depth. The soil samples were collected from a boring core and capped with PTFE lids, and after that, they were stored at 4°C in an opaque anaerobic box.

## 3.2 Analytical methods for waters

Temperature, dissolved oxygen (DO), pH, and EC were measured on the sampling spot using a portable meter (HQ40D Field Case, cat. No. 58258-00, HACH, Colorado, United States). The portable gel-filled ORP probe (MTC10103, HACH) was used to measure Eh. The total concentration value was determined for dissolved ions (Mg and Fe) using an

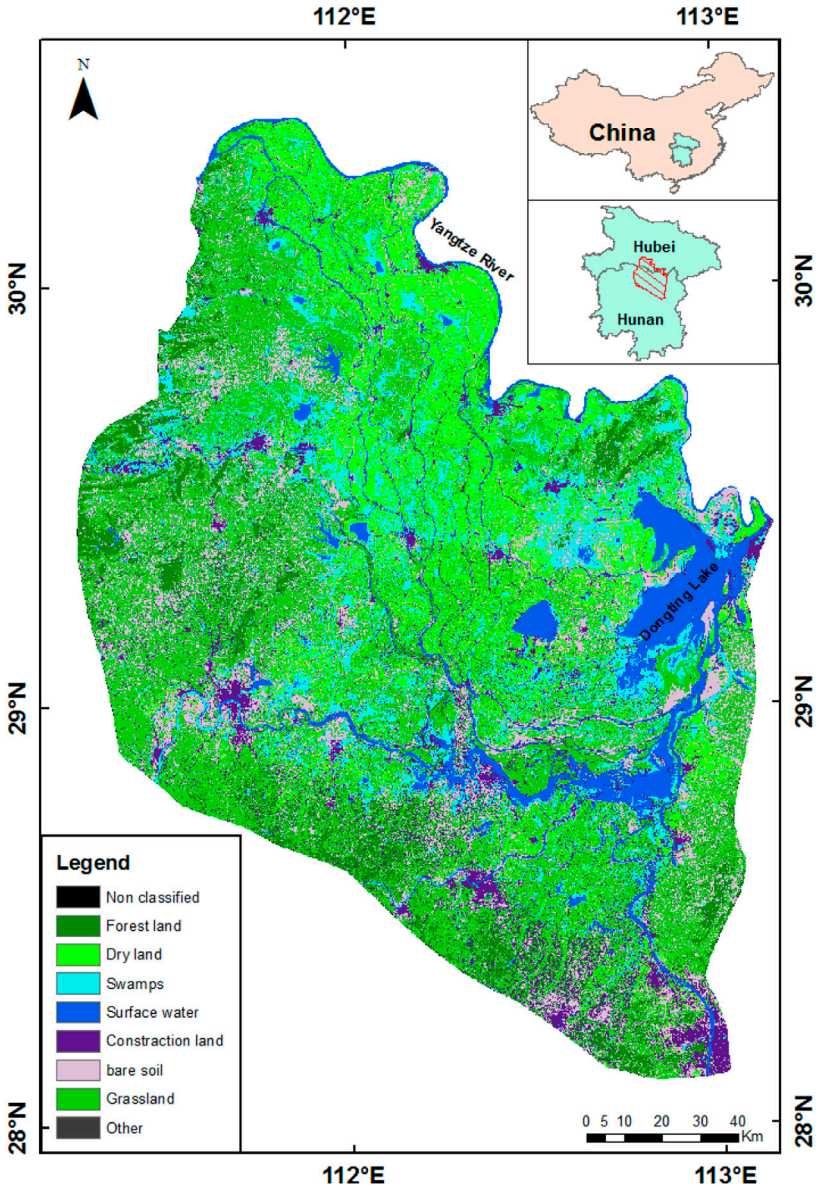


FIGURE 1
Location of the selected area at Hunan province (Dongting Plain).

inductively coupled plasma atomic emission spectrometer (ICP-AES) (IRIS Intrepid II XSP, United States). For trace elements, inductively coupled plasma mass spectrometry (ICP-MS) (ELAN 9000/DRC-e, PerkinElmer) was used. Verification of the accuracy of major elements analyzed by ICPAES and ICP-MS was found within 4% and 5%, respectively. Anions ($NO_3$, and $SO_4$) were measured using an ion chromatograph (Dionex 2500, United States). The analytical precision was better than 5%. The total organic carbon analyzer (multi N/C 3100, Germany) was used to measure dissolved organic carbon (DOC) and the detected value of 0.004 mg/l with a precision of 8%. Total As of groundwater and surface water were measured using a hydride generation-atomic fluorescence spectrometer (HG-AFS, 930, Titan, China).

## 3.3 Soil analyst method

To measure the mineralogical compositions of the soil samples, an automated powder X-Ray Diffractometer (Cu–K radiation and a graphite monochromator) (X'Pert PRO DY2198, PANalytical) was used with a detection limit of 2%. Chemical elements were

TABLE 1 Models frequencies of factors correlation with arsenic concentration in waters and soil.

| Groundwater and surface water | | | Soil | | |
|---|---|---|---|---|---|
| **Model no.** | **Factors and ranks** | **Equal frequency %** | **Model no.** | **Factors and ranks** | **Equal frequency %** |
| Model_51 | GW*Wl | 64.47 | Model_151 | Soil*Wl | 50.57 |
| Model_52 | GW*LU | 64.33 | Model_152 | Soil*Lu | 73.19 |
| Model_53 | GW*POP | 66.86 | Model_153 | Soil*POP | 48.77 |
| Model_54 | GW*PUMP | 60.32 | Model_154 | Soil*PUMP | 73.07 |
| Model_55 | GW*SE | 59.41 | Model_155 | Soil*SE | 68.63 |
| Model_56 | GW*RAIN | 31.26 | Model_156 | Soil*RAIN | 13.62 |
| Model_57 | GW*CONT | 56.26 | Model_157 | Soil*CONT | 61.14 |
| Model_49 | GW*(1WL+2pop) | 63.05 | Model_149 | Soil*(1pump+2lu) | 74.45 |
| Model_50 | GW*(2WL+1pop) | 65.49 | Model_150 | Soil*(2pump+1lu) | 62.37 |
| Model_43 | GW*(3WL+2lu+1pop) | 61.4 | Model_143 | Soil*(3pump+2lu+1SE) | 60.33 |
| Model_44 | GW*(3WL+1lu+2pop) | 55.91 | Model_144 | Soil*3pump+1lu+2SE) | 59.37 |
| Model_45 | GW*(2WL+3lu+1pop) | 63.41 | Model_145 | Soil*(2pump+3lu+1SE | 68.11 |
| Model_46 | GW*(2WL+1lu+3pop) | 62.02 | Model_146 | Soil*(2pump+1lu+3SE) | 64.71 |
| Model_47 | GW*(1WL+3lu+2pop) | 63.61 | Model_147 | Soil*(1pump+3lu+2SE) | 61.35 |
| Model_48 | GW*(1WL+2lu+3pop) | 61.06 | Model_148 | Soil*(1pump+2lu+3SE) | 61.76 |

determined by X-Ray Fluorescence Spectroscopy (Spectro Xepos HE XRF Spectrometer). The rest of the chemical tests were done at the China University of Geosciences in Wuhan at the State Key Laboratory of Biogeology and Environmental Geology and the State Key Laboratory of Geological Processes and Mineral Resources.

## 3.4 GIS models development

The study area's topographic map (1:50,000) was used to create a thematic map that contains comprehensive information about the boundaries and land use in Figure 1. The simple Kriging method was used in the ArcGIS Geostatistical analyst toolbar to develop arsenic distribution zones in groundwater, surface water, and soil for the study area. The 2014 arsenic levels of pumping wells were used to fulfill this aim. Kriging and co-kriging are parts of the geostatistical techniques, which are found to be superior in several functions for data analysis. For example, they are included in exploratory spatial data analysis tools to handle statistical properties and to create various types of maps such as probability, prediction, quantile, simple and ordinary. Kriging can be divided into two other sub-methods: ordinary kriging and indicator kriging, which provide two types of information. Ordinary kriging is useful for the prediction and development of contamination potential maps, whereas indicator kriging is important for the identification of probabilities. To design the distribution map, the 2012 arsenic value were categorized into five levels using the Quantile method as shown in Table 1. Then, six different factors were tested to examine their influence on arsenic levels in groundwater, surface water, and soil in the study area, such as:

### 3.4.1 Groundwater level

Since local groundwater level is the main factor for infiltration and transport of various pollutants, the simple kriging method in the geostatistical analysis was used again to create groundwater level zones for the study area. Pumping Ratio: Total pumping quality per annum was calculated for each county located in the Dongting Plan. ArcGIS was used for further analysis. Finally, the result was converted from vector data format to raster data format for the final analysis process.

### 3.4.2 Rain

Rain data for the year 2014 was collected from the website of the Hydrology and Water Resources Survey in Hunan Province, and a total of 90 meteorological stations' data was used to show rainfall tendency through the geostatistical analyst tool in GIS.

### 3.4.3 Heavy metal contamination

A heavy metal concentration distribution map was developed based on data available in a report titled "The Ecological Geochemical Assessment Report of Dongting Lake in Hunan Province" published by the Geological Research Institute of Hunan Province in the year 2007. A geostatistical analyst tool was applied to show the final contamination elevated concentration in GIS.

### 3.4.4 Landuse

Landuse is an important factor for generating and infiltrating arsenic. A recent Landsat-8 image was used to create a supervised land use classification for the study area in the ENVI software environment. Seven major categories (Woodland, Dryland, Paddy Field, Surface Water, Construction Area, Bareland, and Greenland) were exploited to understand real local land use.

### 3.4.5 Topography

Elevation is a factor that could control water flow while low elevation produces more chances of water infiltration. An ASTER Digital Elevation Model (DEM) was used to create a contour map for the study area using 3D-analyst tools in the ArcGIS environment. The results from each factor were categorized into five groups according to the quantile method using the reclassify tool included in the spatial analysis toolset. The reclassifies were applied to modify the values in the raster, and the input raster was classified into different class ranges for the reclassification. The "Raster calculator" tool was used to determine the most important factor influencing arsenic distribution in the study area. It allows for creating and executing an algebraic expression that outputs a raster. Spatial Analyst operators were employed to transform two inputs into a single expression. The Raster Calculator is designed to execute a single-line algebraic expression. It is developed using multiple tools and operators included in the simple calculator tool interface. Forty different models were developed using a raster calculator. The models were built by combining different factors to find the most effective combination among them. Single and multi-factor models were carefully established by assigning coefficients 1 to 6 as rank because each model must contain unique values. Then, the quantile method included in the Reclassify tool was repeated for each model to categorize the results into five classes. To evaluate the eighty-four models, the "Equal to frequency" tool was applied based on a cell-by-cell match with the Arsenic distribution model result, and then the best frequency match combination models were selected. Additionally, the frequency range was computed with the "Band Collection Statistic" tool that provides statistics results from a multivariate analysis of a set of raster bands. The frequency range was also used to count the matched and unmatched pixels in each of the forty models. Finally, statistical analysis was computed to investigate the effect of factors (groundwater, surface water, and soil arsenic) with high equal frequency ratio factors. The collected data was first analyzed using Microsoft Office Excel 2007 spreadsheets. Several classes were built for each factor to evaluate their variation in arsenic. Correlation analysis was applied to verify arsenic value in water with other factors (population density and water level) and arsenic distribution in soil with land use and pumping. Results and discussion are presented in detail in the next sections based on the described methodology.

# 4 Results and discussions

## 4.1 Arsenic presence in surface and subsurface water

### 4.1.1 Chemical analysis of water samples

Three hundred groundwater samples were collected from different drinking water sources such as wells, hand-pump, and motor pumps. Minimum and maximum concentration of arsenic was computed during the analysis process as 0.0001 and 0.1582 mg/l, respectively. The statistical results showed a variance range of 0.00026 and the standard deviation was 0.0159. However, arsenic distribution in groundwater showed local variations within the distribution pattern. Figure 2A displayed that high concentration of arsenic areas were on the east side (higher than the Chinese permissible limit) and the north area showed slightly lower but higher than the WHO limit. However, the south and west have fewer pollution ratios. In Figure 2A, the red color represented arsenic concentration of over 0.05 mg/l, which is believed to be higher than WHO (0.01 mg/l) and Chinese (0.05 mg/l), and water in the corresponding area is supposed to be harmful to the community's health. Based on available data from different residential areas, commercial, industrial, and agricultural areas, the pumping wells were scattered throughout the whole area, but the northern part of the counties contained low risk, where the average concentration was less than 0.02 mg/l, and water in these towns is considered safe for drinking. The highest concentration of arsenic was observed in Junshan county in the east and the surrounding areas of Anxiang city in the north. During a study on groundwater quality, the results showed that 76 cities were seriously polluted, while 39 cities were slightly polluted, and the groundwater pollution trend is from urban to suburban areas in China (Mei and Feng, 1993). China Daily (2006) reported that Yueyang County, located in Hunan Province, has contained dangerous levels of concentration of arsenic in drinking water.

Surface water samples were collected from rivers and lakes at Dongting Plain. On the basis of the chemical analysis results of 125 samples, low and high values were determined to be 0.0001 and 0.0287 mg/l, respectively, while the calculated variance was $9.5 \times 10^{-5}$ and standard derivative 0.0098. The surface water concentration of arsenic developed map was depicted with spatial variation. The eastern and central parts had the highest concentrations of more than 0.02 mg/l, while the northwest had the lowest values compared to WHO and Chinese standards. Previous researchers have identified a lot of surface water resources in the form of lakes, rivers, and open water bodies, but the quality of water is not good (He and Charlet, 2013). In Figure 2B, Dongting lake, located in the east, exhibits a high arsenic value. It was observed that the contamination level of river waters was higher than that of waters in lakes at Dongting Plain. Economic development pressures have accelerated human

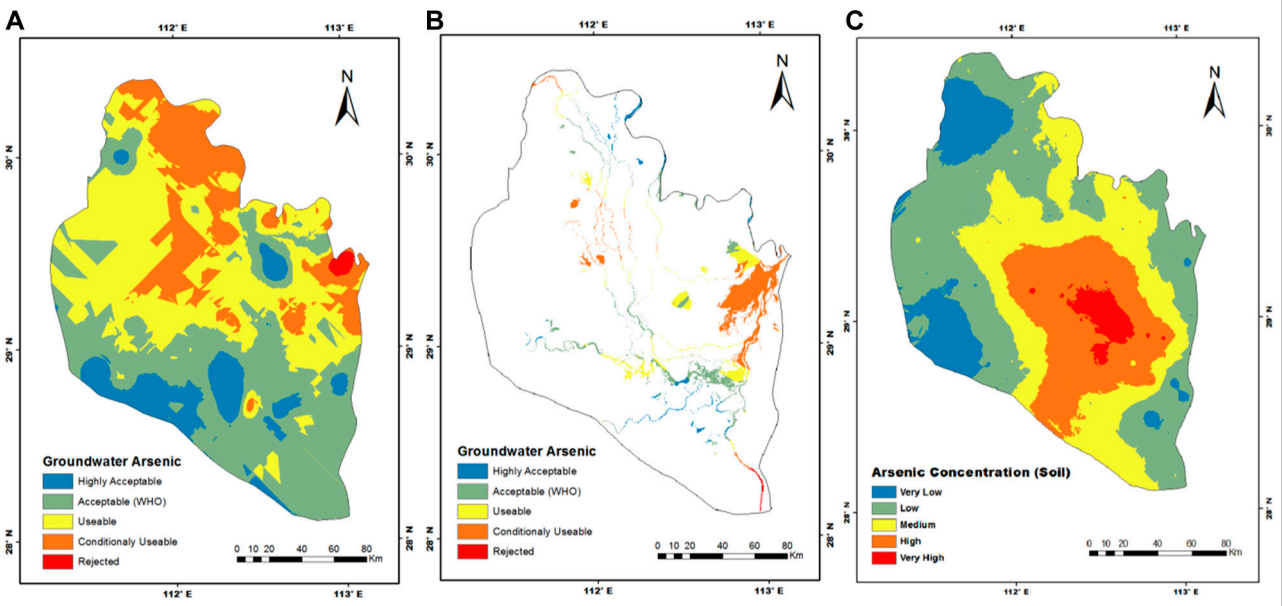


FIGURE 2
Arsenic distribution in groundwater **(A)**, surface water **(B)** and soil **(C)**.

activities to rise in production (industrial as well as agricultural) and urbanization is a major source of surface water pollution in the Dongting plan. BI observed that in China, domestic sewage has polluted lakes (Akhtar et al., 2015; Bi et al., 2018), while another researcher identified agricultural activities caused by watersheds (Gao and Mucci, 2003). Similarly, due to untreated industrial effluents and wastes, various pollutants values in river waters did not meet standards. In the year 2005, toxic arsenic events were reported in branches and reaches of the Li River and Xiang River (Hunan Water Administration, 2006). According to statistics, the amount of untreated polluted water drained into rivers is $3.42 \times 10^{10}$T, with $2.565 \times 10^{10}$T (7.5 percent) from industrial sewage and $8.85 \times 10^{3}$T (25 percent) from domestic sewage (Guogang et al., 1991). It can be concluded that polluted surface water affects groundwater quality. Controlling fresh watershed pollution in China is important to integrate issues related to population, economic development, and future planning. It will help to address human health-related issues.

### 4.1.2 GIS base spatial distribution model of water

The permissible level of arsenic in drinking water in China is 0.05 mg/l (50 ppb) in groundwater and surface water, and 40 mg/kg in soil (Ministry of Health of ChinaStandardization Administration of China, 2006), which is safe enough for human health. The distribution of concentration of arsenic in waters was compared using similar frequency values of a single factor (7 models), two factors (4 models), three factors (9 models), and multi-factors (42 models), which are included in raster models. The results of the estimated frequency values, according to the models, are displayed in Table 1. The single model's frequencies of population density (Model 53 with 66.86%) and water level (Model 51 with 64.47%) were greater than the other single and combined factor model frequencies. The model results showed that high matching related to population density and water level individually greatly affects the concentration of arsenic in the Dongting basin. Furthermore, for the single models, the population density model gave the highest matching frequency with arsenic, while rainfall (Model 56, with 31.26%) provided the lowest frequency. The observed moderate frequency values were 64.33% and 60.32% for land use and pumping, respectively. However, this model frequency in a single factor was lower than that of its combination in the multi-factor models (Table 1). The best matching frequency for the multi-factor models was observed for the 2WL*1Pop (model 50 with an equal frequency of 65.49%) and the 1WL+2Pop+3LU (model 47 with an equal frequency of 63.61%). The highest matching frequency percentages were 65.49% among two factor combination models, 63.61% between three factor models, and the lowest, 55.91%, while the four and five factor values ranged from 10.9% to 55.66%. The most effective factors were population density and water level, which have the two highest matching frequencies between the models. This result was confirmed by the frequency maps of the best four models shown in Figure 3. The analysis with an equal frequency tool explored the various factors contributing to the decreasing water quality in the Dongting basin. This result helped to identify the affectivity of single factors as well as the different groups of multi-

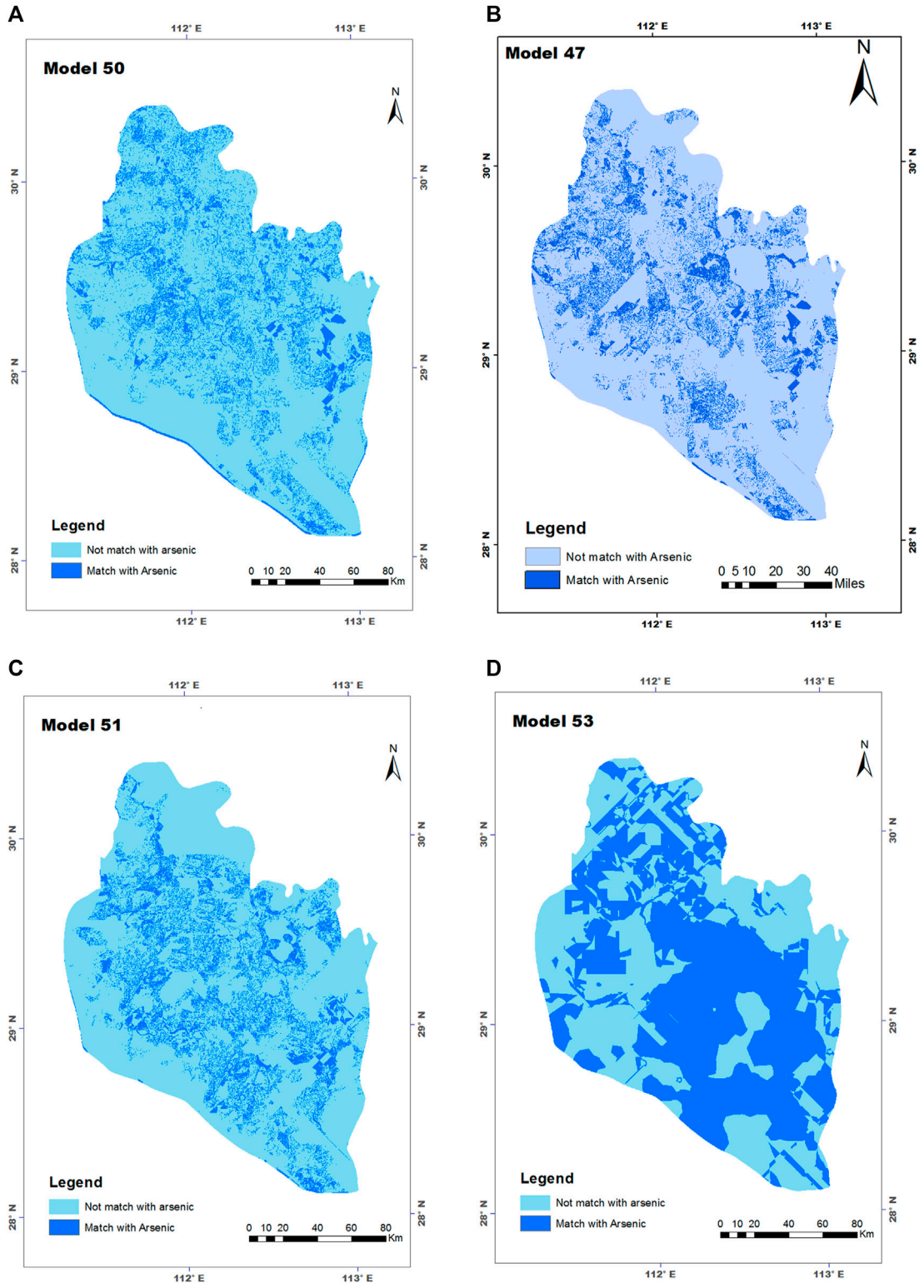


FIGURE 3
Final equal frequency map of best models with groundwater and surface water concentration of arsenic: **(A)** (1*WL+3*LU+2*Pop), **(B)** (2*WL+1*Pop), **(C)** WL, and **(D)** Pop.

TABLE 2 Seven factors classifications and average arsenic concentration of each class in waters and soil.

| | | | | | |
|---|---|---|---|---|---|
| Population ($10^5$) | | | | | |
| Classes | 1–10 | 10–30 | 30–60 | 60–90 | 90–120 |
| As in Soil (mg/kg) | 14.5626 | 13.1940 | 13.3100 | 14.0350 | 15.3900 |
| As in SW (mg/L) | 0.0176 | 0.0201 | 0.0166 | 0.0051 | 0.0200 |
| As in GW (mg/L) | 0.0164 | 0.0193 | 0.0182 | 0.0152 | 0.026 |
| Pumping ($10^6$ $m^3$/a) | | | | | |
| Classes | 4–9 | 10–15 | 16–21 | 22–27 | 28–33 |
| As in Soil (mg/kg) | 13.6500 | 13.4886 | 13.6813 | 15.2960 | 15.2350 |
| As in SW (mg/L) | 0.0065 | 0.0197 | 0.0216 | 0.0194 | 0.0180 |
| As in GW (mg/L) | 0.0130 | 0.0174 | 0.0181 | 0.0180 | 0.0246 |
| Water Level (m) | | | | | |
| Classes | 21–50 | 51–80 | 81–110 | 111–180 | 181–260 |
| As in Soil (mg/kg) | 15.8053 | 13.0560 | 15.5400 | 15.3400 | 14.6500 |
| As in SW (mg/L) | 0.0198 | 0.0116 | 0.0210 | 0.0041 | 0.0112 |
| As in GW (mg/L) | 0.0176 | 0.0166 | 0.085 | 0.0180 | 0.0165 |
| Rain (mm) | | | | | |
| Classes | 850–970 | 970–1,090 | 1,090–1,210 | 1,210–1,330 | 1,330–1,450 |
| As in Soil (mg/kg) | 14.8600 | 13.9160 | 14.8633 | 13.2650 | 13.1000 |
| As in SW (mg/L) | 0.0380 | 0.0135 | 0.0203 | 0.0129 | 0.0260 |
| As in GW (mg/L) | 0.0066 | 0.0181 | 0.0466 | 0.0160 | 0.0102 |
| Contamination (heavy metals) (mg/kg) | | | | | |
| Classes | 22–27 | 28–32 | 33–37 | 38–42 | 43–47 |
| As in Soil (mg/kg) | 13.1700 | 12.6750 | 15.2775 | 14.0100 | 15.5240 |
| As in SW (mg/L) | 0.0021 | 0.0144 | 0.0204 | 0.0211 | 0.0216 |
| As in GW (mg/L) | 0.0112 | 0.0176 | 0.0158 | 0.0170 | 0.0241 |
| Surface elevation (m) | | | | | |
| Classes | 21–60 | 61–100 | 101–140 | 141–180 | 181–220 |
| As in Soil (mg/kg) | 14.6900 | 14.6400 | 15.3100 | 14.3400 | 15.4500 |
| As in SW (mg/L) | 0.0197 | 0.0101 | 0.007 | 0.011 | 0.021 |
| As in GW (mg/L) | 0.0169 | 0.0188 | 0.0208 | 0.0187 | 0.0213 |
| Land use (constructed area %) | | | | | |
| Classes | 6–12 | 13–19 | 20–26 | 27–33 | 34–40 |
| As in Soil (mg/kg) | 13.7029 | 12.9973 | 15.4220 | 16.7367 | 14.3800 |
| As in SW (mg/L) | 0.0042 | 0.0073 | 0.0076 | 0.0103 | 0.0245 |
| As in GW (mg/L) | 0.0196 | 0.0168 | 0.0679 | 0.0263 | 0.0266 |
| Land use (greenland area %) | | | | | |
| Classes | 9–20 | 21–32 | 33–43 | 44–55 | 56–67 |
| As in Soil (mg/kg) | 13.6133 | 13.6475 | 17.9667 | 13.9225 | 15.0757 |
| As in SW (mg/L) | 0.0147 | 0.0193 | 0.0144 | 0.0171 | 0.0221 |
| As in GW (mg/L) | 0.0153 | 0.0413 | 0.0267 | 0.0190 | 0.0184 |
| Land use (dryland area %) | | | | | |
| Classes | 1–7 | 8–14 | 15–21 | 22–28 | 29–35 |
| As in Soil (mg/kg) | 13.7331 | 12.9957 | 15.3775 | 26.0250 | 16.9800 |
| As in SW (mg/L) | 0.0178 | 0.0088 | 0.0720 | 0.0210 | 0.0062 |
| As in GW (mg/L) | 0.0181 | 0.0546 | 0.0179 | 0.0523 | 0.0105 |

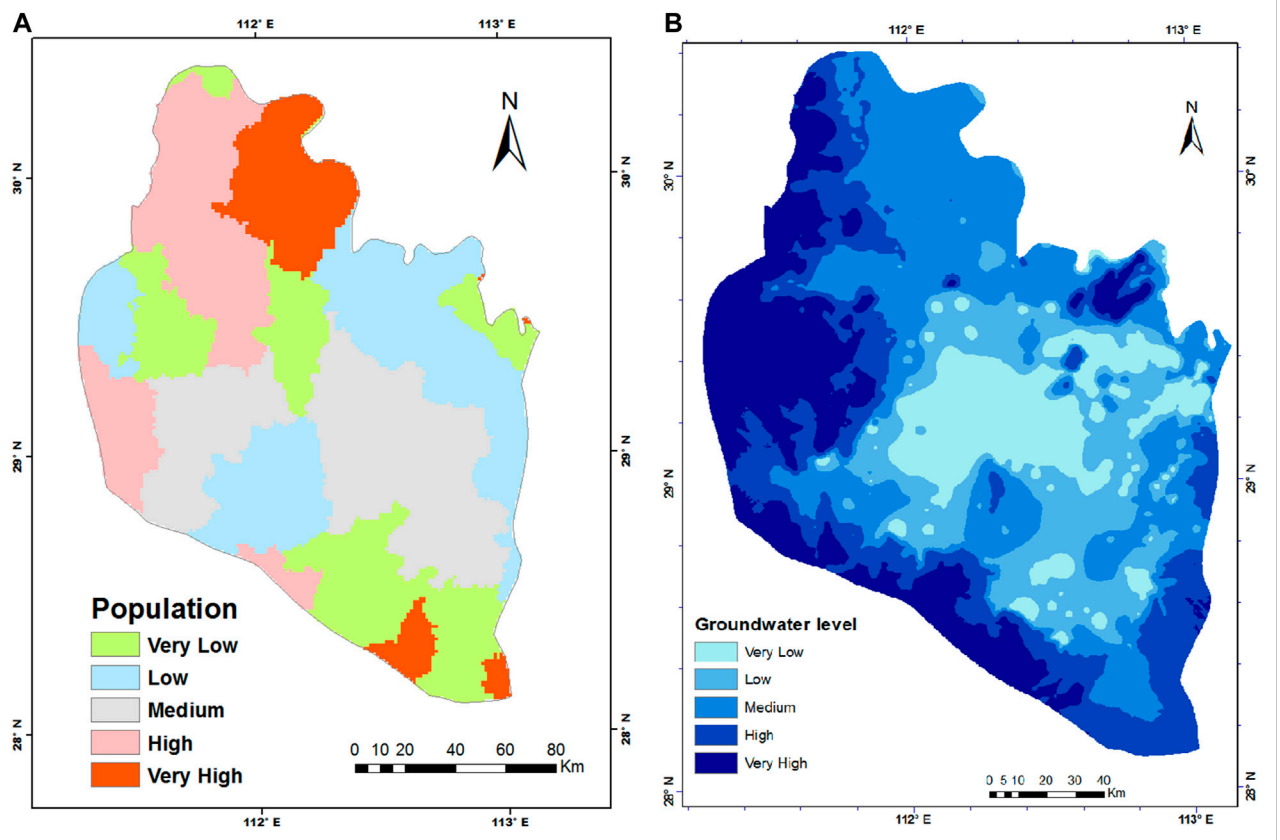


FIGURE 4
Population density **(A)** and water level **(B)** presented in Dongting basin.

factors. Human activities based on water demand impacting the water level through pumping were diagnosed as major factors enriching the water resources with arsenic.

### 4.1.3 High equal frequency factors in water

#### 4.1.3.1 Population density vs. arsenic distribution

According to the National Bureau of Statistics, the annual national population growth rate was 0.49% between 2010 and 2013, and in Hunan Province, it was 0.62% in the last 3 years. The population strength was between $1 \times 10^5$ and $120 \times 10^5$, as displayed in the results of the population distribution in Table 2. The population distribution map (Figure 4A) also showed a wide spatial dispersion of the population in the available area. The central area had medium density compared to other parts of the Dongting Basin. Additionally, high spatial distribution was found in the northern part, and four districts such as GongAn, Ning Xiang, and Changsha showed the highest population capacity, while in the south (HaoShan and WangCheng), east (JunShan), and west (LinLi and Anxiang) contained the lowest population. However, the medium population densities were located in the east and central parts of the study area. China's population growth will undoubtedly affect and increase these distractions over time. Therefore, population pressures could involve an increase in solid waste production, urban non-point runoff, and a decline in water quality. In a case study of the Dongting basin, population distribution showed a low relationship with concentration of arsenic distribution. Figure 3D depicts the effect of population on the average concentration of arsenic of distractions in the Dongting basin. The statistical results are based on the average arsenic of each district, and the population density in the study area has a significant impact on the concentration of arsenic and its distribution with the value of the calculated correlation coefficient of +0.442. The average concentration of arsenic in distracts were divided into five classes, where the lowest population class ($1–10 \times 10^5$) showed a 0.0164 mg/l concentration of arsenic under China's permissible standards. A high arsenic (0.026 mg/l) value in the densely populated class ($90–120 \times 10^5$) indicates that human activities are affecting contaminated groundwater resources. It is reported worldwide that groundwater resources in highly populated areas have elevated concentration of arsenic (Van Geen et al., 2002), with similar results in Dongting plain. Gaus founded a strong correlation between concentration of arsenic

and population density in many areas of Dhaka (Gaus et al., 2003). China occupies only 7% of the total world's land but feeds about 25% of its population. Therefore, water scarcity and quality are significant issues for a huge population (Impending Water Crisis in China, Nina Brooks). Concentration of arsenic in surface water resources was found to be significantly high, with concentrations of 0.02 while lowest value mg/l 0.005 mg/l. A mixed-correlation between arsenic range and population strength was observed with regard to classes. Therefore, it can be concluded that human activities have an influence on the control of pollution concentration in surface water resources. A comprehensive study was conducted to explore the population under arsenic risk, which showed that in highly populated areas of China, a greater percentage of inhabitants are affected by toxic arsenic (Rodriguez-Lado et al., 2013).

#### 4.1.3.2 Water table vs. arsenic distribution

The unconfined nature of the Dongting plain contributes to its high vulnerability to pollution. Figure 4B depicts the water levels in Dongting Plain. From Figure 4B, it was found that the west-south and west-north boundary areas showed the highest water table levels due to the presence of the mountains, and the whole central and east parts showed low water levels linked to plenty of natural lakes and other surface water resources. The groundwater level in the study area is gradually rising from east to west (Figure 4B). Joseph reported that concentration of arsenic has no significant relation to changing water levels in California, while New England shows a strong impact (Ayotte et al., 2015). Anthropogenic factors may affect concentration of arsenic by including land development and solutes in the aquifer (Harte et al., 2012), or by artificially changing the flow system, well development, and over-exploitation, which affect aquifer storage and recovery capacity (Ayotte et al., 2015; Katz et al., 2009; Price and Pichler, 2006). Excessive groundwater exploitation can activate the Fe-reducing process and mobilize arsenic in the aquifer system (Berg et al., 2008). The results on the impact of water level on arsenic distribution are displayed in Table 2. The results are in the Table 2 presented the average concentration of arsenic in groundwater, where a high value was observed at the middle class of water level (81–110 m) with 0.085 mg/l and low in deep water (Class 181–260). Surface water also contained high and low arsenic values in the same classes. Water levels less than 50 m and between 81–110 m in both surface and groundwater was affected, and arsenic in the soil was also significantly high. Therefore, the general trend showed that concentration of arsenic decreased with increasing groundwater depth in the Dongting basin. Yanhua's study in central China's Jianghan plain confirmed that concentration of arsenic variation has a highly positive correlation with groundwater level changes (Gan et al., 2014). The lowest water quality observed in the shallow aquifer is found to be due to surface water, urban water, and sanitation system, high urban density, poor solid waste, and agriculture activities, while high arsenic in the deep aquifer is related to the high pumping for different sectors such as urban, industrial, etc., (Farooqi et al., 2003). Additionally, Moqbul Hossain concluded in his study that the deep aquifer can be protected against arsenic percolation by shallow pumping (Hossain and Piantanakulchai, 2013). Our findings show that a high water table has more concentration of arsenic due to contaminated recharge, while the high concentration of arsenic in deep groundwater has a valid reason for high pumping for years.

#### 4.1.3.3 Groundwater extration vs. arsenic distribution

Groundwater is a major source for drinking and domestic purposes in the Dongting plan. Groundwater exploitation is associated with seasonal water demand and may vary with seasons. Here, we evaluated the effect of the pumping rate on the concentration of arsenic of groundwater in the Dongting plain. The estimated total groundwater for various purposes of each district of the study area lies between 1.4 $m^3/a \times 10^6$ $m^3/a$ and 4.48 $m^3/a \times 10^6$ $m^3/a$. Ravenscroft showed that the operational age of a well and the period of pumping have a serious link with groundwater quality and can elevate its concentration of arsenics (Erickson et al., 2019). The north and south parts show low groundwater exploitation as compared to other areas, while the results show that Linyi has low pumping and TaoYuan flows large amounts of groundwater. The distribution map of soil arsenic showed a significant close relationship with total groundwater exploitation; the central parts had elevated arsenic (Figure 2C) and similar areas had high pumping intensity (Figure 5B). The vulnerability of water supply wells to natural and anthropogenic contaminants depends on the pumping stress level of the groundwater system. Cuthbert et al. (2002) report that arsenic breakthroughs may occur within to 20 years of pumping, which depends on various hydraulic parameters. Regarding the concentration of arsenic and pumping quantity relationship, total groundwater exploitation has been divided into five classes to verify soil concentration of arsenic variation with increasing pumping quantity. The statistical findings investigated the general trend of positive correlation between two factors ($r^2 = +0.5782$). The elevated arsenic value in soil is 22–27 $m^3/a \times 10^6$ $m^3/a$, while the lowest concentration of arsenic in the second class is 16.63 mg/kg (10–15 $m^3/a \times 10^6$ $m^3/a$). The soil arsenic value is slightly higher in the first class, but it gradually increases with pumping in subsequent classes. Researchers observed that redox conditions rapidly change due to exploitation, and concentration of arsenic varies with changes in pumping rate. Therefore, infiltration of high-arsenic induced water and increasing discharge rates into aquifers indicate the possible risks of arsenic contamination in groundwater.

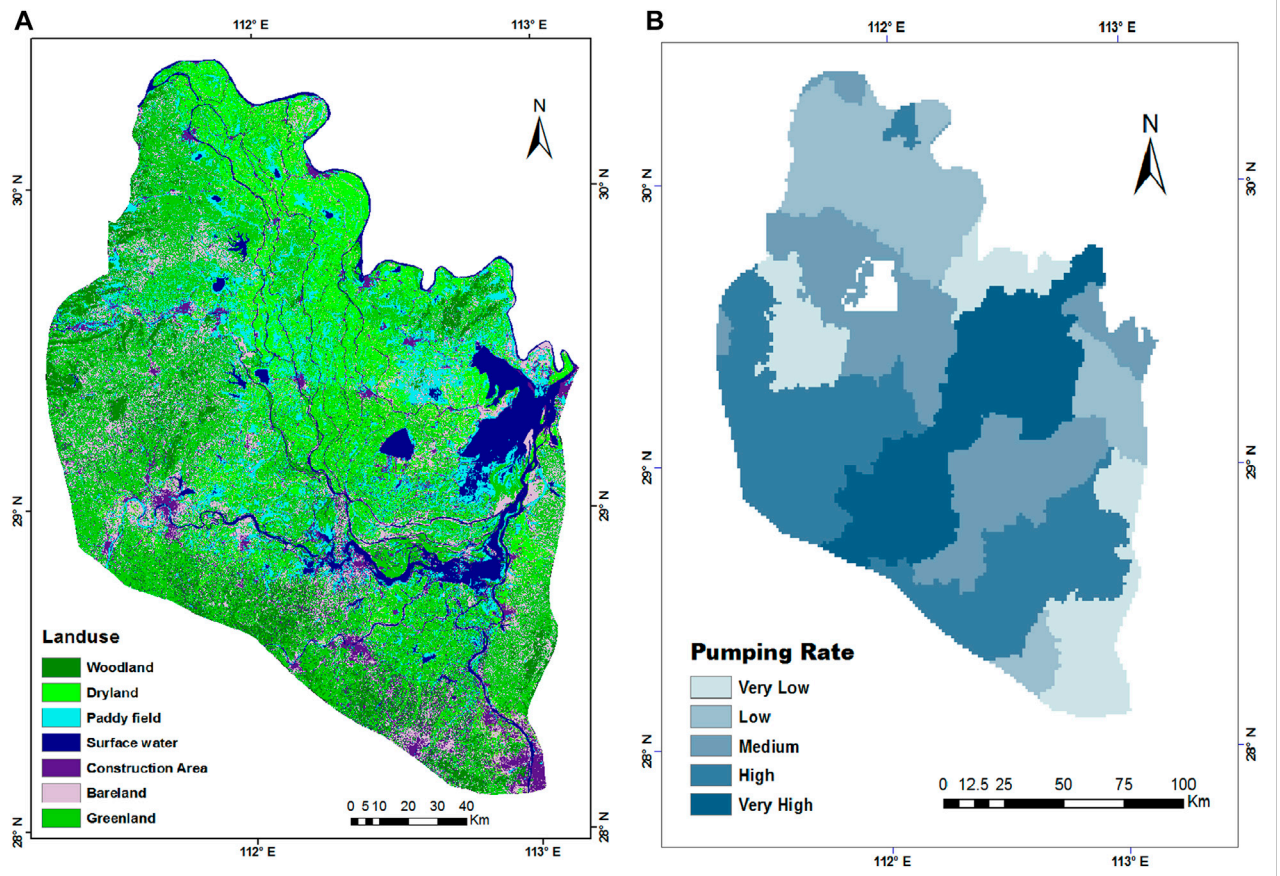


FIGURE 5
Land use **(A)** and groundwater pumping **(B)** presented in Dongting basin.

## 4.2 Arsenic presence in soil

### 4.2.1 Chemical analysis of soil samples

Arsenic in soil and its impact on other natural resources and human health are gaining researchers' attention worldwide (Zhang et al., 2015a; Biswas et al., 2020). Chemical analysis of 75 soil samples revealed a wide variation in a concentration range between 1.8 and 45.69 mg/kg. Weng explored arsenic levels of 2.5–33.5 mg/kg in the soil of China, where mountain soil (16 mg/kg) had comparatively higher levels than siallitic soil (4 mg/kg) (Wang and Shpeyzer, 2000). According to the researchers, a general baseline of arsenic value in soil should be 5–10 mg/kg (Firdaus et al., 2018). According to chemical analysis, 18% of soil samples have higher concentrations than the Chinese upland contamination standard (20 mg/kg) and 3% have higher concentrations than the WHO (50 mg/kg) limit. Li found that 58% of soil sediment samples exceeded PEL (probable effect level, dry weight (Smith et al., 1998) arsenic value (Fei et al., 2013). Additionally, the variance and standard derivative values were computed at 200.376 and 14.155, respectively. Fei et al. (2013) did an analysis of sediment samples at Dongting Lake and got an average arsenic value of 23.03 mg/kg (Fei et al., 2013). Figure 2C was developed by using an arsenic level in soil and showing the presence of the pollutant in the whole area. The north and west parts exhibited low concentrations, while the central area (with low surface elevation) showed a high-risk value. NanXian, YuanJiang, and Ziyang are the most affected counties in the central part, where Guo has identified the same location with high As content in soil due to agricultural activities, surface water flow (Guo et al., 2012), industrialization, and urbanization (Mu et al., 2019). Surface elevation may be a factor that enhances pollutants' mobility towards low-elevation counties. Additionally, surface water quality impacts on sediments cannot be ignored, as previous research showed that rivers, lakes, and other bodies of water contain high arsenic quantities (He and Charlet, 2013), which infiltrate the aquifer through upland.

### 4.2.2 GIS base spatial distribution model of soil

The sections that follow will show the results of developed single and multi-factor models, as well as their correlation with

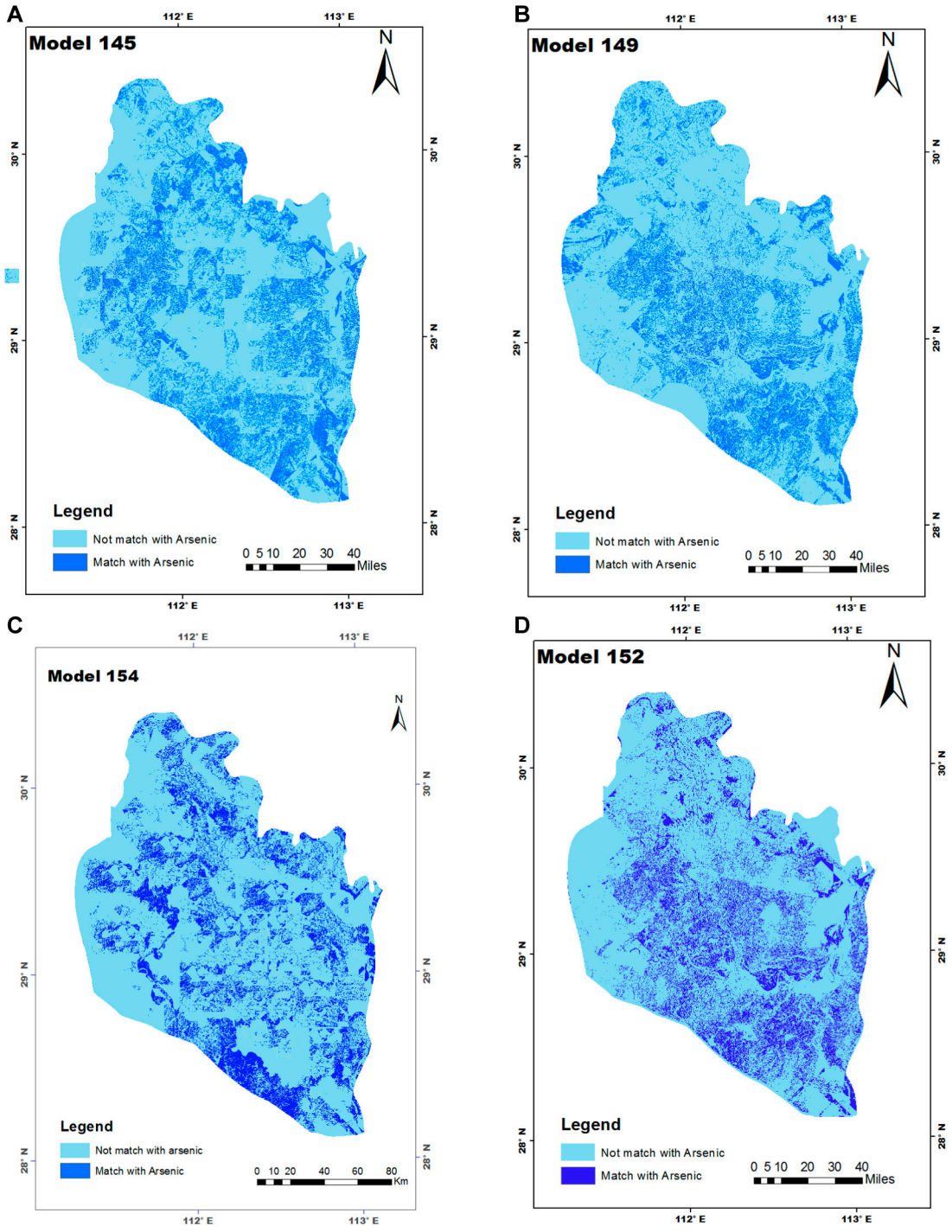


FIGURE 6
Final equal frequency map of best models with soil arsenic concentration: **(A)** (2*Pump+3*LU+1*SE), **(B)** (1*Pump+1*LU), **(C)** Pump, and **(D)** LU.

elevated soil concentration of arsenic. It is extremely important to explore the impacts of local factors which increase arsenic value, their causes, and their relationship. The soil arsenic distribution model was compared with a total of 64 models (single and multi-factor). The highest equal frequency multi-factor models were used to develop gradually low factor models, but single, two, and

three-factor models with high equal frequency are presented in Table 1. Among seven single model frequencies, land use (model_152) and pumping quantity (model_154) were depicted as equal frequency percentages of 73.19 and 73.07, respectively, while the lowest similar frequency could be seen with rainfall factor (model_156) with 13.62% in Table 1. Individual models of groundwater pumping and land use in the Dongting basin revealed a high equal frequency with soil concentration of arsenic. The highest and lowest equal frequency values among developed models were model-149 (1Pumping*2LU) and model-156 (rain) with 74.45% and 13.6% arsenic, respectively. The results of these models indicated that local anthropological activities had a negative impact on soil, which was eventually transmitted to the groundwater system. In the GIS "Raster Calculator" tool used to develop multi-factor models, a ranking technique is also applied to verify the highest and lowest impact of a factor. Table 1 represents the best model results and shows the most effective factor for pumping and land among all selected factors. However, the four highest equal frequency model diagrams are displayed in Figure 6.

### 4.2.3 High equal frequency factors in soil

Land use is regarded as a major factor that directly generates various wastes and pollutants. The variation of groundwater concentration of arsenic within seven groups of land use classes is represented in Figure 5A. The land use map (Figure 5A) showed that greenland, dryland, surface water, and urbanization (domestic and commercial areas) were the most intense, followed by agricultural land use and industrial activities (others). As shown in Figure 5A, urban settlements and other construction cover nearly 15% of the study area. A large quantity of agrochemical use and the industrial revolution have subjected the soil to stress due to the rise in pollution levels (Zhong et al., 2012; Patle et al., 2019) worldwide. Human activities are regarded as an important factor, involved in elevating different pollutants' ratios in the topsoil of the Dongting basin. Heavy metal distribution causes industrialization and farmland in the Dongting region. Additionally, Xiangjiang river water used for irrigation is suspected as a source of pollutants in the soil around Dongting Lake, which is a constant risk for local food production and the general community (Zhong et al., 2012; Yao et al., 2009). The aquifers beneath urban, industrial, and agricultural areas may become polluted by toxic metals, organic compounds, and major anions and cations that have the potential to deteriorate the water quality and the environment (Vidal et al., 2000; Akhtar et al., 2014). However, the correlation value ($r^2$ = 0.338) calculated the effect of human activities on the concentration of arsenic in the Dongting Basin. Table 2 shows that concentration of arsenic in soil increased with increased landuse frequency. Less than 19% of landuse (construction base) areas were indicated as having an average concentration of arsenic of between 12.9973 and 13.7029 mg/kg, the lowest among five classes, while the 4th class (27%–33%) covered areas had the highest concentration of 16.7367 mg/kg. However, the high percentage of construction distracts from the high arsenic in soil caused by solid waste and effluents. Table 2 revealed that with more agricultural and dry land percentages could affect pollutants' concentrations, while low arsenic quantity (13.61 mg/kg) was noted in areas with less than 20% vegetated land. By comparing Table 2 and Figure 2C, high population density areas showed a good correlation with elevated arsenic in the soil. The atmospheric arsenic impact on raising the arsenic level in aqueous systems and soils is significant (He and Charlet, 2013).

## 4.3 Compare concentration of arsenic in three water cycle media

Comparing three areas (SW, Soil, and GW) that are involved in the water cycle can give a deep understanding of toxic arsenic's presence and mobility. The interaction process may clarify complex pollutant transport concepts at the soil-surface-water-aquifer interface (Shao et al., 2006). Figure 2 shows the significant relationship among concentration of arsenic levels in soil, surface water, and groundwater, where SW and GW contained high concentrations in the east part and low in the west. Other parts of both diagrams (Figures 2A,B) depicted deep closeness regarding concentration of arsenic. This significant resemblance of spatial arsenic distribution identified SW's impact on GW at Dongting. Fei investigated heavy metal pollutants in the Dongting Plan and observed that cities located near Dongting Lake and the Xiangjiang River contained high concentrations of them because of the close relationship between surface and groundwater (Fei et al., 2013). Concentration of arsenic in GW and soil showed a strong association in some parts in the west, south, and west, while the east part represented a negative relationship. Groundwater systems and topsoil chemistry depend on different hydrogeological parameters and factors which can affect their movement and pollutants' flow direction. Previous studies observed that anthropogenic factors such as sewage discharge, industrial wastewater discharge, agricultural fertilizer leaching, etc., are major sediment contamination sources (Fei et al., 2013). Heavy metals naturally sink to the bottom of lakes and river sediments and eventually become part of the groundwater system (Yu et al., 2008). When surface water (Figure 2B) and

soil (Figure 2C) were compared, a weaker relationship was found between concentration of arsenic s in both interfaces than in others. However, the west and some extended north parts of the study area depicted a high correlation, while the central and eastern regions had contrary arsenic content. Due to the direct interaction of surface water and soil particles, contamination particle exchange is very convenient between both faces. It is normal practice worldwide to deposit solid waste and effluent into soil or surface water resources. Various pollutants from anthropogenic factors have changed soil composition in China (Sodango et al., 2018). Over 80% rivers of China have different level of contamination in surface water (Wong et al., 2002) and elevated levels of arsenic (Sun et al., 2019), which have a direct impact on soil, sediments, and, indirectly, local groundwater systems. From Table 2, population classes showed a significant relationship with arsenic in surface water and groundwater, and the arsenic contamination level in the soil had a trend to increase with population density. Arsenic in three media [soil (15.39 mg/kg), SW (0.2 mg/l), and GW (0.26 mg/l)] contained the highest arsenic values in class 90–120 × 105, whereas the first class (1–10 × 105) contained slightly higher values in soil as compared to other classes. The statistical analysis revealed a high pumping class (28–33) with a good correlation with soil and GW with concentrations of, respectively, 15.2350 mg/kg and 0.0246 mg/l. SW in the middle class (16–22) with an elevated arsenic value of 0.0216 mg/l and a low concentration of 0.0065 mg/l in the first class. Groundwater exploitation appears to be an effective factor in the Dongting Plain for increasing and mobile arsenic in soil and aquifer systems. WL (81–110 m from surface) in soil had a high arsenic impact at 15.54 mg/kg, SW 0.21 mg/l, and GW 0.085 mg/l among the five water level classes. The arsenic trend in soil was mixed with the trend in both water media, and the middle class contained the most elevated concentration of arsenic in the middle class as compared to low and high water levels. The deep aquifer had good quality water in Dongting Plain. Rain is regarded as a major source of groundwater recharge and also affects arsenic transportation from the surface to the aquifer through the water cycle process. Areas were observed where rain intensity between 1,090 and 1,210 mm/year had a high concentration of arsenic in soil (14.8633 mg/kg), SW (0.0203 mg/l), and GW (0.0466 mg/l). Statistical comparison and analyst results revealed that rain's impact on surface water resources are much higher than on soil and groundwater. Areas with heavy metal contamination with a range of 43–47 mg/kg perceived high arsenic in soil, groundwater, and surface water with values of 15.5240 mg/kg, 0.0216 mg/l, and 0.0241 mg/l, respectively (Table 2). The first and last classes (21–60 m) showed significant variation in concentration of arsenic in three different media. From statistical results, it can be concluded that mountain areas contained high arsenic values while plain surfaces had low arsenic levels. There may be geogenic effects on soil and water. The highest arsenic range of 0.0168–0.0679 mg/l was observed, but the surface water contamination level was slightly lower when compared with other factors. The land use factor was observed in the results of GIS models (Table 1) that had a high equal frequency percentage with soil concentration of arsenic. Table 2 displayed three parameters that identified additional land use activity sources to increase arsenic levels in the soil. Land use had a low or high impact in different classes, but it had a low impact in low percentage range classes. Counties with a construction density of more than 20% gradually increased concentration of arsenic in soil (14.3800 mg/kg) and groundwater (0.0263 mg/l), while surface water had an arsenic pollution level of 0.0245 mg/l. Similarly, the area with green land where agricultural activities and forests are on a large scale is also regarded as a major contamination source of surface water (0.0221 mg/l). A region with a low percentage of dry land had lower concentration of arsenics in three media, but where there was more than 15% of dry land, the arsenic impact was greater. From the above discussion, it can be concluded that arsenic is present in three phases in the Dongting plain, and naturally, these interfaces have their own interaction systems based on various parameters which can transport pollutants from one to another interface. As a result, surface water and soil pollutants have an impact on groundwater quality in the Dongting plain.

## 4.4 Correlation of arsenic with hydro-geochemical parameters

•A summary of laboratory analysis results for hydro-chemical data and their correlation with concentration of arsenic in soil, surface water, and groundwater from the Dongting plain is presented in Table 2. Maximum arsenic levels in soil (45.69 mg/kg) and groundwater (0.1582 mg/l) were above WHO and Chinese standards, respectively, while a 0.0287 mg/l level in surface water was below the Chinese standard (>0.05 mg/l). However, average concentration of arsenic values in three phases were found within the range of both standards. Variable concentrations of trace amounts (Cr, Fe, Cu, Co, Mg, F, Cu, Mn, and Pb) in soil, surface water, and groundwater were detected (Table 2). The statistical results showed a high correlation in soil (As-Mn = 0.7), SW (As-pH = 0.341), and GW (As-Fe = 0.0792). Arsenic's correlation with other hydro-geochemical parameters in three phases had significant variation based on concentration range. pH values in groundwater are near acidic to alkaline (pH 5.34–8.7 with an average of 7.239) and in surface water are neutral to alkaline (pH 7.23–8.7 with an average of 7.974). Overall, pH values were within the standard limit suitable for human use. Often,

high pH indicates anions' presence and causes the reduction process to control arsenic mobility (Source: USGS). Arsenic levels were found to be high in waters with pH values greater than 8. pH (8) may be indicative of arsenic desorption due to oxidation of the surface (Smedley and Kinniburgh, 2002). The maximum concentration of Pb was 0.0385 mg/l in groundwater and 0.0144 mg/l in surface water, which were higher than the WHO value of 0.01 mg/l. Furthermore, Pb concentrations in soil were found to be significantly high, at 21.932 mg/kg. The correlation between As-Pb in groundwater was computed at 0.311, while in surface water and soil it was 0.135 and 0.2, respectively. (Put-As-Pb influence) Due to redox-sensitive elements, lower pH conditions can enhance Pb mobility (Mapoma et al., 2014). Arsenic's correlation with Fe ($r^2$ = 0.16) in soil indicates that arsenic has no significant association with minerals (Xie et al., 2008). The correlation values of Fe with arsenic were computed at 0.792 and 0.01 in GW and SW. Based on the results of geochemical analysis of collected soil samples and statistical calculations, a significant correlation was presented between arsenic with Fe ($r^2$ = 0.16), and $SO_4$ ($r^2$ = −0.25). The correlation of other geochemical parameters was higher than iron, indicating that As had no strong association with iron minerals. The relationship between arsenic and $SO_4$ is consistent with the process of reduction dissolution of iron oxides/oxyhydroxides, as has been shown in other case studies (Pathak et al., 2022), similar findings in Datong Basin, China (Xie et al., 2008). A study in Jianghan Plain show that the spatial heterogeneity of arsenic and iran has good correlation with the local features of geological, hydrological and lithology under the anthropogenic influence and redox conditions (Duan et al., 2015; Ying et al., 2017). Under oxidizing conditions, correlation between Fe-As is common. The reduction of As-bearing Fe oxides can cause the release of arsenic in the long term in a good borehole (Jiang et al., 2022). Interestingly, high concentrations of $SO_4$ (GW: max = 194.063 mg/l; SW: max = 81.85 mg/l) indicated that the slow occurrence of reduction processes in the system for the production of sulfide minerals precipitates (Xie et al., 2008). The arsenic correlation with $SO_4$ in three phases did not have a significant trend. The low concentration of Fe in the phases may be linked to the reduction processes that identify the primary source of groundwater arsenic rather than the Fe/$SO_4$ cycle in Dongting plain. The correlation of Fe and alkalinity with groundwater and surface water demonstrates a strong influence of redox processes on elevated concentration of arsenic. Many studies have proved that elevated Fe concentrations could be due to the reduction process in water (Nur et al., 2019). The suboxic to anoxic conditions of chemical reactions and the correlation of $NO_3$ and $SO_4$ with arsenic could not support a reduction mechanism for the dissolution of Fe in soil. Fe concentration levels in sediments and groundwater are used to predict arsenic mobility and sources. Groundwater statistical results depicted significant correlations between As and Fe ($r^2$ = 0.792), and As with Mn ($r^2$ = 0.382), while the concentration of arsenic in surface water showed a low relationship with Fe ($r^2$ = 0.01), but with Mn ($r^2$ = −0.318). It was observed that a positive correlation between Fe and As indicated reductive dissolution of arsenic linked with Fe oxides under reductive conditions. However, the statistical analysis also indicated a weak correlation between Fe and As, with a significant correlation with Mn as in the Table 2. Reductive dissolution of As-correlated Fe oxides/hydroxides is regarded as the major arsenic mobility controlling process in groundwater (Kumar et al., 2020). The value of $r^2$ with arsenic in surface water and groundwater also provided a low relationship with arsenic mobility. Thus, a consortium of mechanisms such as reductive dissolution and pH-dependent desorption can influence the mineralization of As in the aquifer system of the Dongting plain. The abovementioned arsenic correlation with other hydro-geochemical data proved that there may be some other factors affecting concentration of arsenic in the groundwater system of Dongting basin because the oxidation/reduction mechanism was observed to have a weak relationship. Therefore, other factors were considered to investigate arsenic's elevated concentration in the groundwater system.

## 5 Conclusion

In this paper, a study was carried out concerning concentration of arsenic in groundwater, surface water, and soil and investigated their relationships with seven factors in the Dongting basin. Arsenic was diagnosed in three media of the water cycle with a variation in concentration (some higher than the WHO and Chinese prescribed limit). Thus, direct use of groundwater is not recommended for drinking purposes because the shallow water is highly contaminated. The major factors to elevate arsenic in groundwater and surface water in the single, bi-, and triple combined factor models were population and groundwater level, while land use and groundwater pumping in soil. Low value indicates a slow reduction process and the correlation of As-Fe ($r^2$ = 0.16) depicted a weak association of soil with mineralization. The relationship between arsenic and $SO_4$ is consistent with the process of reduction dissolution of iron oxides/oxyhydroxides. So, the arsenic relationship with other hydrochemical parameters revealed that geogenic sources have a minor influence on concentration of arsenic in groundwater, but groundwater and soil have a positive relationship. Modeling techniques on factors and statistical analyses of hydrogeochemical parameters, it was indicated that both anthropogenic and geogenic factors are active in contaminating groundwater. To control high concentration

of arsenic in potable water, local water resource managers and planners in the Dongting basin should develop water treatment and alternative water resources. Thus, the urban planning, industrial, environmental and water departments must solve groundwater, surface water, and soil contamination problems by sharing information and future planning.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Revealing effectiveness and heterogeneity of the impact of China's coal consumption control policy on air quality

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Whether China's coal consumption control policy (CCCP) improves air quality is controversial. This study used city-level panel data and applied a DID model to identify it. We found that 1) The CCCP has a positive effect on AQI and $PM_{25}$, which decrease by 7.6327 μg/m3 and 8.4293 μg/m3, respectively, but fails to reduce $O_3$ concentration. 2) The effect of CCCP has regional heterogeneity. The CCCP has not significantly reduced $PM_{2.5}$ emissions or improved air quality in the PRD region as in the BTHS and YRD regions. Additionally, in the YRD and PRD regions, CCCP can reduce $O_3$ significantly. But the BTHS region failed to reduce the $O_3$, and the introduction of CCCP made the $O_3$ in pilot cities even higher by 4.1539 μg/m3. This study recognized the effects of the CCCP and its regional heterogeneity, which were supportive for policymakers to optimize coal-related policies to ensure environmental sustainability. We suggested that policymakers should differentiate policies according to regional differences and pay attention to reducing $O_3$ pollution to establish sustainable ecosystems.

KEYWORDS

**environmental sustainability, air quality, economy, coal, GIS, China**

## 1 Introduction

The adoption of information and communication technologies (ICT) has progressively been known as crucial for economic affluence, over the last few decades, the rapid growth of China's population and economy has made China the world's largest energy consumer and producer (O'Meara, 2020; EIA, 2020; Jin et al., 2017; Mahfooz et al., 2017, Rasool, Jundong et al., 2017, Sohail, Mahfooz et al., 2017, Yen, Wang et al., 2017). Coal, the most polluting source (Barreira et al., 2017), has remained the dominant energy source in China over the past 20 years (see Figure 1). While the coal-based energy framework has contributed to the economic boom, it also poses significant challenges to China's long-term development, i.e., aggravating environmental pollution (Yang & Teng, 2018; Sohail et al., 2022b; Sohail M. et al., 2022; Yang, Zhou et al., 2022; Zhao, Huangfu et al., 2022), causing substantial health damage (Yang et al., 2013; Sun et al., 2018), and accelerating climate change (Edwards, 2019). Among those problems, air pollution has developed into a major economic and social concern in China (Sohail et al., 2021a; Sohail

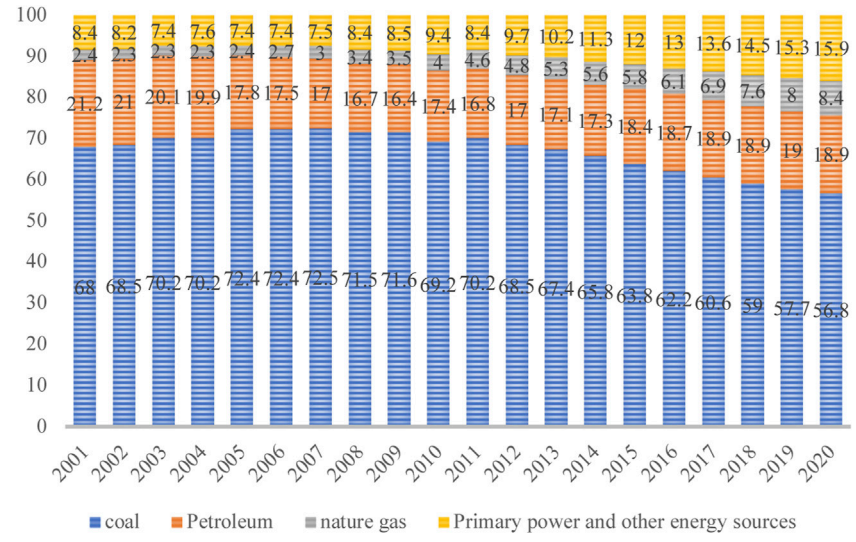


FIGURE 1
China's total primary energy consumption 2001–2020 (%).

et al., 2021b; Chen et al., 2022; Fami and Sohail 2022; Lan et al., 2022; Liu N. et al., 2022). According to the Global Burden of Diseases study, air pollution is one of the top five disease-related risk factors, affecting between 4 and 9 million deaths annually (Burnett et al., 2018; Christopher and Murray, 2019; Sohail et al., 2021a; Chai et al., 2021; Sohail et al., 2021c; Jian et al., 2021; Vohra et al., 2021; Lan et al., 2022). In response to these multiple challenges, China has identified coal control as a crucial measure for environmentally balanced development. In 2016, the National Development and Reform Commission (NDRC) released the [1]*Notice on Coal Consumption Reduction and Substitution*, proposing a two-pronged initiative to control coal—"Reduction + Substitution"—to promote clean air and implement the goal of "dual control" of total energy consumption and energy intensity in polit city. However, as a command-and-control policy, the cost and effect of the CCCP have fueled debates, and the complexity is compounded by renewable energy subsidies. The core of this debate is whether the CCCP has a positive effect on air quality, as initially expected.

The academics who were confident about the CCCP acknowledged that the CCCP could help control the amount of pollution released. But the increase in air quality comes at the cost of reducing social welfare and economic development. Lin and Jia (2020), Shou et al. (2020) and Yang & Teng (2018) concluded that coal control measures would contribute to pollution reduction and carbon mitigation. While employing the developed CGE model, Xiao et al. (2020) found that coal-cutting policies will promote the environment but reduce residents' consumption welfare, GDP growth, and employment. Zhang et al. (2021) also employed a scenario analysis model that predicts that the CCCP will inevitably reduce social welfare in the short run.

However, there are also some scholars who argue that CCCP is technically infeasible, which will lead not only to an increase in economic costs significantly (Shi et al., 2018; Mahfooz, Yasar et al., 2019; Sohail, Mahfooz et al., 2019; Zhao, Yen et al., 2019; Arif et al., 2020; Mahfooz et al., 2020; Sohail et al., 2020) but also not reduce air pollutant emissions. Some empirical studies supported this opinion. Using empirical data from the BTH region, Shi et al. (2018) have shown that CCCP fails to reduce $SO_2$ emissions due to cost and technical constraints. Guo et al. (2020) also support the results by using realistic panel data from 289 Chinese cities; they find that only with the help of other supporting policies can CCCP reduce $SO_2$ emissions as expected. According to the analyses shown in Figures 2A,B, the average Air Quality Index (AQI) has improved in almost all Chinese provinces from (2013 to 2015) to (2016 to 2019). Before and after the implementation of the CCCP, the distinction between CCCP pilot provinces and other provinces is insignificant. Therefore, it is unreasonable to attribute the improvement in air quality to CCCP. Whether the CCCP has successfully reduced air pollution is far from obvious.

As the different methodologies and the heterogeneous group of cities in the various studies, some uncertainty remains. With industrialization and urbanization, regional air pollution in China has seriously threatened people's daily life and health.

1 Notice on Coal Consumption Reduction and Substitution in year 2016 defined the new group of CCCP pilot areas: the Beijing-Tianjin-Hebei and surrounding Region; the Yangtze River Delta region Area, the Pearl River Delta Area.

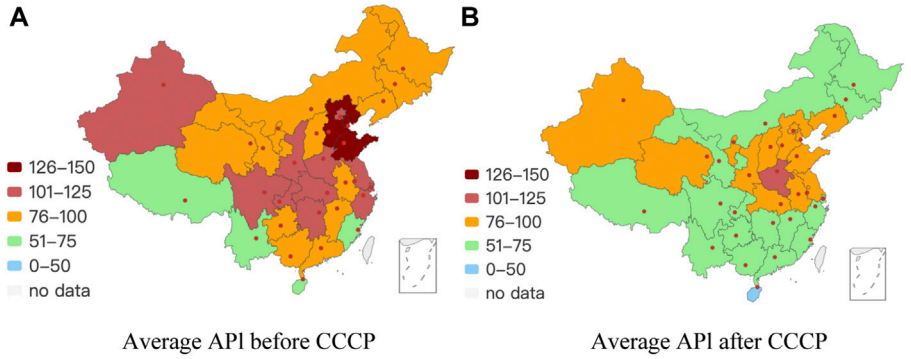


FIGURE 2
China's provincial API before (2013–2015) and after (2016–2019) the implementation of CCCP.

More than 50% of China's population is exposed to unsafe air, and one-fifth of all deaths can be attributed to air pollution (Hsu et al., 2016), which kills between 1.2 million and 2 million people yearly (X. Yang et al., 2017). Specifically, the life expectancy of people living in urban areas north of the Huai River in China is about 5.5 years less than that of people living in other regions due to coal-fired heating in winter (Chen et al., 2013). Therefore, whether or not CCCP curbs air quality degradation has become one of the most important issues for environmental sustainability. In light of this debate, we quantitatively evaluate the impact of CCCP on air quality using actual data. The empirical findings would not only provide policymakers with strategies for implementing additional plans to improve air quality. Still, they would also serve as guidance for public health researchers developing interventions to create a healthy environment.

# 2 Materials and methods

## 2.1 Data

Data for this research was obtained from urban statistical yearbooks, China city statistical yearbooks, and China Air Quality Online Monitoring and Analysis Platform. Specifically, the data of AQI, $PM_{2.5}$, and $O_3$ are gathered from the "China Air Quality Online Monitoring and Analysis Platform" website, which provides daily data on air quality conditions in 367 cities across the country, with data sourced from the China Environmental Protection General Station. Additionally, we collect meteorological conditions at the city level, including indicators of temperature and precipitation from "2345 Weather.com," which is sourced from the China Meteorological Administration. It should be noted that due to the city-level database being limited, few researchers pay attention to total energy consumption issues at the city level. To fill this gap, original data on 24 energy types are collected from the urban statistical yearbooks. The total energy consumption is then calculated by uniformly converting them to standard coal and adding them up. In addition, the 12 coal energies used by the industry are uniformly converted to standard coal and added to determine coal consumption. The remaining data are obtained from the China city statistical yearbooks. We removed cities lost to follow-up and invalid data, and 462 observations from 73 cities were maintained. All cities' information is reported in Table A1. Table 1 provides descriptive statistics for the variables.

## 2.2 Variables

### 2.2.1 Explanatory variables

The three explanatory variables in this paper are AQI, $PM_{2.5}$, and O3. We take AQI, $PM_{2.5}$, and $O_3$ to measure air quality and pollution emissions.

AQI is a comprehensive key indicator of the status of air quality in a city. It is derived from the concentration limits of six individual pollutants ($SO_2$, CO, $NO_2$, $O_3$, $PM_{2.5}$, and $PM_{10}$) and takes values from 0 to 500, with higher values representing poorer air quality conditions. The AQI is the main variable used to measure the effectiveness of air quality improvement.

The Global Burden of Disease (GBD) states that O3 and PM2.5 are typically used as indicators to measure the effects of air pollution on human health (Forouzanfar et al., 2016). Thus, in order to test the different effects of the CCCP on the concentrations of various pollutants, $PM_{2.5}$ as well as $O_3$ were also selected as explanatory variables, all of which are yearly data at the city level. Co-control of $PM_{2.5}$ and $O_3$ is an important target for environmental protection in the 14th Five-Year Plan period. With the strengthening of air pollution control in China in recent years, $PM_{2.5}$ and other conventional pollutants have considerably improved. However, $O_3$ concentrations are growing and have become the primary pollutant in many regions (Wang

TABLE 1 Summary statistics of the variables.

| Symbol | Variable | Unite | Mean | S.D. |
|---|---|---|---|---|
| Aqi | Air quality index | μg/m3 | 93.045 | 33.461 |
| pm25 | N/A | μg/m3 | 57.597 | 30.586 |
| o3 | N/A | μg/m3 | 85.251 | 21.184 |
| Gdp | GDP per capita | CNY/people | 11.283 | 0.624 |
| Industry | The percentage of secondary industry in total output value | % | 44.458 | 8.860 |
| Pop | Total population at the end of the year | Million | 6.260 | 0.624 |
| electric_c | The percentage of electricity consumption in total energy consumption | % | 0.136 | 0.113 |
| coal_c | The percentage of coal consumption in total energy consumption | % | 0.643 | 0.246 |
| Tempreture | N/A | ℃ | 15.955 | 4.488 |
| Precipitation | N/A | mm | 604.549 | 384.608 |

et al., 2017; Sohail et al., 2022a, Sohail et al., 2022b, Sohail and Chen 2022, Sohail et al., 2022c; Muhammad, Zhonghua et al., 2014, Sohail et al., 2014a, Sohail et al., 2014b, Sohail, Delin et al., 2015, Shahab et al., 2016). High near-surface $O_3$ concentrations are major components of photochemical smog, which can damage air quality and adversely affect ecosystems. Controlling $O_3$ has become a hot topic in current research (Liu et al., 2017; Chen et al., 2019; Wang et al., 2020; Hong et al., 2022, Liu Y. et al., 2022, Mustafa et al., 2022, Sohail et al., 2022d). Therefore, we chose $PM_{2.5}$ as well as $O_3$ as our explanatory variables to represent air quality improvement.

### 2.2.2 Explanatory variables

Explanatory variables: coal consumption control policy (CCCP), a dummy variable for the indicator selected in the base regression as coal consumption control policy.

### 2.2.3 Control variables

As air quality is also influenced by other factors, the following control variables have been introduced into the model.

Urban characteristics variables: Urban characteristics variables can reflect the development level, and there is a correlation between urban development level and urban air pollution, so controlling urban characteristics variables can eliminate some of the endogeneity. In the study, three indicators are selected to describe the characteristics of the cities and regions in the sample: total population, per capita gross regional product, and industrial structure.

Meteorological conditions variables: meteorological conditions can have a significant impact on air quality (Liu et al., 2020). We collect temperature and precipitation to represent meteorological conditions. The models all control for yearly average temperatures and precipitation.

Energy consumption characteristics variables: the production and consumption of energy is the principal source of human-caused air pollution (IEA, 2019). In the study, the percentage of electricity consumption in total energy consumption and the percentage of coal consumption in total energy consumption are used to measure the regional energy consumption structure.

## 2.3 Model

The CCCP, introduced in 2016, is expected to reduce air pollution and improve air quality. Additionally, the variables discussed above also affect both air pollution and air quality. CCCP, such a piloted policy can be regarded as a natural experiment, which enables us to explore CCCP's relationship with air quality using a difference-in-differences (DID) specification. By partially controlling for trends in city air quality and pollution emissions that are across different regions, the DID can effectively eliminate the influence of unobservable factors and thus identify the net effects of the CCCP. In the study, the DID is employed to compare the difference in air quality between pilot and non-pilot cities before and after the implementation of the CCCP. Following (Beck et al., 2020), we set pilot cities as the treatment group and others as the control group to assess the impact of the CCCP implementation at the prefecture-level. The baseline regression model is set up as follows:

$$Y = \alpha + \beta D_{it} + \gamma X_{it} + \tau_t + \mu_i + \varepsilon_{it}$$

$$D_{it} = \text{treated}_i * \text{period}_t$$

Cities in the treatment group: treat = 1, cities in the control group: treat = 0; When the year comes after the CCCP implements date: time = 1, otherwise time = 0; i and t are city and year, respectively; Y is the explanatory variables, representing the annual average concentrations of the AQI, $PM_{2.5,}$ and $O_3$ at the city level; $X_{it}$ is a set of control variables including lnpgdp, industry, lnpop, Coal_c, electricity_c, temperature, and precipitation; The core explanatory variable $D_{it}$ is a policy dummy, which takes the value of 1 when the year is in the CCCP implementing period, which means after 2016, otherwise,

TABLE 2 Estimation results of the effects of CCCP.

| | Aqi | pm25 | o3 |
|---|---|---|---|
| D | −7.6327** | −8.4293*** | −4.3643 |
| | (−2.3129) | (−2.8241) | (−1.5341) |
| lnpgdp | 4.0727 | −0.204 | −10.508 |
| | −0.3522 | (−0.0198) | (−1.1322) |
| industry | −0.4062 | −0.3879 | −0.0718 |
| | (−1.0812) | (−1.0941) | (−0.2406) |
| lnpop | 37.1777* | 27.8367 | −51.7514** |
| | −1.864 | −1.5481 | (−2.3501) |
| electric_c | 2.5131 | −10.2093 | −13.3123 |
| | −0.0996 | (−0.4398) | (−0.6950) |
| coal_c | 12.9921 | 10.3913 | −4.9704 |
| | −1.1882 | −0.9988 | (−0.6451) |
| temperature | 0.9882 | 0.342 | 0.0623 |
| | −0.4765 | −0.1782 | −0.0408 |
| precipitation | −0.0098* | −0.0061 | −0.0133*** |
| | (−1.6668) | (−1.2659) | (−2.8452) |
| _cons | −1.80E+02 | −1.00E+02 | 543.1888*** |
| | (−0.9486) | (−0.5863) | −2.9446 |
| city | Yes | Yes | yes |
| year | Yes | yes | yes |
| N | 419 | 419 | 419 |
| r2_a | 0.7944 | 0.8057 | 0.6109 |

Note: *, **, and *** indicate significance at 10%, 5%, and 1% levels, respectively. The values in parentheses are the robust standard errors.

it takes the value of 0; The coefficient $\beta$ is the parameter to be estimated, indicating the net effect of the CCCP policy; if the CCCP is indeed effective in improving air quality, $\beta$ should be significantly negative; $\tau_t$ *and* $\mu_i$ are vectors of year and city dummy variables that represent year and city fixed effects. $\varepsilon_{it}$ is the random disturbance term.

# 3 Results and discussion

## 3.1 Basic estimation results

To comprehensively evaluate the impact of the CCCP on air quality improvement, AQI was first introduced as an explanatory variable in Model 1 for regression. Then regression analysis was conducted separately with the concentrations of $PM_{25}$ and $O_3$, two individual pollutants, as the explanatory variables. The regression results (as shown in Table 2) demonstrate that the AQI of the CCCP polit cities decreased by 7.6327 μg/m3, and the regression coefficients were significant at the 5% statistical level; the $PM_{25}$ decreased significantly after the implementation of the CCCP by 8.4293 μg/m3 at the 1% statistical level. However, the $O_3$ fell after the implementation of the policy by 4.3643 μg/m3 but not significant. The regression results verified the hypothesis that the CCCP effectively improved the air quality, but it failed to reduce $O_3$, a new focus of pollution by the public and government.

Detailed, $PM_{2.5}$ decreased obviously. $PM_{2.5}$ is mostly produced by the combustion of fossil fuels and biomass (straw, firewood, *etc.*), road and construction dust, industrial dust, and other pollution sources directly discharged by particulate matter. The CCCP focuses on regulating the burning of loose coal and fossil fuels, which will undoubtedly lead to effective control of particulate matter emissions from air pollution. However, little is known about $O_3$ pollution due in part to the lack of monitoring of atmospheric $O_3$ and its precursors until recently (Wang et al., 2017).

Therefore, many scholars (Wang et al., 2020; Wang et al., 2021; Xiao et al., 2021) agree that it is urgent for the relevant departments to pay close attention to the $O_3$ pollution problem and work together to decrease it and update policies to synchronous control the $O_3$ and $PM_{2.5}$.

## 3.2 Robustness test

### 3.2.1 Parallel trend

The DID approach is predicated on a series of assumptions. To ensure the robustness of results, our DID still needs a range of tests.

Before constructing the DID, it is necessary to test whether the parallel trend hypothesis is supported. Therefore, in this paper, the event study is employed to test the parallel trend hypothesis and the dynamic impact analysis of the policy. The test results are shown in Figures 3A–C, which highlight two important points: the reduction in AQI and $PM_{2.5}$ did not occur prior to CCCP, and CCCP has a negative impact on AQI and PM2.5. In more detail, the coefficients of the AQI and $PM_{2.5}$ for the 2 years before the CCCP are not significantly different from zero and do not show any trends, which suggests that the parallel trend assumption is satisfied. The coefficients of the AQI and $PM_{2.5}$ are significantly less than 0 after the implementation of the CCCP and show significant decreasing trends, implying that CCCP has a negative effect on AQI and $PM_{2.5}$. However, the parallel trend assumption of $O_3$ is not satisfied, indicating the CCCP policy has not had a significant impact on $O_3$ in the pilot cities.

### 3.2.2 Placebo test: Re-grouping analysis

To ensure that the conclusions obtained in this paper are induced by CCCP rather than other factors, we randomly selected several virtual experimental groups in the sample and regressed them consistent with the DID basic regression to provide robustness assurance for the original findings. Specifically, we conducted a 1,000 sample among 73 cities, 40 cities were randomly selected as a pseudo-experimental group for each sampling, and for each individual pseudo-

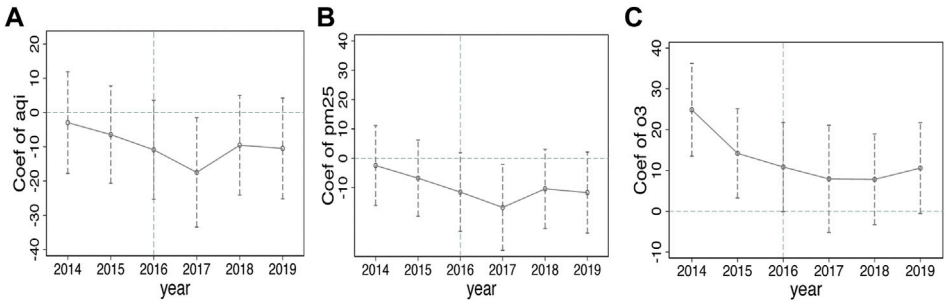


FIGURE 3
Parallel trend hypothesis test.

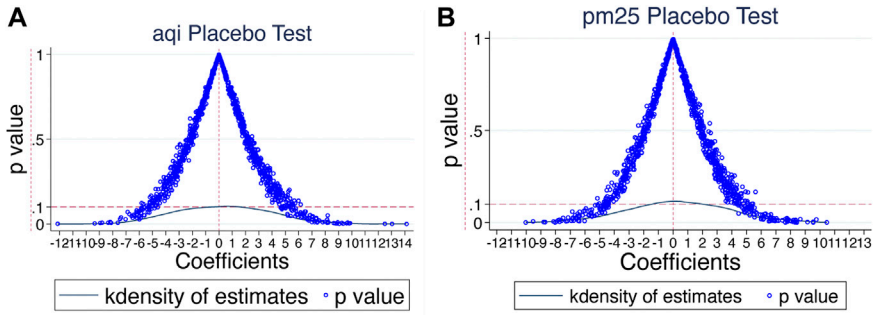


FIGURE 4
Placebo test.

experimental group, 1 year was chosen randomly as its policy time.

Figures 4A,B shows the kernel density distribution and *p*-values of the estimated coefficients (the *X*-axis denotes the magnitude of the estimated coefficients of the "pseudo-policy dummy variables," and the *Y*-axis indicates the magnitude of the density values and *p*-values). As seen, the estimated coefficients of the dummy pseudo-policies are mostly concentrated around 0. Whereas the true coefficients of the policies are all significant outliers; the *p*-values of most of the estimates are greater than 0.1 representing the CCCP pilot cities in these 40 samples without any significant effect.

Therefore, the conclusion of DID is again verified by the placebo test, which suggests that the effect of CCCP on AQI and $PM_{25}$ has no causal relationship with other unknown factors.

## 4 Regional heterogeneity analysis

In this section, we implemented the estimation of regional heterogeneity. The reasons for implementing this estimation are two: 1) In the process of China's urbanization, urban agglomerations have become the main spatial organizational form in China, and regionalized environmental management based on urban agglomerations has become a new trend. 2) There were differences in policies implemented between regions due to the inequality of resources, economic development, and geographical location. This study consolidates our study area into three key regions based on the priority areas defined by the CCCP policy and the needs of environmental management during the 14th Five-Year Plan period, namely: 1) The BTH region and surrounding areas(BTHS), including Tianjin, Beijing, Shijiazhuang, Tangshan, Handan, Weifang, Jinan, Qingdao, Jining, Nanyang, Zhengzhou; 2) the Yangtze River Delta region (YRD): Shanghai, Nanjing, Taizhou, Nantong, Jiaxing, Hefei, Suqian, Ningbo, Changzhou, Wenzhou, Wuxi, Yancheng, Huzhou, Suzhou, Shaoxing, Lianyungang, Zhenjiang, Jinhua, Maanshan; and 3) the Pearl River Delta region (PRD): Zhongshan, Foshan, Huizhou, Guangzhou, Shenzhen, Jiangmen, Zhuhai, Zhaoqing. Except for the above cities, the remaining cities are collectively referred to as non-focused cities for regional atmospheric management.

TABLE 3 Estimation results of the heterogeneity effects of CCCP.

| | BTHS region | | | PRD region | | | YRD region | | |
|---|---|---|---|---|---|---|---|---|---|
| | aqi | pm25 | o3 | aqi | pm25 | o3 | aqi | pm25 | o3 |
| D | −14.1517*** | −13.7035*** | 4.1539 | 7.3817* | 2.9266 | −10.6535** | −12.3679*** | −13.2597*** | −6.1876* |
| | (−2.9418) | (−2.8298) | −1.0327 | −1.8212 | −1.0322 | (−2.1510) | (−3.2269) | (−3.9432) | (−1.8974) |
| lnpgdp | 20.3774* | 14.2846 | −12.4198 | −1.9982 | −5.3837 | −19.1314 | 1.3868 | −4.1224 | −15.1471 |
| | −1.7002 | −1.3359 | (−1.1713) | (−0.2045) | (−0.7690) | (−1.5919) | −0.1144 | (−0.4164) | (−1.3899) |
| industry | −0.6237 | −0.5712 | −0.0601 | 0.0667 | 0.0048 | 0.3001 | −0.1764 | −0.0674 | 0.0401 |
| | (−1.3163) | (−1.2793) | (−0.1526) | −0.1711 | −0.0161 | −0.7586 | (−0.4273) | (−0.1967) | −0.1199 |
| lnpop | 25.9153 | 17.0792 | −62.2843*** | 30.797 | 23.9105 | −51.0895** | 35.3963 | 22.7189 | −64.3298** |
| | −0.8917 | −0.6452 | (−2.6437) | −1.3545 | −1.2027 | (−2.3055) | −1.0812 | −0.7894 | (−2.4847) |
| electric_c | −20.3858 | −18.4969 | −31.7954 | −16.6284 | −24.8105 | −9.9551 | −28.5596 | −33.2582 | −5.7837 |
| | (−0.4965) | (−0.5608) | (−1.0246) | (−0.4830) | (−0.8783) | (−0.3385) | (−0.7999) | (−1.0312) | (−0.2037) |
| coal_c | 16.7707 | 11.6279 | 11.1036 | −3.3179 | −7.4571 | 7.5318 | 7.1047 | 2.2321 | −5.862 |
| | −0.877 | −0.667 | −0.9368 | (−0.2286) | (−0.5857) | −0.7035 | −0.5298 | −0.1806 | (−0.6604) |
| tempreture | −0.9429 | −1.3733 | 0.8253 | −0.2378 | −0.0605 | −2.3655 | −0.4272 | −0.0296 | −0.5016 |
| | (−-0.4652) | (−0.6560) | −0.5093 | (−0.1216) | (−0.0412) | (−1.2433) | (−0.2054) | (−0.0181) | (−0.2969) |
| precipitation | −0.0201** | −0.0103 | −0.0236*** | −0.0137* | −0.0074 | −0.0112* | −0.0163** | −0.0092* | −0.0142*** |
| | (−2.3081) | (−1.4951) | (−3.3060) | (−1.8759) | (−1.4823) | (−1.8665) | (−2.5432) | (−1.8534) | (−2.6325) |
| _cons | −2.50E+02 | −1.60E+02 | 607.7524*** | −66.2837 | −19.2697 | 633.1200*** | −1.20E+02 | −22.3122 | 669.7477*** |
| | (−1.1286) | (−0.7878) | −2.9174 | (−0.3507) | (−0.1240) | −3.011 | (−0.4759) | (−0.1051) | −3.0058 |
| city | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| year | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| N | 252 | 252 | 252 | 226 | 226 | 226 | 295 | 295 | 295 |
| r2_a | 0.789 | 0.7937 | 0.6327 | 0.7745 | 0.8343 | 0.4875 | 0.798 | 0.8339 | 0.6208 |

The regression results of the three regions are shown in Table 3. We can see that CCCP significantly reduces $PM_{2.5}$ emissions and improves air quality in the BTHS region and YRD after controlling for other influencing factors. In contrast, in the PRD, air quality shows the opposite trend that does not decrease but increases.

Specifically, in the BTHS and YRD regions, CCCP can significantly reduce AQI by 14.1517 μg/m3 and 12.3679 μg/m3, respectively; CCCP can also reduce $PM_{2.5}$ by 13.7035 μg/m3 and 13.2597 μg/m3, respectively, demonstrating that the introduction of CCCP reduces the emission of $PM_{2.5}$ and improves the regional air quality significantly. There may be reasons for this result: In April 2014, the State Council put out a notice called "Notice on the Issuance of the Measures to Assess the Implementation of the Action Plan for the Prevention and Control of Air Pollution." This notice made it clear that the percentage of reduction in $PM_{2.5}$ and AQI would be the main basis for controlling air pollution, and the assessment measures reflected this. Furthermore, local governments have a strong motivation to increase the control of the pollutants since the public is more sensitive to $PM_{2.5}$ and AQI in daily life.

CCCP can lower $O_3$ by 6.1876 μg/m3 at the 10% significant level in the YRD region and 10.6535 μg/m3 at the 5% level in the PRD region. However, BTHS has not been able to do so, and the implementation of CCCP made $O_3$ even higher in pilot cities by 4.1539 μg/m3. It might be that in the BTHS region, strong solar radiation and high summertime temperatures favor the development of $O_3$. Especially in the BTHS region, the temperature in spring is lower than in summer; the dryness, low rainfall, and strong solar radiation make the meteorological conditions conducive to ozone production. Additionally, the high winds in springtime in the BTHS area make it easier for $O_3$ to travel long distances, which is also a key reason why $O_3$ levels in the area are higher than in other regions. And in the southern part of Hebei, where the mainstay industries are high emission industries such as iron, steel, oil refining, chemicals, and coal, resulting in higher $O_3$ concentrations in summer in northern Hebei and cities such as Beijing and Tianjin.

What surprised us is that the CCCP has not reduced $PM_{2.5}$ emissions and also improved the regional AQI in the PRD region. As a leading rapid economic development region in China, the PRD region has suffered from environmental problems such as air pollution earlier. Since 2014, Guangzhou has been the first in China to promote "ultra-clean emissions" from coal-fired power plants from the source

of pollution. The environmental quality standards for the six primary pollutants have been met by the PRD for 4 years running as of 2015. It has also performed well in the three major pollution control regions in China, namely BTH, YRD, and PRD regions. Therefore, although the CCCP further adjusted the energy mix of the PRD region, it did not significantly impact the overall air quality due to the fact that the PRD region has already gotten rid of the air problem disturbance.

## 5 Conclusion and policy implementations

To improve air quality, China introduced the coal capacity cutting policy. Based on the background of such a policy, in this study, we have identified whether CCCP improves the quality using panel data of 73 cities from 2013 to 2019. Compared with previous studies, this paper reconciles the contradiction of the influence of CCCP on air quality by using realistic data. The result was robust, supported by a parallel trend test and re-grouping test.

The main results can be summarized as follows:

(1) This study has identified that the CCCP has reduced AQI and $PM_{2.5}$ in the pilot cities by 7.6327 μg/m3 and 8.4293 μg/m3, respectively, as compared to other cities. CCCP also had a negative effect on $O_3$, but it was not significant.
(2) The effect of CCCP has regional heterogeneity. The CCCP has not significantly reduced $PM_{2.5}$ emissions or improved air quality in the PRD region as in the BTHS and YRD regions. Additionally, in the YRD and PRD regions, CCCP can reduce $O_3$ significantly. But the BTHS region failed to reduce the $O_3$, and the introduction of CCCP made the $O_3$ in pilot cities even higher by 4.1539 μg/m3.

The aforementioned conclusions have important policy implications:

From the macro perspective, to comprehensively maintain the environmental effects of coal control-related policies, how to effectively reduce $O_3$ concentration to establish a healthy environment should be focused on a sustainable topic. More work is required to ensure the anticipated effectiveness and lower $O_3$ concentration. Firstly, scientific research is the foundation of pollution control policies. We should attach importance to scientific research on $O_3$ pollution control. Secondly, policymakers should strengthen the construction of $O_3$ monitoring networks to provide timely and comprehensive data support for the adjustment and evaluation of ozone prevention and control policies. Thirdly, focus on regional co-control of ozone pollution. The central government must take action to carry out organizational planning and regional coordination to achieve regional synergy and policy synergy in $O_3$ prevention and control. Fourth, further restructuring the energy structure. Burning fossil fuels like oil and coal is the primary source of $O_3$. To reduce $O_3$ pollution in the long run, China needs to control its use of coal and work hard to develop green energy sources, increase its supply of renewable energy, and optimize its energy mix. From the micro perspective, under the trend of regionalized environmental management, the management of coal consumption control requires differentially implemented related policies according to regional differences. In summary, the effect of CCCP was estimated in this study, and the difference between regions showed that heterogeneity existed in CCCP. The results suggest the role of coal-related policies in environmental sustainability in the age of environmental-concentration prevalence. This study was conducted in China, so results of this study maybe use for China.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

WZ: Software, validation, data curation, writing—original draft. MC: Formal analysis, conceptualization, supervision, visualization. JH: Methodology, writing—review and editing, project administration, funding acquisition. LY: Conceptualization, writing—review and editing, funding acquisition.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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# Appendix

TABLE A1 List of 73 cities.

| CCCP pilot cities | Without CCCP cities |
|---|---|
| Tianjin, Beijing, Shijiazhuang, Tangshan, Handan, Weifang, Jinan, Qingdao, Jining, Nanyang, Zhengzhou, Shanghai, Nanjing, Taizhou, Nantong, Jiaxing, Hefei, Suqian, Ningbo, Changzhou, Wenzhou, Wuxi, Yancheng, Huzhou, Suzhou, Shaoxing, Lianyungang, Zhenjiang, Jinhua, Maanshan, Zhongshan, Foshan, Huizhou, Guangzhou, Shenzhen, Jiangmen, Zhuhai, Zhaoqing, Dalian, Shenyang | Baotou, Fuzhou, Chengdu, Guiyang, Guilin, Haikou, Jincheng, Harbin, Jingzhou, Huhehaote, Kunming, Nanchang, Nanning, Shangrao, Shuozhou, Xiamen, Siping, Taiyuan, Xi'an, Xianyang, Xianning, Xinzhou, Urumqi, Xinyu, Yangquan, Yinchuan, Yichang, Yulin, Changchun, Zunyi, Changsha, Chongqing, Changzhi |

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# How does corporate management affect green innovation *via* business environmental strategies?

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Environmental issues are getting greater attention now that experts and authorities are paying attention to global warming. The industrial segment is mostly to blame for these environmental hitches, according to past research. The industrial sector is actively addressing the issues brought on by climate change. This study's primary focus is on business environmental strategies in green innovation, which takes into account the company's goals for sustainable development. This study also takes into account the importance of corporate management (CEO, ownership concentration, and gender diversity) for green innovation. This study evaluated fact by natural resource theory, resource dependency theory, agency theory and Porter hypothesis. Results from practical generalized least squares and generalized moments approaches provide various conclusions. The findings of this study demonstrated that companies with business environmental strategies as, environmental regulation, proactive environmental plans, corporate social responsibility, and board sustainable committees were more likely to implement green innovation practices. Additionally, corporate management (CEO, ownership concentration, and gender diversity) supports businesses' efforts to innovate in the green sector. Importantly, our research showed that the importance of corporate management (CEO, ownership concentration, and gender diversity) in business environmental policies cannot be overstated (environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee, and green innovation). green innovation, as well. These findings significantly expand the scant amount of knowledge on corporate environmental initiatives and green innovation. In order to encourage green innovation for higher profitability while minimizing negative industrial consequences, this study also provides a number of suggestions and recommendations for stakeholders, including regulators, owners, and governments.

KEYWORDS

**business environmental strategies, green innovation, corporate management, GMM model, moderating function**

## 1 Introduction

The enormous increase in the use of industrial manufacturing, greenhouse gas emissions, and resource exploitation pose a constant threat to environmental preservation. Business environmental strategies and its potential impact on corporate performance are topics that interest a growing number of stakeholders, including environmentalists, lawmakers, civil society organizations, markets, shareholders, and regulators (Wang et al., 2022). The importance of sustainable development (SD) is also frequently emphasized at the highest levels of the United Nations, most recently with the approval of the UN's agenda for sustainable development (2015–2030), which monitors improvements in both environmental and social spheres (Boluk et al., 2019). Sustainable development goals have motive to control the environmental bad effects as well. The United Nation has more concern for industrial sector (Huan et al., 2021). The United Nations has developed 17 Sustainable Development Goals to combat the problems facing humanity on a global scale. Future policymakers and other socially significant individuals must value these objectives for them to be attained (Hák et al., 2016).

Since environmental concerns are particularly critical for businesses in developing nations, this research is pertinent to the context of rising economies (Rafique et al., 2022). According to past studies, the industrial sector has a detrimental effect on the environment because it helps a nation's economy flourish (Javeed et al., 2021). China's economic liberalization and progress are now significantly hampered by environmental degradation. The prestige and economic health of the nation suffer greatly as a result. Even if China's economy is expanding, there are significant environmental problems because of significant investment, excessive pollution, and high consumption (Javeed et al., 2021). The environmental performance of Chinese businesses will undoubtedly improve in the face of criticism and scrutiny from around the globe. In this way, green creation is given special attention in the Chinese business sector.

Thankfully, the Chinese government has made a number of steps to handle the terrible condition, predominantly in the business and industrial sectors, both of which have a significant impact on pollution and output (Liu et al., 2022a). To encourage corporate social responsibility, green policies and other environmental programs have been developed (Huang et al., 2021). As a result, in this situation, it is being pushed for firm strategies to include ecological expansion targets in order to achieve sustainable goals (Javeed et al., 2021). "Green innovations" are brand-new production, management, or service models that lessen environmental problems. Green innovation is therefore more crucial as a tactical instrument for achieving environmental goals (Liu et al., 2022a).

The benefits of green innovation have been extensively researched (Cai et al., 2020), but the reasons why certain businesses invest in it more than others have not yet been adequately analyzed (Liu et al., 2022a). The corporate governance elements that affect green innovation are particularly understudied. The literature also emphasizes the differences in green innovation research among nations. These nations have particularly requested green innovation research due to the tremendous environmental harm they are currently facing (Javeed et al., 2021). Thus, business environmental approaches are imperative for green invention and conservational controlling (Mio et al., 2022). This study combines various business environmental strategies together to inspect the effect on green innovation. For example, Javeed et al. (2021) stated that environmental regulation as business environmental strategy is beneficial for improving green innovation.

Moreover, Zhou et al. (2019) underlined the significance of using pro-active environmental strategies in business to promote corporate social policies and green practices. In addition, Madueno et al. (2016) explained that corporate social practice is serve as business environmental strategy that have significant effects on firm level green practices. Orazalin and Environment (2020) presented the role of board sustainable committee as a business environmental strategies for improving firm long-run profit *via* green innovation. Therefore, this study proposes business environmental strategies for promotion of green innovation and combine all business environmental strategies together for presenting as framework of business environmental strategies. As a result, the composition and business environmental initiatives may determine the quality of green innovation (Kraus et al., 2020).

The importance to SGDs also falling for industrial sector. For the Sustainable Development Goals to be met, the business sector is a crucial partner. Businesses might contribute as a byproduct of their primary activities. As a result, we urge businesses all across the world to set ambitious goals, measure the effects of their efforts, and honestly communicate their progress (Boluk et al., 2019). Moreover, Chinese government also focusing on SGDs for improving environmental effects. In this context, the following query is posed: What are the key determinants that underpin this beneficial link, if corporate environmental initiatives can strengthen the company's green innovation practices? The report recommends leveraging corporate management to advance business environmental objectives and encourage green innovation as a result.

Corporate top executive as the perception of the CEO is positively correlated with workplace environmental policies that support green innovation (Li, 2016). If the CEO is knowledgeable about environmental and sustainability measures, green innovation may be promoted (Huang et al., 2021). Furthermore, corporate management as ownership concentration also valuable for promoting business environmental strategies and green innovation. According to Chen et al. (2021), a company's market orientation and green

innovation are positively impacted by the concentration of its ownership. In addition, Younas et al. (2017) also demonstrated that ownership concentration as large shareholders have more concern for corporate environmental strategies. Because they want to make long-run profit through reputation. Besides, gender diversity as corporate management is also beneficial tool for corporate environmental and green practices (Harjoto et al., 2015). The relevance of female directors in promoting environmentally friendly operations for green innovation is also highlighted by (Boukattaya and Omri, 2021). They believed that females are more supporting to business environmental strategies for green practices.

As a result, this study advises using corporate management ideas to improve green innovation and to balance the rapport amid business ecological policies and sustainable actions. According to what we understand, no prior studies have specifically looked at the controlling upshot of corporate management (CEO, ownership concentration, and gender diversity) in the context of a connection concerning business environmental strategies (environmental regulations, proactive environmental strategies, corporate social responsibility, and board sustainable committee) and green innovation. In addition, the corporate governance also concerning for achieving SDGs (Chien, 2022). Unaware of it, many business owners and organizations already support sustainable development. They accomplish this, for instance, by doing the following: ensuring the health and welfare of their staff (Goal 3), being aware of the circumstances in which their supply chains operate (Goals 8, 12), by being informed of ways to lower their business's carbon footprint (Goal 13), paying workers equally and impartially based on gender (Goals 5, 8), and the SDG Business Hub's CEO Guide on Sustainable Development Goals provides information on the different steps CEOs of firms may take to better align their organizations with the SDGs (Chien, 2022). Besides, gender diversity is also vital part of SGDs (Singh et al., 2021).

In order to investigate the aforementioned issues, this study makes use of a range of theoretical frameworks for suitable theoretical support. For example, natural resource theory, resource dependency theory, agency theory, and Porter hypothesis uses for supporting the function of business environmental strategies and green innovation with the interactive role of corporate management (Jensen and Meckling, 1976; Porter and Van der Linde, 1995; Liu et al., 2022b; Suriyapongprapai et al., 2022). All theories encourage corporate for social and environmental actions. For example, the idea behind resource dependency theory is that in order for an organization, such a commercial corporation, to acquire resources, it must transact with other individuals and organizations in its environment and support corporate social actions (Hillman et al., 2009). Similarly, natural resource theory also considering corporate social actions for improvement of global warming. Importantly, Porter supported the corporate all environmental strategies for innovation and better performance. Lastly, the agency theory backed the corporate management factors for the improvement of corporate social actions.

All non-financial A-listed firms in China that were registered with both stock exchanges, Shanghai and Shenzhen, were included in this analysis, which used data from 2010 to 2019. The results show that business environmental strategies, which comprises elements of environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee, and green innovation are substantially and positively associated to green innovation. Secondly, result reveals that corporate management, including the CEO, ownership concentration, and gender diversity, may compel businesses to engage in green innovation. Most importantly, this study suggests that Corporate management, including the CEO, ownership concentration, and gender diversity, can make positive association amid business environmental strategies environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee and green innovation.

Our results indicate that corporate environmental plans are advantageous for green innovation. Additionally, corporate management can help to strengthen the connection between green innovation and company environmental policies. Additionally, our discovery broadens our understanding for policymakers who want to advance corporate-level sustainable improvement intentions. Regulatory organizations can concentrate on these discoveries in a manner similar to this to eliminate undesirable industrial results. By contributing in the mitigation of negative industrial consequences, firm sustainable practices, such as green innovation and corporate environmental plans, can be profitable for businesses in emerging and developed countries. With the aid of this study, the sustainable development goals of the UN might be accomplished. The study's remaining components are divided into various groups. The empirical analysis and theoretical assessment of evolving hypotheses are presented in Section 2. Section 3 discusses the methods for gathering data, measuring variables, and doing research. Section 4 of this study presents the findings. Section 5 contains a summary of the conclusions, implications, limitations, and suggested next measures. Figure 1 highlights the context of the study.

## 2 Theoretical analysis framework

### 2.1 The natural resource theory

Business environmental strategies are crucial because they can give organizations a competitive edge while also enhancing their operations. As a result, the theory based on natural resources shed light on corporate actions when businesses are engaged in maintaining the natural environment in this context

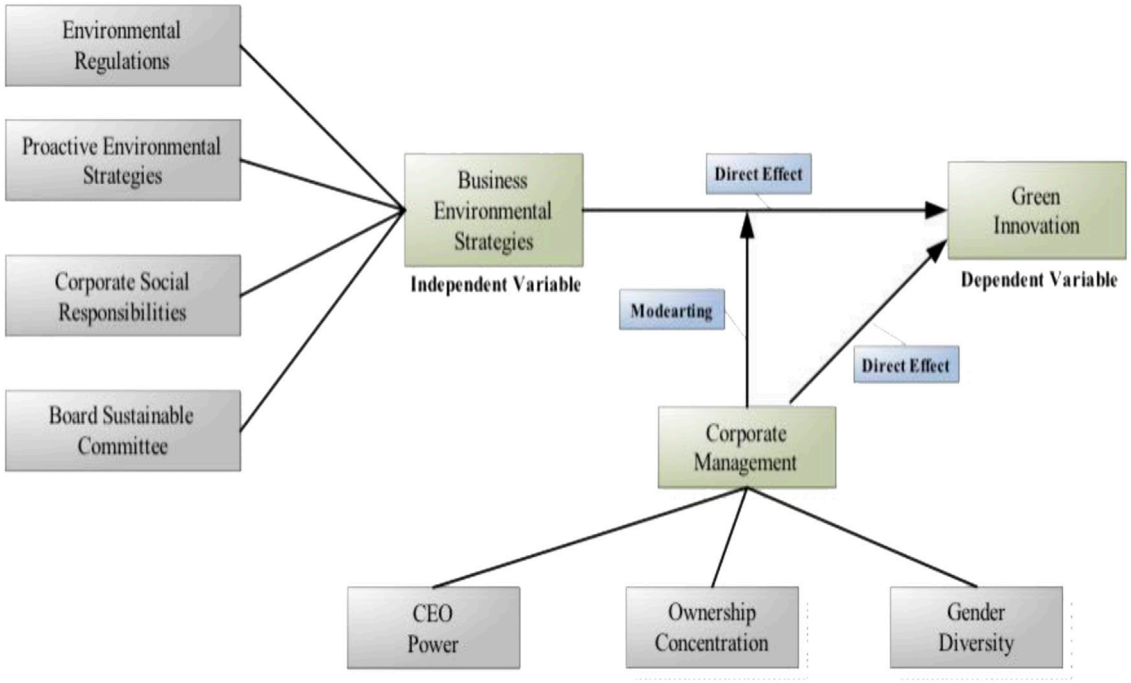


FIGURE 1
Context of study.

(Hart, 1995). The three main goals of this theory are long-term development, product stewardship, and pollution control strategies. Cost-saving, distinctiveness, and hybrid environmental initiatives are typically investigated (Walsh et al., 2017). For example, environmental regulations, proactive environmental strategies, CSR, and board sustainable committee are the part of corporate environmental strategies. Every corporation want to make long-run development (Nunkoo and Boateng, 2010), product differentiation (Porter and and Kramer., 2007) and trying for removing industrial negative effects (Javeed et al., 2022). Thus, the natural resource theory supported the corporate sustainable practices. Moreover, this theory shed the light on the protection of natural resources which are being damaged by global warming (Walsh et al., 2017). Therefore, this theory supported the function of business sustainable policies for green innovation.

## 2.2 Porter hypothesis

The Porter put up ideas that supported the contribution of environmental laws to innovative business strategies for gaining competitive advantage (Porter, 1991). Porter essentially provided two viewpoints: the innovative compensation idea and the first mover advantage (Porter, 1991; Porter and Van der Linde, 1995; Ambec and Barla, 2002). These theories emphasized the significance of environmentally friendly business methods for innovation. Similarly, Porter and and Kramer. (2007), Porter and Kramer. (2011) learn that how corporate social strategy may increase the value of shareholders while also being a crucial instrument for innovation and competitive advantage. In light of this, this theory also emphasized the necessity of corporate sustainability plans for green innovation. Porter highlighting the importance of sustainable and social practices for firms for achieving competitive advantage. This study selected various factors as business environmental strategies for improvement of green innovation. These actions may create differentiation among firms. Furthermore, it will help to gain long-run survival of the firm. These actions encourage firms for making innovation practices and it can compel firms to be part of environmental cleaning. Our selected factors related to environmental and social aspect of the firms and it will surely increase the firm reputation in the market. Therefore, Porter hypothesis also supported the role of business environmental actions for innovation.

## 2.3 Resource dependency theory

Resource dependency theory stated that top executives make significant contributions to corporate strategy development, providing expertise and guidance, improving corporate

reputation and legitimacy, enabling access to resources, and improving relationships with all internal and external stakeholders (Hillman and Dalziel, 2003). Moreover, this theory also supported the role of gender diversity for business sustainable strategies. Women on boards serve a different societal purpose than men, and gender diversity leads to greater strategic decision-making (Bantel, 1993). In order to construct sustainable practices at firm level, the resource dependency theory also supported the role of top executives (Sun and Sun, 2021). This theory is imperative for the evaluation of our selected corporate governance variables for environmental and innovation practices. This theory entices the corporate governance top executives especially CEOs, large shareholders, and gender diversity for the improvement of corporate reputation. These business environmental strategies can be beneficial for firms for attaining long-term development and cleaning environment as well. Moreover, these practices can also protect the corporate resources for long-run.

## 2.4 Agency theory

Ross discovers the agency dilemma for the first time. Jensen and Meckling (1976) proposed the agency theory to cover up the agency cost. In this idea, the role of corporate environmental strategy for green innovation is emphasized. Because they believe that presence of sustainable practices may reduce agency conflict (Jensen and Meckling, 1976). Furthermore, the top governance also willing to reduce the agency cost in this scenario (Fama et al., 1983). The role of the CEO, ownership concentration, and gender diversity for green innovation and company environmental practices were thus backed by this theory. The agency issues harmful for corporate performance and reputation. Firms in social and environmental actions are supposed to be reputed and well-managed. Therefore, corporate executives try for removing agency issues by encouraging the business environmental strategies for green innovation. The development of green innovation is also beneficial for enhancing stakeholder confidence. So, this way firms can solve agency issue.

## 2.5 Hypothesis development

This study majorly focuses on business sustainable strategies for green innovation. Prior literature explained the position of different sustainable approaches for green innovation (Song et al., 2018). Therefore, this study tries to use appropriate business sustainable strategies for completing this probe. As sustainable business practices, environmental laws, proactive environmental measures, corporate social responsibility, and board sustainability committee have been chosen (Hart, 1997).

### 2.5.1 Environmental regulations

Porter (1991) gave the theoretical perspective on the connection concerning environmental rules and organizational innovation, stating that well-managed environmental restrictions force enterprises to move toward innovation. Porter also identified two theoretical perspectives: innovation compensation theory and first-mover advantage theory (Porter, 1991; Porter and Van der Linde, 1995). These theories highlight the critical role of environmental rules in helping businesses become more inventive and lucrative. Environmental rules encourage businesses to create unique items for the market, which leads to business innovation.

These restrictions may impose a cost burden on businesses, but they also encourage them to look for methods to innovate in order to offset the regulatory cost (Kneller et al., 2012). Environmental restrictions, according to Barbera et al. (1990), improve business productivity and market repute. Furthermore, Jaffe et al. (1995) pointed out that environmental rules are critical for firms to survive in a competitive market by driving green innovation. Manufacturing enterprises are more liable for pollution, thus they adhere to environmental regulations with a high rate and they have major focus on green innovation (Brunnermeier et al., 2003). Environmental restrictions, according to Porter (1991), offer a win-win situation for enterprises in a highly competitive market by pushing them to generate unique and original items for green innovation. Besides, a number of academics have demonstrated that environmental rules are critical for promoting environmental practices and reducing industrial negative impacts (Arimura et al., 2007). Thus, this study proposes that environmental regulations can be helpful for corporate green innovation. The question of whether sustainable development approaches can solve these concerns while boosting competitiveness and sustainability has been stoked by these pressures, which have increased the focus on green and sustainable value creation (Yousaf et al., 2021). As a result, we've come up with the following hypothesis:

H1: Environmental regulations influence green innovation in a major and favorable way.

### 2.5.2 Proactive environmental strategies

Firms' readiness to promote a sustainable environment has not yet been formalized (Haffar et al., 2018). As a result, there is still discussion regarding gaining a competitive edge by implementing proactive ecological policies. Green novelty is seen as a long-term corporate development approach (Rehman et al., 2021). According to Zhou et al. (2019), academics' attention has switched to proactive environmental methods for improving long-term performance. In support of this claim, Solovida et al. (2017) pointed out that enterprises with environmental plans had better long-term performance than those without. Through the use of green practices, companies with proactive environmental policies are thought to have a sound business approach (Kong et al., 2020).

Proactive environmental tactics include the use of acceptable raw resources, the reduction of waste, and the creation of goods that adhere to environmentally beneficial standards (Singh et al., 2020). Green innovation can be boosted by the effectiveness of proactive environmental policies (Rehman et al., 2021). Environmental solutions that are proactive are critical for gaining a competitive advantage through innovation (Porter, 1991). Stakeholders are more interested in companies that are environmentally conscious (Liao and Environment, 2018). As a result, proactive environmental policies boost stakeholder trust. As a result, businesses who have proactive environmental initiatives ought to have an advantage in terms of green innovation. Furthermore, they came to the conclusion that the firms' long-term success is linked to proactive environmental initiatives. Environmentally proactive tactics compel businesses to engage in environmentally friendly practices in order to avoid environmental problems (Zhang et al., 2019).

Numerous researchers have already found a link concerning proactive environmental policy and business gain, but green innovation has not received enough attention. (Ryszko, 2016). As a result, there is a pressing need to investigate manufacturing companies' environmental procedures. Furthermore, Liu et al. (2015) argued for the importance of proactive environmental initiatives in improving ecological policies. Environmental legality contributes to the improvement of green novelty processes at the corporate stage (Zhang et al., 2022). According to Chen et al. (2016), aggressive actions enhancing green product innovation and creativity. As a result, based on the previously indicated justifications, we proposed the hypothesis.

H2Environmental strategies that are proactive are beneficial to the advancement of green innovation.

### 2.5.3 Corporate social responsibility

McWilliams and Siegel (2000) come to the conclusion that CSR and corporate innovation are favorably linked. Their findings backed with Porter's assertions (Porter and Van der Linde, 1995). Porter and and Kramer. (2007) find that CSR is a critical instrument for green innovation and competitive advantage, as well as a way to increase shareholder value. The competitive advantage can help a company operate better, and CSR is tied to the competitive advantage (Saeidi et al., 2015). Hull and Rothenberg (2008) claims that enterprises' participation in CSR activities leads to green innovation. They also argued that CSR activities boost corporate innovation capability, which might give businesses a competitive advantage (Russo and Fouts, 1997). Shahzad et al. (2020) demonstrates the favorable relationship between green innovation and corporate social accountability.

In addition, Hong et al. (2020) also believes that CSR activities can be work as booster for corporate green innovation. Various research, on the other hand, support the link between CSR and corporate green innovation (McWilliams and Siegel, 2000). According to Wagner (2010), CSR delivers multi-dimensional benefits for improving corporate performance, with innovation being a key component of those benefits. Martinez-Conesa et al. (2017) also believe that CSR can help firms innovate more effectively. They highlight how CSR may help a company innovate. CSR, they say, boosts investment chances in the research and development section which leading to green innovation. In light of the aforementioned literature, a hypothesis has been formulated for this investigation.

H3: Corporate Social Responsibility positively influences on Green Innovation.

### 2.5.4 The board sustainable committee

The most important part of corporate governance is the board's sustainability committee, which plays a key role in supporting sustainable practices (Hussain et al., 2018). The presence of a sustainable committee promotes corporate governance, which automatically increases firm performance (Liu et al., 2021). The board sustainable committee is supposed to be good business sustainable strategy (Chams and García-Blandón, 2019). Spitzeck (2009) stated in this context that sustainable committees urge corporations to participate in corporate social practices, resulting in enhanced long-term sustainability. Biswas et al. (2018) also provided evidence of the benefits of a sustainable board committee for enhancing Australian companies' social and environmental performance. Dixon-Fowler et al. (2017) Employing information from S&P 500 corporations, researchers looked into how environmental board committees affected corporate environmental performance. Their findings also confirmed the hypothesis that environmental board committees are associated with superior environmental performance. In addition, the function of board sustainable committees in improving sustainable practices was endorsed by (Orazalin and Environment, 2020).

H4: The Board of Directors' Sustainable Committee has a supportive view of green innovation.

### 2.5.6 The role of CEO

The CEOs normally approve all key investment and finance choices (Cronqvist et al., 2012). The longevity of diverse businesses is usually linked to the important decisions made by the CEO in terms of business innovation (Aghion et al., 2013). A strong CEO is more focused on company innovation to make the company lucrative for the sake of his good reputation (Griffin et al., 2007). CEO has various skills to invest in social or environmental issues (Hirshleifer et al., 2012). Galasso and Simcoe (2011) discover that a self-assured CEO may drive innovation within a business by investing in risky and challenging projects. According to Hirshleifer et al. (2012), A CEO who exudes confidence is more willing and able to contribute to a company's R&D project in order to foster green innovation. Similarly, Quan et al. (2021) show that a strong CEO promotes green innovation and is continuously seeking for ways to increase the company's profit.

Green innovation is frequently viewed as a pro-social corporate behavior, making CEOs inclined to engage in its activities (Ren et al., 2021). The role of CEO is highly important for long-run survival of the firm. According to previous studies, corporate social actions are really helpful for making reputation in the market (Quan et al., 2021). Thus, CEO especially from developing economy firms trying to participate in environmental and social actions (Berger et al., 2008), which will help to achieve in long-term success in the form of reputation and innovation. CEOs can also accomplish this goal through green innovation, which not only helps the environment by reducing pollution but also benefits society at large by lowering environmental threats and enhancing environmental quality (Ren et al., 2021). Besides, better business innovation outcomes may result from CEOs' pilot credentials, superior educational experience, and transformative leadership (Huang et al., 2021).

Additionally, a strong CEO benefits a company's innovation for a number of reasons. First off, a strong CEO holds a position of authority within the business, therefore he controls the company's reputation and course. A strong CEO employs cutting-edge strategies not only to raise profits but also to enhance brand perception and staff satisfaction (Lewellyn and Muller-Kahle, 2012). Boyd et al. (2011) also support the notion that strong CEO traits and green innovation are positively correlated. Quan et al. (2021) further points out that a powerful CEO has a detrimental impact on green innovation. Moreover, CEO wants to clear his position and they invest in social practices for the satisfaction of shareholders (Javeed et al., 2021). Green innovation is a good way for CEO's to make company positive image in market. As a result, we propose the fifth hypothesis:

H5: Green Innovation is influenced by CEO power in a major and beneficial way.

A strong CEO is advantageous not just to the firm's innovation (Griffin et al., 2007), but also to environmental regulations and corporate social activities (Li, 2016). Green innovation could be boosted if the CEO is well-versed in environmental and sustainability objectives (Huang et al., 2021). According to Kassinis et al. (2016), the perception of the CEO and workplace regulations are positively correlated. A strong CEO is constantly looking for methods to boost the company's reputation, and sustainable business practices are a great weapon for him to use (Javeed et al., 2021). Environmental strategies, according to Porter (1991), are beneficial to enhancing corporate innovation and profitability as well. Environmental regulations and other long-term objectives are crucial instruments for promoting green innovation since an excellent CEO is always keen to invest in business innovation and profitability (Porter, 1991).

Furthermore, a CEO who is knowledgeable of environmental standards might reduce costs by involving businesses in green innovation (Huang et al., 2021). In general, if a powerful CEO is concerned about environmental policies and other sustainable practices, then he puts pressure on company management to implement business sustainable strategies, which leads to increased green innovation (Roxas and Coetzer, 2012). In this sense, Javeed and Lefen (2019) Considering the moderating effect of CEO authority, examine the correlation amid corporate social responsibility and company success in Pakistan. They found that a capable CEO positively moderates the relationship amid corporate social accountability and firm performance. Because the globe is currently beset by environmental challenges, environmental rules are expected to be a top priority for businesses (Luo et al., 2021). Business sustainable strategy is a critical instrument for improving corporate innovation, and CEOs can exert pressure on companies to implement CSR policies (Javeed and Lefen, 2019).

Due to the fact that climate change is becoming increasingly important to company operations, corporations must be instrumental in lowering GHG emissions (Luo et al., 2017) and CEO has more concern to participate in sustainable practices (Javeed et al., 2021). Recently, corporate governance techniques have been applied to track GHG emissions and the risks associated with climate change (Haque, 2017). One such mechanism is the characteristics of the CEO, as they are crucial in managing, monitoring, directing, and rewarding carbon-related behaviors in day-to-day business operations (Jaffe et al., 1995).

H6: A powerful CEO is beneficial to moderate the association amid business sustainable strategies and green innovation.

### 2.5.7 The role of ownership concentration

Because large shareholders can considerably influence corporate decisions, ownership concentration plays an important role in green innovation (Hu et al., 2021). The proportion of big shareholders who participate in corporate decision-making to improve the firm's action is referred to as ownership concentration. Large shareholders support corporate innovation strategies because they are the most effective way to increase the value of the company (Li, 2016). Large shareholders are solely concerned with increasing the value of the company, and they keep a close eye on management (Wu and Hu, 2020). Large shareholders place pressure on executives to improve the company's performance, which may encourage them to develop new goods (Deng et al., 2013).

Furthermore, voting rights come with ownership concentration, putting pressure on management and tiny shareholders to perform green practices (Al-Jaifi, 2017). Ownership concentration is beneficial in limiting over-investment and diversification by management (Bethel and Liebeskind, 1993). Companies with significant ownership concentrations effectively control management and other shareholders, enabling them to engage in social initiatives that support green innovation (Alchian and Demsetz, 1972). Furthermore, the significant stockholders are more concerned with the needs of the customers. As a result, they observe the

actions of competitors and the market condition; this circumstance forces businesses to implement creative tactics in order to achieve potential growth (Baysinger et al., 1991). Song et al. (2018) argue that a firm's ownership concentration has a favorable impact on its green innovation and market orientation. We establish the following hypothesis based on the foregoing discussion:

H7: The concentration of ownership has a favorable impact on Green innovation.

According to previous research, ownership concentration is beneficial to company innovation and social practices (Alchian and Demsetz, 1972). Environmental performance is connected to business decisions since ownership concentration has such a significant impact on them, and when major shareholders are willing to invest in environmental standards, the company's reputation is immediately improved (Kagan et al., 2003). Furthermore, Javeed and Lefen (2019) argument that ownership concentration is a practical tool for enhancing corporate performance and social activities.

Ownership concentration not only encourages management to embrace environmental policies for a positive image in the market, but it also encourages them to innovate (Baysinger et al., 1991). Agency conflicts may be reduced by large owners' participation in societal norms (Liu et al., 2021). Large shareholders, according to Maung et al. (2016), possess a great deal of decision-making authority and can decide whether to engage in social and environmental initiatives for business novelty. Major shareholders are constantly seeking for ways to grow their wealth, according to a number of specialists, and as a result, they are interested in exploring R&D practices in order to create innovation (Hill and Jones, 1992). To back up this claim, Liu et al. (2022b) discovered that ownership structure had a favorable impact on manufacturing enterprises' environmental performance.

Furthermore, Calza et al. (2016) find that substantial shareholders benefit environmental proactivity since they focus on long-term earnings and environmental practices in order to improve the firm's market image. Minority stockholders are just interested in making a quick profit and are unconcerned about the company's long-term sustainability. Large shareholders, on the other hand, are supposed to be the owners of companies, thus they require the companies to survive in the long run (Iatridis, 2013). Businesses engage in social initiatives that enhance their market standing and spur the creation of novel products that will satisfy both shareholders and society (Howell and Allen, 2017).

The level of voluntary corporate transparency is influenced by the ownership structure. The level of monitoring and consequently the breadth of voluntary disclosures is determined by an organization's ownership structure (Giannarakis et al., 2020). Tang et al. (2018) examined the connection between ownership structure and voluntary disclosures and found no connection between managerial or governmental ownership and voluntary disclosures, but a substantial inverse association between block holder ownership and voluntary disclosures. To meet their investment estimation needs, corporate investors may put pressure on companies to reveal more information (Sparkes and Cowton, 2004).

Ownership concentration is particularly essential in the corporate sector because it includes the majority or top shareholders (Javeed et al., 2021). Ownership concentration assists in enhancing social norms at the corporate level (Alchian and Demsetz, 1972). The willingness to participate in corporate social practices for long-term development is crucial because the ownership concentration has significant decision-making power in the organization (Delmas et al., 2010). Strong sustainable development targets can be accomplished with the willingness to concentrate ownership, according to Javeed and Lefen (2019).

H8: Ownership concentration is beneficial to moderate the association amid business sustainable strategies and green innovation.

### 2.5.8 The role of gender diversity

The social behaviors of businesses are significantly impacted by gender diversity Multiple studies have linked female directors to effective, long-term practices (Hillman et al., 2002). Furthermore, Harjoto et al. (2015) found that compared to male directors, female directors are more concerned with the long-term viability of corporate social activity. According to a meta-analysis study, female directors are crucial for increasing a company's social initiatives (Byron and Post, 2016). Furthermore, Harjoto and Rossi (2019) exposed that companies can engage in long-term, sustainable corporate social initiatives by having female directors.

Boukattaya and Omri (2021) highlighted the value of having female directors in order to improve environmentally friendly operations. Several academics have investigated the association among gender diversity and corporate social performance, including (Post et al., 2015). It was also determined that having female directors was essential for long-term progress, according to their findings. Furthermore, according to Landry et al. (2016), A company's ethical behavior is reflected by the presence of female directors on its board of directors, which enhances its reputation in society. Besides, administrations with female executives, according to Qiu et al. (2016), possess effective corporate social programs.

Female directors strive to collect more profit for the delight of shareholders by attending social gatherings (Hussain et al., 2018). Droms Hatch et al. (2015) asked participants what they thought about the role of male and female directors in social activities in two separate areas of corporate social aspects. According to their findings, people have a considerably more favorable opinion of female directors than male directors when it comes to sustainable habits. Female directors, on the other hand, take corporate social

responsibility more seriously than male directors, according to (Hyun et al., 2016). Corporate social practices, according to Romano et al. (2020), have a positive association with gender diversity.

H9: The growth of green innovation is aided by gender diversity.

According to the vast majority of studies on how female board directors affect social performance, they are more effective in numerous facets of green finance. For instance, it has been found that boards with higher gender diversity are more likely to accomplish the organization's social goal (Al Fadli et al., 2019). Amorelli et al. (2021) women on boards were shown to be positively correlated with "institutional strength CSR," but not with "technical strength CSR." The majority of academics in this topic have focused on a single CSP component, such charity (McWilliams and Siegel, 2000), the quality of the working environment Landry et al. (2016), the natural environment Post et al. (2011), or ethics Ibrahim and Angelidis (1994).

Cabeza-García et al. (2018) looked examined the connection between board diversity and how much GHG information is disclosed in the United Kingdom and found a strong correlation. Additionally, they reported on the long-term effects of female directors on corporations. Al Fadli et al. (2019) investigate how the board's qualities may be linked to CSR and find a favorable link. Cordeiro et al. (2020) stated that female executives more concern for business environmental policies. Ma et al. (2022) examine how female board directors respond to gender issues reporting and find a positive link. Orazalin and Environment (2020) A positive association was shown when the effects of board gender diversity and CSR strategy were examined in Europe. Tingbani et al. (2020) also supported the function of gender diversity for corporate environmental approaches.

Ferrero-Ferrero et al. (2015) highlighted that gender diversity could be helpful for sustainable reporting at firm level. Lu et al. (2019) also encouraged the role of gender diversity for business sustainable strategies. Pucheta-Martinez et al. (2018) demonstrated that board diversity enhances corporate reputation *via* environmental policies. Haque (2017) state a positive correlation between carbon reduction operations and greenhouse gas (GHG) emissions of a corporation in the United Kingdom was found when the effects of board characteristics and sustainable pay policies were examined.

H10: Gender diversity is beneficial to moderate the association amid business sustainable strategies and green innovation.

# 3 Sample selection

The manufacturing industry in China is part of the study's sample. We selected this sample for the following reasons: First, manufacturing, one of China's core industries, is essential to the economy of the country and to the livelihoods of many people. Second, the manufacturing sector is currently faced with enormous societal challenges such as tax fraud, corruption, and high risks for health and safety (Kong et al., 2020). We use two stock exchanges to conduct our investigation; Shanghai and Shenzhen are two Chinese stock exchanges that fall under the "A" category. We examined manufacturing companies that were listed on both stock exchanges. The manufacturing businesses that we chose for this study were also chosen for a variety of reasons. As an illustration, manufacturing firms actively participate in environmental preservation and have positive relationships with philanthropic causes (Zhang et al., 2021).

Additionally, it is believed that Chinese manufacturing companies pollute more (Cai and Li, 2018). Chinese manufacturers benefit from a wealth of resources, strong production rates, and higher rates of investment in environmental restoration. The waste, air, water, and manufacturing industries all contribute significantly to pollution (Rehman et al., 2021). As a result, manufacturing corporations are under more pressure than companies in other industries to disclose accurate information about corporate social issues (Haniffa et al., 2005). For a sample of all A-share listed firms in China from 2010 to 2019, we use the following selection criteria. First, financial organizations are not included due to concerns with accounting statement comparability and a few environmental issues. Second, data anomalies do not include companies with negative net assets. Finally, we exclude companies whose data cannot be accessed. The sample distribution is based on the most recent revision of the Industry Classification Guidance for Listed Companies published by the China Securities Regulatory Commission (CSRC). In addition to other significant data from the China Stock Market and Accounting Research Database, we gather patent information from the corporation's annual reports (CSMAR). Finally, 297 companies are chosen to complete this inquiry.

## 3.1 Variable measurement

### 3.1.1 Green innovation

A previous researcher asserted that precise variable measurement yields successful results in empirical tests (Javeed et al., 2021). Investors in exclusive rights are frequently seen working on green innovation projects. Therefore, environmental patent applications filed by businesses constitute green innovation (Cai et al., 2021). Typically, businesses file patents to increase sales, get technological advantages, and safeguard their name in society. Therefore, it is believed that patent filings are the best tool for assessing a company's intellectual property operations (Cai and Li, 2018). In light of these findings, this study maintains the course of green invention policies based on quantity, such as

patent applications made by businesses over time. This study using green innovation as a dependent variable.

### 3.1.2 Environmental regulation

Due to environmental problems, environmental regulations are becoming more and more popular worldwide. In this analysis, we use a proxy that is consistent with earlier research to estimate environmental regulations: annually cost for environmental and ecological programs divided by business output value (Javeed et al., 2020).

### 3.1.3 Proactive environmental strategy

This study defines the proactive environmental strategy proxy as the firm's overall investment in R&D (Ge et al., 2018). This proxy for estimating PES had also been supported by earlier academics (Darnall et al., 2010).

### 3.1.4 Corporate social responsibility (CSR)

Corporate social responsibility refers to a company's operations that are concerned not just with profit but also with societal issues. CSR is calculated by dividing total equity by the sum of EPS, total taxes, staff wages, interests, and public spending minus social costs (Feng et al., 2018).

$$Earnings\ per\ Share + (Staff\ Expenses + Total\ Taxes + Public\ Welfare\ Expenses + Interest - Social\ Cost) \times /Total\ Enquity$$

### 3.1.5 Chief executive officer (CEO) power

In this analysis, CEO power, which is measured using the CEO compensation ratio, is used as an independent and moderating variable (Javeed and Lefen, 2019). Determined as, the total compensation of CEO divided by other executives. Cash payment is the finest tool for controlling CEO authority in firms.

### 3.1.6 Ownership concentration (OC)

The percentage of an organization's ownership held by larger shareholders is referred to as ownership concentration. A shareholder is regarded as a major shareholder if they own 10% or more of the company's equity (La Porta et al., 1997).

### 3.1.7 Gender diversity (GD)

In this study, gender diversity is a moderating and independent variable. The proportion of female board members used to determine the board's gender diversity. This important gender diversity measure has been used in earlier investigations (Yasser et al., 2017). Even though this study evaluates gender diversity in accordance with these academics.

### 3.1.8 Control variables

To acquire the best results, this study used a variety of control variables. Control variables at the corporate governance level include the size of the company, the ratio of equipment to other assets, the turnover of assets, and environmental consciousness. The standard log of the business's full assets is used to determine size (Chodorow-Reich et al., 2022). The cost of plant, property, and equipment is divided by the company's overall sales to get at the plant, property, and equipment ratio (Li, 2016). The ratio of total sales to total assets is used to calculate asset turnover (Javeed et al., 2021). The final step in evaluating environmental awareness involves dividing the total workforce by the amount of money spent by the company on redesigning and greenery-related expenses (Javeed et al., 2021).

## 3.2 Empirical methods

In statistics and econometrics, multi-dimensional data that entail measurements across time are known as longitudinal data and panel data, respectively. Panel data are a subset of longitudinal data that include observations made for the same participants across time. Panel data is commonly associated to endogeneity issues, according to prior research (Li, 2016). The overall correlation cannot be construed as a causal influence whenever additional factors exist that contribute to a connection between a treatment and an outcome. The term "endogeneity dilemma" is frequently used to describe this situation. Endogeneity bias, which can result in confusing data and faulty theoretical elucidation, can be caused by uncertain conclusions (Li, 2016). Despite this, the endogeneity issue has not been addressed by the bulk of researchers that work with panel data. For instance, 90% of published panel data research does not address endogeneity issues (Feng et al., 2018).

Therefore, for controlling endogeneity problem, this study focusing on GMM model. Prior author reported that most crucial suggestion for dealing with endogeneity is the generalized method of moments (GMM). The GMM approach to resolving this issue has received support from more academics as well (Wintoki et al., 2012). The dynamic panel model, often known as the generalized mixed model (GMM) approach, was created in 1991 by Arellano and Bond (1991). With time, the factors' relationship changes. A smart strategy for addressing these challenges is to use the GMM model. This approach is also highly helpful for developing accurate equation assessments (Feng et al., 2018). The GMM technique frequently allows for the exploitation of the lags of predicted variables. These variables delays are thus a very helpful technique to avoid endogeneity in panel data [81]. The GMM model uses "internal modifying data" to handle endogeneity (Li, 2016). The GMM model is also the most effective method for removing endogeneity from panel data since it has specific effects for changing coefficients (Li, 2016). In order to overcome the limits of panel data and achieve the best findings, the GMM model is utilized in this study.

## 3.3 Feasible generalized least square (FGLS)

Feasible generalized least square (FGLS) is a technique for assessing the unidentified contour in a linear regression model when data show a high level of residual correlation (Wooldridge et al., 2016). In the first instance, FGLS is discovered by Aitken (1936) in 1934. The best method for dealing with heteroskedasticity is FGLS. The Ordinary Least Square (OLS) approach may become ineffective when the variance of the independent variables is not equal because the estimators may draw the incorrect conclusions as a result of unclear results. It is possible that the incorrect terms in the equation will be connected in a particular pattern (Wintoki et al., 2012). The chance of a subsequent link could therefore bias the outcomes. In this work, the FGLS model is utilized as a robustness test to make sure that the results are accurate.

## 3.4 Econometric equations

This study has been divided into three aspects.

### 3.4.1 The impact of business environmental strategies on green innovation

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_1} + \boldsymbol{\beta_1 ER_{1i,t}} + \boldsymbol{\gamma_1 Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (1)$$

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_2} + \boldsymbol{\beta_2 PES_{2i,t}} + \boldsymbol{\gamma_2 Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (2)$$

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_3} + \boldsymbol{\beta_3 CSR_{3i,t}} + \boldsymbol{\gamma_3 Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (3)$$

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_4} + \boldsymbol{\beta_4 BSC_{4i,t}} + \boldsymbol{\gamma_4 Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (4)$$

From this equation, $GI_{i,t}$: Represents the green innovation of firms i at year t,; $ER_{1i,t}$: environmental regulations: $PES_{2i,t}$: proactive environmental strategies; $CSR_{3i,t}$: corporate social responsibility; $BSC_{4i,t:}$ board sustainable committee: Control variables of firm i at year t; $\mu_{i,t}$: Error term; $\alpha_n$: Constant term, n = 1; $\beta_m$, $\gamma_n$ Coefficients to be estimated; m = 1, 2, 3, 4.

### 3.4.2 The impact of corporate management on green innovation

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_5} + \boldsymbol{\beta_5 CEO_{5i,t}} + \boldsymbol{\gamma_5 Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (5)$$

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_6} + \boldsymbol{\beta_6 OC_{6i,t}} + \boldsymbol{\gamma_6 Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (6)$$

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_7} + \boldsymbol{\beta_7 GD_{7i,t}} + \boldsymbol{\gamma_7 Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (7)$$

From this equation, $GI_{i,t}$: Represents the green innovation of firms i at year t,; $CEO_{1i,t}$: environmental regulations: $OC_{6i,t}$: ownership concentration; $GD_{7i,t}$: gender diversity: Control variables of firm i at year t; $\mu_{i,t}$: Error term; $\alpha_n$: Constant term, n = 1; $\beta_m$, $\gamma_n$ Coefficients to be estimated; m = 1, 2, 3.

### 3.4.3 The impact of business environmental strategies on green innovation with the moderating role of corporate management

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_8} + \boldsymbol{\beta_8 X_{1i,t}} + \boldsymbol{\beta_9 CEO_{4i,t}} + \boldsymbol{\beta_{10} X_{1i,t}{}^{*} CEO_{4i,t}} + \boldsymbol{\gamma_8 Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (8)$$

From this equation, $GI_{i,t}$: Represents the green innovation of firms i at year t,; $\boldsymbol{X_{1i,t}}$ shows green finance all elements as, ER, PES, CSR, and BSC: $\boldsymbol{X_{1i,t}{}^{*} CEO_{4i,t}}$ reveals the interaction between all business environmental strategies and CEO Power.

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_9} + \boldsymbol{\beta_{11} X_{1i,t}} + \boldsymbol{\beta_{12}} OC_{5i,t} + \boldsymbol{\beta_{13} X_{1i,t}{}^{*} OC_{5i,t}} + \boldsymbol{\gamma_9 Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (9)$$

From this equation, $GI_{i,t}$: Represents the green innovation of firms i at year t,; $\boldsymbol{X_{1i,t}}$ shows green finance all elements as, ER, PES, CSR, and BSC: $\boldsymbol{X_{1i,t}{}^{*} OC_{5i,t}}$ reveals the interaction between all business environmental strategies and ownership concentration.

$$\boldsymbol{GI_{i,t}} = \boldsymbol{\alpha_{10}} + \boldsymbol{\beta_{14} X_{1i,t}} + \boldsymbol{\beta_{15}} GD_{6i,t} + \boldsymbol{\beta_{17} X_{1i,t}{}^{*} GD_{6i,t}} + \boldsymbol{\gamma_{10} Z_{i,t}} + \boldsymbol{\mu_{i,t}} \quad (10)$$

From this equation, $GI_{i,t}$: Represents the green innovation of firms i at year t,; $\boldsymbol{X_{1i,t}}$ shows green finance all elements as, ER, PES, CSR, and BSC: $\boldsymbol{X_{1i,t}{}^{*} GD_{6i,t}}$ reveals the interaction between all business environmental strategies and gender diversity.

Control variables of firm i at year t; $\mu_{i,t}$: Error term; $\alpha_n$: Constant term, n = 1; $\beta_m$, $\gamma_n$ Coefficients to be estimated; m = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 from Eqs 8–10).

# 4 Results

Table 1 displays the descriptive statistics for corporate management, green innovation, company environmental strategies, and control variables. The mean and standard deviation values are shown in this table. Table 1 also includes the results of the Pearson correlation test. The outcomes of the examination of Pearson coefficient correlation are shown in Table 1. The majority of the variables show a strong and positive correlation. Similar to this, all of the control variables show a strong and positive relationship.

The outcomes of the GMM technique for the connection between business environmental strategies as (environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee) and green innovation are shown in Table 2. Model 1 shows that, when using the GMM technique, ER has a considerable and favorable influence on GI and values ($\beta$ = 0.751, $p$ = 0.01). Model 2 shows that, when using the GMM technique, PES has a considerable and favorable influence on GI and values ($\beta$ = 5.216, $p$ = 0.01). Model 3 shows that, when using the GMM

TABLE 1 Descriptive statistics and Pearson Correlation.

| Variables | M | SD | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.GI | 0.31 | 0.38 | 1 | — | — | — | — | — | — | — | — | — | — | — |
| 2.ER | 0.28 | 0.39 | 0.93*** | 1 | — | — | — | — | — | — | — | — | — | — |
| 3.PES | 0.48 | 0.71 | 0.95*** | 0.89*** | 1 | — | — | — | — | — | — | — | — | — |
| 4.CSR | 0.85 | 0.23 | 0.13** | −0.14** | −0.03** | 1 | — | — | — | — | — | — | — | — |
| 5.BSC | 0.46 | 0.32 | 0.77*** | 0.17*** | 0.72*** | −0.15*** | 1 | — | — | — | — | — | — | — |
| 6.CEO | 0.83 | 0.33 | 0.85*** | 0.28*** | 0.48*** | −0.75*** | 0.65*** | 1 | — | — | — | — | — | — |
| 7.OC | 0.84 | 0.37 | 0.25*** | 0.21*** | 0.30*** | −0.14*** | 0.69*** | 0.71*** | 1 | — | — | — | — | — |
| 8.GD | 0.85 | 0.22 | 0.45*** | 0.18*** | 0.36*** | 0.18*** | 0.35*** | 0.26*** | 0.18*** | 1 | — | — | — | — |
| 9.SIZE | 0.42 | 0.43 | 0.77*** | 0.27*** | 0.19*** | 0.16** | 0.34*** | 0.64*** | 0.92*** | 0.38*** | 1 | — | — | — |
| 10.ATO | 0.22 | 0.39 | −0.11*** | 1.12*** | −0.73*** | 0.99*** | −0.18 | 0.26*** | −0.26*** | 0.32*** | 0.38*** | 1 | — | — |
| 11.PPE | 0.50 | 0.52 | 0.26*** | 0.33*** | 0.21*** | −0.28 | 0.76*** | 0.82*** | −0.17*** | 0.52*** | 0.39*** | 0.43*** | 1 | — |
| 12. EA | 0.79 | 0.83 | 0.45*** | 0.26*** | 0.31*** | −1.02 | 0.17*** | 0.21*** | −0.11*** | 0.71*** | 0.49*** | 0.32*** | 0.46** | 1 |

Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. GI, green innovation; GMM, generalized method of moment; ER, environmental regulation; PES, proactive environmental strategies; CSR, corporate social responsibility; BSC, board sustainable committee; CEO, chief executive officer; OC, ownership concentration; GD, gender diversity; Size, firm size; PPE, the ratio of plant, property, and equipment; ATO, asset turnover ratio; EA, environmental awareness; N, number of observation

TABLE 2 Results of link between Business Environmental Strategies and Green Innovation, Corporate Management and Green Innovation.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 |
|---|---|---|---|---|---|---|---|
| | GI | GI | GI | GI | GI | GI | GI |
| | GMM | GMM | GMM | GMM | GMM | GMM | GMM |
| **ER** | 0.753*** | — | — | — | — | — | — |
| **PES** | — | 5.216*** | — | — | — | — | — |
| **CSR** | — | — | 0.382*** | — | — | — | — |
| **BSC** | — | — | — | 0.147*** | — | — | — |
| **CEO** | — | — | — | — | 0.369*** | — | — |
| **OC** | — | — | — | — | — | 0.370*** | — |
| **GD** | — | — | — | — | — | — | 0.382*** |
| **SIZE** | −0.247*** | −0.115*** | 0.615*** | −0.617*** | 0.616*** | −0.611*** | −0.416*** |
| **PPE** | 0.197*** | 0.089*** | 0.578*** | 0.581*** | 0.79*** | 0.477*** | 0.573*** |
| **ATO** | −0.033*** | −0.007 | −0.011 | −0.008 | −0.010*** | −0.110*** | 0.121*** |
| **EA** | 0.128*** | 0.020 | 0.431*** | 0.329** | 0.482*** | 0.381*** | 0.431*** |
| **Constant** | 0.093*** | 0.054*** | 0.169*** | 0.141*** | 0.195*** | 0.196*** | 0.169*** |
| **N** | 2403 | 2403 | 2403 | 2403 | 2403 | 2403 | 2403 |
| **Wald Chi²** | 41107.07*** | 38585.40*** | 4141.27*** | 4118.49*** | 4226.75*** | 4122.39*** | 4341.27 |

Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. GI, green innovation; GMM, generalized method of moment; ER, environmental regulation; PES, proactive environmental strategies; CSR, corporate social responsibility; BSC, board sustainable committee; CEO, chief executive officer; OC, ownership concentration; GD, gender diversity; Size, firm size; PPE, the ratio of plant, property, and equipment; ATO, asset turnover ratio; EA, environmental awareness; N, number of observation.

technique, CSR has a considerable and favorable influence on GI and values ($\beta = 0.382$, $p = 0.01$). Model 4 shows that, when using the GMM technique, BSC has a considerable and favorable influence on GI and values ($\beta = 0.147$, $p = 0.01$). So, all these results reveal that business environmental strategies as, environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee are really valuable for green innovation practices.

Furthermore, the outcomes of the GMM technique for the connection between corporate management as (CEO power,

TABLE 3 Moderating role of CEO.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 |
|---|---|---|---|---|
| | GI | GI | GI | GI |
| | GMM | GMM | GMM | GMM |
| ER | 0.726*** | — | — | — |
| PES | — | 3.520*** | — | — |
| CSR | — | — | 0.167** | — |
| BSC | — | — | — | 0.071 |
| CEO | 0.023 | 0.010 | −0.112 | −0.012 |
| CEOER | 1.198*** | — | — | — |
| CEOPES | — | 4.434*** | — | — |
| CEOCSR | — | — | 44.17*** | — |
| CEOBSC | — | — | — | 98.52*** |
| SIZE | −0.241*** | −0.143*** | −0.512*** | 0.524*** |
| PPE | 0.190*** | 0.105*** | 0.460*** | 0.467*** |
| ATO | −0.032*** | −0.015** | −0.021 | −0.022 |
| EA | 0.134*** | 0.021 | 0.365*** | 0.310*** |
| Constant | 0.090*** | 0.067*** | 0.164*** | 0.156*** |
| N | 2403 | 2403 | 2403 | 2403 |
| Wald Chi$^2$ | 42882.07*** | 41610.23*** | 6411.25*** | 6643.49*** |

Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. GI, green innovation; GMM, generalized method of moment; ER, environmental regulation; PES, proactive environmental strategies; CSR, corporate social responsibility; BSC, board sustainable committee; CEO, chief executive officer; CEOER, Interaction of chief executive officer and environmental regulation; CEOPES, Interaction of chief executive officer and proactive environmental strategies; CEOCSR, Interaction of chief executive officer and corporate social responsibility; CEOBSC, Interaction of chief executive officer and board sustainable committee; Size, firm size; PPE, the ratio of plant, property, and equipment; ATO, asset turnover ratio; EA, environmental awareness; N, number of observation.

TABLE 4 Moderating role of OC.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 |
|---|---|---|---|---|
| | GI | GI | GI | GI |
| | GMM | GMM | GMM | GMM |
| ER | 0.702*** | — | — | — |
| PES | — | 3.055*** | — | — |
| CSR | — | — | 0.028 | — |
| BSC | — | — | — | −0.062 |
| OC | 0.144*** | 0.007 | 0.349*** | 0.314*** |
| OCER | 0.961*** | — | — | — |
| OCPES | — | 7.554*** | — | — |
| OCCSR | — | — | 22.10*** | — |
| OCBSC | — | — | — | 43.69*** |
| SIZE | −0.243*** | −0.071*** | −0.518*** | −0.537*** |
| PPE | 0.189*** | 0.045*** | 0.454*** | 0.473*** |
| ATO | −0.031*** | −0.005 | −0.022** | −0.023** |
| EA | 0.088** | −0.041 | 0.170** | 0.256** |
| Constant | 0.095*** | 0.038*** | 0.195*** | 0.228*** |
| N | 2403 | 2403 | 2403 | 2403 |
| Wald Chi$^2$ | 44265.07*** | 47564.40*** | 7527.94*** | 6985.17*** |

Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. GI, green innovation; GMM, generalized method of moment; ER, environmental regulation; PES, proactive environmental strategies; CSR, corporate social responsibility; BSC, board sustainable committee; OC, Ownership concentration; OCER, Interaction of Ownership concentration and environmental regulation; OCPES, Interaction of Ownership concentration and proactive environmental strategies; OCCSR, Interaction of Ownership concentration and corporate social responsibility; OCBSC, Interaction of Ownership concentration and board sustainable committee; Size, firm size; PPE, the ratio of plant, property, and equipment; ATO, asset turnover ratio; EA, environmental awareness; N, number of observation.

ownership concentration, gender diversity) and green innovation are also revealed in Table 2. Model 5 shows that, when using the GMM technique, CEO has a considerable and favorable influence on GI and values ($\beta = 0.369$, $p = 0.01$). Model 6 shows that, when using the GMM technique, OC has a considerable and favorable influence on GI and values ($\beta = 0.370$, $p = 0.01$). Model 7 shows that, when using the GMM technique, GD has a considerable and favorable influence on GI and values ($\beta = 0.382$, $p = 0.01$). Thus, all these results also stated that corporate management as, CEO power, ownership concentration and gender diversity is powerful tool for enhancing firm green innovation.

Table 3 displays the findings of the GMM technique for the relationship between business environmental strategies such as (environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee) and green innovation with the interaction of powerful CEO. Model 1 shows that, when using the GMM technique, CEO*ER has a considerable and favorable influence on GI and values ($\beta = 1.198$, $p = 0.01$). Model 2 shows that, when using the GMM technique, CEO*PES has a considerable and favorable influence on GI and values ($\beta = 4.434$, $p = 0.01$). Model 3 shows that, when using the GMM technique, CEO*CSR has a considerable and favorable influence on GI and values ($\beta = 44.18$, $p = 0.01$). Model 4 shows that, when using the GMM technique, CEO*BSC has a considerable and favorable influence on GI and values ($\beta = 98.52$, $p = 0.01$). According to all of these findings, there is a positive moderating effect of corporate management, specifically the CEO, on the connection between business environmental strategies like environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee and green innovation.

Aside from that, Table 4 presents the results of the GMM technique for the relationship between business environmental strategies like (environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee) and green innovation with the interaction of ownership concentration. Model 1 shows that, when using the GMM technique, OC*ER has a considerable and favorable influence on GI and values ($\beta = 0.961$, $p = 0.01$). Model 2 shows that, when using the GMM technique, OC*PES has

TABLE 5 Moderating role of GD.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 |
|---|---|---|---|---|
| | GI | GI | GI | GI |
| | GMM | GMM | GMM | GMM |
| ER | 0.730*** | — | — | — |
| PES | — | 6.873*** | — | — |
| CSR | — | — | 0.401*** | — |
| BSC | — | — | — | 0.197*** |
| GD | 0.041 | −17.11*** | 0.151*** | 0.420*** |
| GDER | 0.505*** | — | — | — |
| GDPES | — | 34.27*** | — | — |
| GDCSR | — | — | 0.756*** | — |
| GDBSC | — | — | — | 1.111*** |
| SIZE | −0.235*** | −0.066*** | −0.613*** | −0.610*** |
| PPE | 0.185*** | 0.031*** | 0.575*** | 0.568*** |
| ATO | −0.031*** | 0.010** | −0.008 | −0.007 |
| EA | 0.129*** | −0.056 | 0.305** | 0.275** |
| Constant | 0.085*** | 0.040*** | 0.128*** | 0.087** |
| N | 2403 | 2403 | 2403 | 2403 |
| Wald Chi$^2$ | 43779.82*** | 58601.02*** | 4169.28*** | 4228.16*** |

Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. GI, green innovation; GMM, generalized method of moment; ER, environmental regulation; PES, proactive environmental strategies; CSR, corporate social responsibility; BSC, board sustainable committee; GD, gender diversity; GDER, Interaction of gender diversity and environmental regulation; GDPES, Interaction of gender diversity and proactive environmental strategies; GDCSR, Interaction of gender diversity and corporate social responsibility; GDBSC, Interaction of gender diversity and board sustainable committee; Size, firm size; PPE, the ratio of plant, property, and equipment; ATO, asset turnover ratio; EA, environmental awareness; N, number of observation.

a considerable and favorable influence on GI and values ($\beta = 7.554$, $p = 0.01$). Model 3 shows that, when using the GMM technique, OC*CSR has a considerable and favorable influence on GI and values ($\beta = 22.10$, $p = 0.01$). Model 4 shows that, when using the GMM technique, OC*BSC has a considerable and favorable influence on GI and values ($\beta = 43.69$, $p = 0.01$). According to all of these findings, there is a positive moderating effect of corporate management, specifically the ownership concentration, on the connection between business environmental strategies like environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee and green innovation.

In addition, Table 5 presents the results of the GMM technique for the relationship between business environmental strategies like (environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee) and green innovation with the interaction of gender diversity. Model 1 shows that, when using the GMM technique, GD*ER has a considerable and favorable influence on GI and values ($\beta = 0.505$, $p = 0.01$). Model 2 shows that, when using the GMM technique, GD*PES has a considerable and favorable influence on GI and values ($\beta = 34.27$, $p = 0.01$). Model 3 shows that, when using the GMM technique, GD*CSR has a considerable and favorable influence on GI and values ($\beta = 0.756$, $p = 0.01$). Model 4 shows that, when using the GMM technique, GD*BSC has a considerable and favorable influence on GI and values ($\beta = 1.111$, $p = 0.01$). According to all of these findings, there is a positive moderating effect of corporate management, specifically the gender diversity, on the connection between business environmental strategies like environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee and green innovation.

## 4.1 Robustness analysis

This study uses an additional test to confirm the findings as a robustness test. This paper conducts further data analysis for the robustness test using feasible generalized least squares methodology (FGLS). Therefore, Table 6 presents the results of the FGLS technique for the relationship between business environmental strategies like (environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee) and green innovation. Model 1 shows that, when using the FGLS technique, ER has a considerable and favorable influence on GI and values ($\beta = 0.762$, $p = 0.01$). Model 2 shows that, when using the FGLS technique, PES has a considerable and favorable influence on GI and values ($\beta = 5.646$, $p = 0.01$). Model 3 shows that, when using the FGLS technique, CSR has a considerable and favorable influence on GI and values ($\beta = 0.033$, $p = 0.01$). Model 4 shows that, when using the FGLS technique, BSC has a considerable and favorable influence on GI and values ($\beta = 0.101$, $p = 0.01$). Therefore, all of these results using the FGLS technique also support all of the conclusions reached using earlier methods.

Furthermore, the outcomes of the FGLS technique for the connection between corporate management as (CEO power, ownership concentration, gender diversity) and green innovation are also revealed in Table 6. Model 5 shows that, when using the FGLS technique, CEO has a considerable and favorable influence on GI and values ($\beta = 0.571$, $p = 0.01$). Model 6 shows that, when using the FGLS technique, OC has a considerable and favorable influence on GI and values ($\beta = 0.476$, $p = 0.01$). Model 7 shows that, when using the FGLS technique, GD has a considerable and favorable influence on GI and values ($\beta = 0.034$, $p = 0.01$). Therefore, all of these results using the FGLS technique also support all of the conclusions reached using earlier methods.

Table 7 displays the findings of the FGLS technique for the relationship between business environmental strategies such as (environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee) and green innovation with the interaction of powerful CEO. Model

TABLE 6 Robustness test.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 |
|---|---|---|---|---|---|---|---|
| | GI | GI | GI | GI | GI | GI | GI |
| | FGLS | FGLS | FGLS | FGLS | FGLS | FGLS | FGLS |
| ER | 0.762*** | — | — | — | — | — | — |
| PES | — | 5.646*** | — | — | — | — | — |
| CSR | — | — | 0.033*** | — | — | — | — |
| BSC | — | — | — | 0.101*** | — | — | — |
| CEO | — | — | — | — | 0.571*** | — | — |
| OC | — | — | — | — | — | 0.476*** | — |
| GD | — | — | — | — | — | — | 0.034*** |
| SIZE | −0.061*** | −0.027*** | −0.244*** | −0.248*** | −0.239*** | −0.239*** | −0.244*** |
| PPE | 0.226*** | 0.031*** | 0.591*** | 0.566*** | 0.579*** | 0.577*** | 0.591*** |
| ATO | −0.012*** | −0.013*** | 0.018 | 0.056*** | 0.019 | 0.111 | 0.017 |
| EA | 0.021*** | 0.118*** | 0.738*** | 0.474*** | 0.758*** | 0.758*** | 0.738*** |
| Constant | 0.014*** | 0.016*** | 0.036*** | 0.020*** | 0.035*** | 0.033*** | 0.036*** |
| N | 3006 | 3006 | 3006 | 3006 | 3006 | 3006 | 3006 |
| Wald Chi$^2$ | 27033.84*** | 19543.40*** | 26109.96*** | 22679.49*** | 25503.80*** | 25503.39*** | 26109.96 |

Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. GI, green innovation; FGLS, feasible generalized least square; ER, environmental regulation; PES, proactive environmental strategies; CSR, corporate social responsibility; BSC, board sustainable committee; CEO, chief executive officer; OC, ownership concentration; GD, gender diversity; Size, firm size; PPE, the ratio of plant, property, and equipment; ATO, asset turnover ratio; EA, environmental awareness; N, number of observation.

1 shows that, when using the FGLS technique, CEO*ER has a considerable and favorable influence on GI and values ($\beta = 3.184$, $p = 0.01$). Model 2 shows that, when using the FGLS technique, CEO*PES has a considerable and favorable influence on GI and values ($\beta = 2.703$, $p = 0.01$). Model 3 shows that, when using the FGLS technique, CEO*CSR has a considerable and favorable influence on GI and values ($\beta = 48.85$, $p = 0.01$). Model 4 shows that, when using the FGLS technique, CEO*BSC has a considerable and favorable influence on GI and values ($\beta = 95.42$, $p = 0.01$). According to all of these findings, FGLS technique also support all of the conclusions reached using earlier methods.

Moreover, Table 8 presents the results of the FGLS technique for the relationship between business environmental strategies like (environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee) and green innovation with the interaction of ownership concentration. Model 1 shows that, when using the FGLS technique, OC*ER has a considerable and favorable influence on GI and values ($\beta = 1.243$, $p = 0.01$). Model 2 shows that, when using the FGLS technique, OC*PES has a considerable and favorable influence on GI and values ($\beta = 1.852$, $p = 0.01$). Model 3 shows that, when using the FGLS technique, OC*CSR has a considerable and favorable influence on GI and values ($\beta = 22.18$, $p = 0.01$). Model 4 shows that, when using the FGLS technique, OC*BSC has a considerable and favorable influence on GI and values ($\beta = 42.12$, $p = 0.01$). According to all of these findings, FGLS technique also support all of the conclusions reached using earlier methods.

Moreover, Table 9 presents the results of the FGLS technique for the relationship between business environmental strategies like (environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee) and green innovation with the interaction of gender diversity. Model 1 shows that, when using the FGLS technique, GD*ER has a considerable and favorable influence on GI and values ($\beta = 1.822$, $p = 0.01$). Model 2 shows that, when using the FGLS technique, GD*PES has a considerable and favorable influence on GI and values ($\beta = 18.13$, $p = 0.01$). Model 3 shows that, when using the FGLS technique, GD*CSR has a considerable and favorable influence on GI and values ($\beta = 0.769$, $p = 0.01$). Model 4 shows that, when using the FGLS technique, GD*BSC has a considerable and favorable influence on GI and values ($\beta = 1.775$, $p = 0.01$). According to all of these findings, FGLS technique also support all of the conclusions reached using earlier methods.

## 5 Discussion

Every country's progress depends on the industrial sector, yet it is also responsible for social and environmental problems

TABLE 7 Robustness of moderating role of CEO.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 |
|---|---|---|---|---|
| | GI | GI | GI | GI |
| | FGLS | FGLS | FGLS | FGLS |
| ER | 0.713*** | — | — | — |
| PES | — | 4.391*** | — | — |
| CSR | — | — | 0.059*** | — |
| BSC | — | — | — | 0.015** |
| CEO | 0.152*** | 0.066*** | 0.288*** | 0.354*** |
| CEOER | 3.184*** | — | — | — |
| CEOPES | — | 2.703*** | — | — |
| CEOCSR | — | — | 48.85*** | — |
| CEOBSC | — | — | — | 95.42*** |
| SIZE | −0.055*** | −0.041*** | −0.190*** | −0.192*** |
| PPE | 0.195*** | 0.061*** | 0.446*** | 0.473*** |
| ATO | −0.014*** | −0.013** | −0.010 | −0.001 |
| EA | 0.034*** | 0.074*** | 0.595*** | 0.523*** |
| Constant | 0.015*** | 0.027*** | 0.041*** | 0.042*** |
| N | 3006 | 3006 | 3006 | 3006 |
| Wald Chi$^2$ | 20785.07*** | 28133.23*** | 50399.11*** | 40680.02*** |

Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. GI, green innovation; FGLS, feasible generalized least square; ER, environmental regulation; PES, proactive environmental strategies; CSR, corporate social responsibility; BSC, board sustainable committee; CEO, chief executive officer; CEOER, Interaction of chief executive officer and environmental regulation; CEOPES, Interaction of chief executive officer and proactive environmental strategies; CEOCSR, Interaction of chief executive officer and corporate social responsibility; CEOBSC, Interaction of chief executive officer and board sustainable committee; Size, firm size; PPE, the ratio of plant, property, and equipment; ATO, asset turnover ratio; EA, environmental awareness; N, number of observation.

TABLE 8 Robustness of moderating role of OC.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 |
|---|---|---|---|---|
| | GI | GI | GI | GI |
| | FGLS | FGLS | FGLS | FGLS |
| ER | 0.715*** | — | — | — |
| PES | — | 5.047*** | — | — |
| CSR | — | — | 0.005 | — |
| BSC | — | — | — | 0.031*** |
| OC | 0.301*** | 0.039* | 0.592*** | 0.553*** |
| OCER | 1.243*** | — | — | — |
| OCPES | — | 1.852*** | — | — |
| OCCSR | — | — | 22.18*** | — |
| OCBSC | — | — | — | 42.12*** |
| SIZE | −0.059*** | −0.023*** | −0.187*** | −0.195*** |
| PPE | 0.210*** | 0.027*** | 0.462*** | 0.486*** |
| ATO | −0.028*** | −0.011** | −0.018 | −0.005 |
| EA | 0.052*** | 0.125*** | 0.499*** | 0.433*** |
| Constant | 0.011*** | 0.013*** | 0.044*** | 0.037*** |
| N | 3006 | 3006 | 3006 | 3006 |
| Wald Chi$^2$ | 14772.26*** | 23891.13*** | 43246.12*** | 38891.21*** |

Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. GI, green innovation; FGLS, feasible generalized least square; ER, environmental regulation; PES, proactive environmental strategies; CSR, corporate social responsibility; BSC, board sustainable committee; OC, Ownership concentration; OCER, Interaction of Ownership concentration and environmental regulation; OCPES, Interaction of Ownership concentration and proactive environmental strategies; OCCSR, Interaction of Ownership concentration and corporate social responsibility; OCBSC, Interaction of Ownership concentration and board sustainable committee; Size, firm size; PPE, the ratio of plant, property, and equipment; ATO, asset turnover ratio; EA, environmental awareness; N, number of observation.

(Javeed et al., 2021). Environmental problems that affect both the natural environment and human life are currently being dealt with in many countries. As a result, numerous governments have put into practice various strategies for sustainable development, which tries to increase profitability by resolving environmental challenges (Fan et al., 2021). The purpose of this study is to examine the qualities that can aid a business in achieving long-term success in this situation. This study combined different environmental or social practices for firms under the head of "business environmental strategies". For example, environmental regulations, proactive environmental strategies, corporate social responsibility, and board sustainable committee have been selected as business environmental strategies. The primary aim of this study is that business environmental strategies plays significant role for improving green innovation.

This study has inspected environmental strategies impact on green innovation separately. From hypothesis one to four, our outcomes concluded that business environmental strategies like environmental regulations, proactive environmental strategies, corporate social responsibility, and board sustainable committee are really valuable for improving green innovation at firm level. For supporting these outcomes, prior many authors findings are consistent with it. For example, Pan et al. (2021) supported environmental regulations, Mio et al. (2022) supported CSR, Solovida et al. (2017) supported proactive environmental strategies, Dixon-Fowler et al. (2017) supported board

TABLE 9 Robustness of moderating role of GD.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 |
|---|---|---|---|---|
| | GI | GI | GI | GI |
| | FGLS | FGLS | FGLS | FGLS |
| ER | 0.698*** | — | — | — |
| PES | — | 6.246*** | — | — |
| CSR | — | — | 0.084*** | — |
| BSC | — | — | — | 0.238*** |
| GD | 0.069*** | −9.114*** | 0.192*** | 0.166*** |
| GDER | 1.822*** | — | — | — |
| GDPES | — | 18.13*** | — | — |
| GDCSR | — | — | 0.769*** | — |
| GDBSC | — | — | — | 1.775*** |
| SIZE | −0.058*** | −0.019*** | −0.234*** | −0.282*** |
| PPE | 0.172*** | 0.024*** | 0.551*** | 0.525*** |
| ATO | −0.019*** | 0.007 | 0.056*** | 0.094*** |
| EA | 0.060*** | 0.039*** | 0.337*** | 0.375*** |
| Constant | 0.013*** | 0.022*** | 0.022*** | −0.027*** |
| N | 3006 | 3006 | 3006 | 3006 |
| Wald Chi$^2$ | 23699.36*** | 30725.41*** | 30438.62*** | 30860.67*** |

Significance levels: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$. GI, green innovation; FGLS, feasible generalized least square; ER, environmental regulation; PES, proactive environmental strategies; CSR, corporate social responsibility; BSC, board sustainable committee; GD, gender diversity; GDER, Interaction of gender diversity and environmental regulation; GDPES, Interaction of gender diversity and proactive environmental strategies; GDCSR, Interaction of gender diversity and corporate social responsibility; GDBSC, Interaction of gender diversity and board sustainable committee; Size, firm size; PPE, the ratio of plant, property, and equipment; ATO, asset turnover ratio; EA, environmental awareness; N, number of observation.

sustainable committee. Moreover, according to Palmer et al. (1995), environmental regulations are essential for businesses to thrive in a cutthroat market by spurring green innovation. Utilizing appropriate raw materials, cutting waste, and producing things that correspond to environmentally beneficial norms, or "green innovation," are all proactive environmental measures (Singh et al., 2020).

According to Hull and Rothenberg (2008), businesses who participate in CSR initiatives promote green innovation. Additionally, they contended that CSR initiatives improve corporate innovation capacity, which may provide organizations a competitive edge. A sustainable board committee has been shown to improve Australian companies' social and environmental performance, which is helpful for green innovation, according to Biswas et al. (2018). Theoretically, the natural resources theory and Porter hypothesis supported these outcomes (Porter, 1991; Hart and Dowell, 2011). Moreover, firms in developing economies have motive to compete in the international market. Therefore, to fulfill the international quality, environmental, and social standards also compel them to participate in business environmental strategies. The pressure of global warming and sustainable development goals also encouraging firms to make environmental friendly strategies. Importantly, firms with green innovation can also enhance profit ratio. Moreover, they can entice more shareholders by participating in business environmental strategies. China is fast growing economy in the world and have a lot of pressure for environmental issues as well. Therefore, the Chinese authorities have proper rules, regulations, and laws for industrial sector to participate in environment cleaning projects.

In addition to this, our study hypothesis five, seven, and nine concluded that corporate management as CEO power, ownership concentration and gender diversity is also valuable for improving green innovation. Prior studies such as, Hirshleifer et al. (2012) supported the role of CEO power, Song et al. (2018) supported the role of ownership concentration, Harjoto and Rossi (2019) supported the role of gender diversity for corporate green innovation. Corporate top management is very important for social practices as green innovation. A strong CEO has the skills to invest in green or social aspects and is more concerned with business innovation to make the company profitable for the sake of his good reputation (Griffin et al., 2007).

Moreover, companies with significant ownership concentrations effectively control management and other shareholders, enabling them to engage in social initiatives that support green innovation (Alchian and Demsetz, 1972). The social behaviors of businesses are significantly impacted by gender diversity. In numerous studies, female directors have been associated with reliable, enduring practices (Hillman et al., 2002). Furthermore, compared to male directors, female directors are more concerned with the long-term viability of corporate social initiatives. Theoretically, the resource dependency theory and agency theory supported these results. Corporate top executives have major responsibility to increase the profit and reputation of the firms (Javeed et al., 2021). The green innovation is a valuable tool for firms to gain the innovative image in the market (Abbas and Sağsan, 2019). Therefore, corporate management as CEO, ownership concentration, and gender diversity support the firm actions for green innovation. Moreover, female on top position is more concerned for environmental and social actions as compare to men.

Importantly, our study hypothesis six, eight, and 10th reported that corporate environmental strategies as, environmental regulations, proactive environmental strategies, corporate social responsibility, and board sustainable committee are really valuable for improving green innovation with the moderating role of corporate management (CEO power, ownership concentration, and gender diversity). There are various studies which supported the role of CEO power, ownership concentration, and gender diversity for improvement of business environmental strategies and green innovation (Boyd et al., 2011; Harjoto et al., 2015; Orazalin and Environment, 2020). According to Griffin et al. (2007), a great

CEO benefits the company's innovation as well as environmental strategies and corporate social responsibility initiatives. One such mechanism is the characteristics of the CEO, as they are crucial to managing, monitoring, guiding, and rewarding green practices in day-to-day company activities and development efforts (Jaffe et al., 1995). Additionally, ownership concentration is a beneficial tool for enhancing business social practices and performance, according to Javeed and Lefen (2019).

Ownership concentration have a lot of decision-making authority, and they might decide to engage in social and environmental practices for business innovation (Maung et al., 2016). The social activities of a firm can be improved by having more female directors (Byron and Post, 2016). In addition, Harjoto and Rossi (2019) found that the presence of female directors encourages businesses to adopt long-term, sustainable corporate social practices. The significance of having female directors is another point made by Boukattaya and Omri (2021) in order to improve ecologically sustainable operations. These findings also supported by resource dependency theory and agency theory. Corporate top executives are responsible for making all kind of strategies. Therefore, in the context of Chinese market they have a lot pressure from government and other authorities to participate in business environmental strategies (Teets, 2018). In addition, the role of gender diversity is highly important in Chinese market. They are interested in environmental and social actions for reputation and long-term profit. Consequently, they support corporate environmental strategies for green innovation.

# 6 Conclusion

With time, environmental problems have increased in frequency, and most academics think that the industrial sector is mostly to blame. The government and institutions are becoming more concerned about mitigating the detrimental effects of industry on the environment as the strain on the environment and sustainable development increases. Additionally, strong environmental practices are attracting the attention of legislators. Therefore, this study focusing on business environmental strategies as, environmental regulations, proactive environmental strategies, corporate social responsibility, and board sustainable for improving green innovation. Moreover, this study uses corporate management important factors as, CEO power, ownership concentration, and gender diversity for green innovation and as moderators on the association amid business environmental strategies and green innovation.

Panel data of 297 manufacturing companies in China were collected for this study from 2010 to 2019. This study uses two important statistical techniques, firstly, GMM model which also covers endogeneity issues and the FGLS model as a robustness analysis. This study comes to the conclusion that business environmental strategies like environmental regulations, proactive environmental strategies, corporate social responsibility, asnd board sustainable committee playing important role for enhancing green innovation at firm level. Besides, this study concluded that corporate management like CEO power, ownership concentration, and gender diversity is also imperative tool for increasing corporate green innovation. Importantly, this study stated that corporate management like CEO power, ownership concentration, and gender diversity positively moderates the link amid business environmental strategies like environmental regulations, proactive environmental strategies, corporate social responsibility, board sustainable committee and green innovation.

## 6.1 Policy implications

The findings of this study provide a number of recommendations and implications for policymakers, owners, institutions, governments, and managers. It could be advantageous to have corporate environmental strategy at the enterprise level. Businesses are advised to develop long-term plans to counteract adverse effects of industry. Additionally, this study emphasizes the value of corporate management in advancing sustainable practices. To improve long-term development, every government and policymaker should encourage CEOs and women to work in enterprises. Females must be represented on the board of directors and the sustainability committee since they are more motivated to engage in social behaviors.

The results of this study further highlight the value of ownership concentration for long-term sustainability and growth. Concentrated ownership makes up a substantial portion of corporate ownership, and their decisions are weighted more heavily within the business. This study provides guidance to governments and policy makers to develop these business environmental strategies like environmental regulations, proactive environmental strategies, corporate social responsibility, and board sustainable committee for promoting corporate social practices and improving reputation. This is the first study which investigated all these environmental strategies together for inspecting on green innovation. Importantly, this study highlighting the importance of green innovation at firm which also helps to reduce industrial negative effects.

So, this study entices shareholders and other governance to be a part of business environmental strategies. The environmental and social practices at firm level enhancing reputation in the market. Moreover, firms of developing economies could gain more benefits that having aim to

compete in international market. Additionally, this study's recommendations make social practices for top executives in businesses. Environmentally conscious businesses are viewed as being more socially conscious than others. Corporate social strategies methods enable businesses to boost earnings right away. Every regulatory body should make sure that every business has environmental strategy and corporate management involvement, especially those in developing economies. As a form of moral support and encouragement, institutions and governments can give prizes to businesses that have improved their sustainability policies. Additionally, because business social activities provide organizations with long-term benefits, this research implies that the cost of such activities is lower than the benefits. Additionally, by employing sustainable methods, businesses from developing nations may build a solid reputation and favorable perceptions in the global marketplace. This study also motivates companies to stop acting unethically and take part in civic activities. The study's findings suggest that the industrial sector might be a key player in cleaning up the environment. International social and quality standards can also be useful for putting pressure on companies to follow social norms.

It is crucial to take into account how the study may affect the Chinese context. Chinese listed companies are state- or government-controlled, and in the majority of corporations, the government makes the majority of the decisions. Our findings may aid companies in luring owners, partners, and financiers from both developed and developing countries to join them in business environmental strategies. Policy makers from China could also get benefits by using this study finding for improving environmental glitches. The world economy and community are grappling with a conundrum in this area as a result of the excessive use of resources and rising use of hazardous substances, which have led to environmental issues. The function of business environmental initiatives and green innovation would be of utmost relevance for companies wanting to boost their profit.

Businesses in developing economies focus on green innovation to enhance environmental management and meet international requirements. Environmentally conscious companies are absorbing expenses, reducing resource use, and implementing technology that improve their capacity to compete on both home and international markets. The government should also impose a significant fee on polluting companies that do not use greener production techniques. Government should create a detailed framework that outlines how businesses should transform into organizations that foresee pollution. This would lower the cost of doing business with the government. The results of this study may be useful to organizations, policymakers, and society as a whole. Companies can boost their output and competitiveness in their primary markets with the aid of green innovation. Since green innovation reduces carbon footprints, improves air and water quality, emits fewer toxins into the environment, and employs more sustainable energy sources, it will be advantageous to future generations and have a lasting effect on society.

### 6.2 Limitation and future direction

There are some empirical issues with the study that can suggest new directions for research. In order to analyze the nuanced relationship between corporate environmental objectives and green innovation, the study's initial focus is on China. Future studies could look at various growing nations or contrast them with developed nations. Second, several contextual factors could weaken the main links discovered by the study. Additional industries could be examined in a subsequent study to assess the impact of corporate governance, enterprise pattern, and other factors on the relationship between business environmental strategies and green innovation. Additionally, as business environmental strategy is a broad concept, the current study did not account for the effects of other elements of environmental strategy. Future research on this topic might include additional components like carbon accounting, comprehensive environmental policies, *etc.*

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Author contributions

Conceptualization, Writing-Original Draft Preparation, Formal Analysis, Methodology, SJ; Writing-Review and Editing, RL; Data Collection, NZ; Supervised, XC. All authors have read and agreed to the published version of the manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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# The forging of moral leaders in social entrepreneurship: A comparative study from two public welfare organizations in China

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Young people, including college students, are the main body for the main force of public welfare entrepreneurship and the effective force of future social entrepreneurs. How can college students, who are often self-made and lack entrepreneurial experience, social capital, and resources, grow up to be "moral leaders" of social entrepreneurship organizations? And what role does social entrepreneurship education play? Previous studies have not provided corresponding theoretical explanations to address these questions. This study uses as examples two public welfare organizations and their founders; namely, YinChao Pension Service Center in Yinzhou District, Ningbo City, and Ant Public Welfare Service Center in Yuyao City. The exploratory comparative research method of two cases is used, and the perspective is constructed based on personal significance. Through the open decoding analysis, this study refines the key elements of the individual growth of public entrepreneurs as "moral leaders," including four stages: concept construction, moral conflict, relationship construction, and rule construction, as well as personal meaning construction strategy and public entrepreneurship education strategy. The research results not only explain how individuals grow up to be "moral leaders" in public welfare organizations through self-meaning construction in the context of public welfare entrepreneurship and the construction process from individual to organization morality systems but also provide a theoretical framework for cultivating successful public welfare entrepreneurs and a theoretical reference for the sustainable development of public welfare entrepreneurs and public welfare entrepreneurship education in colleges and universities.

KEYWORDS

**personal meaning construction, moral leader, social entrepreneurship, double cases, sustainability**

## Research background

In recent years, social entrepreneurship education, which emphasizes the solution of social problems by commercial means by insisting on the double bottom line of social and commercial values, has attracted increasing attention due to its unique educational function. Public entrepreneurship education aims to improve people's moral character, enhance innovation ability, and achieve all-around development. Its social, commercial, and practical characteristics are naturally integrated into the educational function of colleges and universities. Social entrepreneurship education also has unique advantages for "developing entrepreneurial skills, consolidating survival value, enriching social capital, enhancing development value, promoting moral consciousness, and digging meaning value" (Yang, 2017).

Young people, mainly college students, are the main force of social entrepreneurship. With the increasing popularity of public entrepreneurship education in colleges and universities, many outstanding public entrepreneurs have emerged. They take responsibility for solving social problems and often start from scratch to perform public entrepreneurship projects and establish public organizations. With their enthusiasm and charisma, they attract many followers and become "leaders" of social entrepreneurship organizations with both business savvy and a strong sense of social responsibility. Due to their non-profit status, public welfare organizations lack natural "interest" bonding within the organization, and the cohesion between the members of the organization depends more on common values and moral standards. However, the founder of an organization often plays the role of "moral leader," and plays a vital role in the key operational links of the start-up of a social organization, such as identifying social problems, attracting organization members, reaching key consensus, establishing a formal organization, integrating social resources, solving social problems, and promoting the development of the organization. Practical observations also show that the core role of "moral leaders" is indispensable for successful public interest organizations. The long-term practice and related research in the field of organization management have shown that in the initial stage of an organization, the leadership of the founder is the key factor for the organization's success or failure. Especially for public welfare organizations, due to their non-profit status, there is a lack of natural "interest" bonding within the organization; thus, the cohesion between members depends more on common values and moral standards. The founder of such organizations often plays the role of "moral leader," and is vital in the key operational links of the start-up of a social organization, such as identifying social problems, attracting organization members, reaching key consensus, establishing a formal organization, integrating social resources, solving social problems, and promoting the development of the organization. Practical observations also show that the core role of "moral leaders" is indispensable for successful public interest organizations.

However, the role of "moral leader" is not endowed by God, nor is it born from thin air. There remains a lack of understanding and in-depth theoretical research on the process of producing and being recognized. Existing studies on "moral leaders" are mostly limited to behavioral studies at the micro level, such as the moral intuition of individuals in organizations (Haidt, 2012; Weaver et al., 2014) and the behavioral qualities of "moral leaders" (Hoch et al., 2018; Lemoine et al., 2019) and conscientiousness (Maak and Pless, 2006). Emerging literature has addressed "values work," involving research on the breaking, creation, and maintenance of values at the organizational level (Kraatz et al., 2010; Gehman et al., 2013; Vaccaro and Palazzo, 2015); however, but research from the organizational interaction perspective is lacking regarding how to connect the micro and macro levels and how "moral leaders" have a broader impact. Moreover, previous research has not considered start-up public welfare organizations, especially college students who lack entrepreneurial experience, social capital, and entrepreneurial resources. There remains no clear theoretical explanation for how they generate moral consciousness and moral courage, express their moral stand, and link their followers and their moral beliefs in an organization or field to become "moral leaders" with charisma and a cohesive entrepreneurial team.

Therefore, this study takes the private non-enterprise units YinChao Pension Service Center in Yinzhou District, Ningbo City, Ant Public Welfare Service Center in Yuyao City and their principals as the case study objects, and uses the exploratory comparative case study method to explore the following problems:

1) From the perspective of individual development, how does the "moral leadership" of start-up public welfare organizations arise? How does an individual raise personal moral principles to organizational morality and become the "moral leader" of the organization? What are the stages of this process? What are the key elements? What are the strategic behaviors in each stage of the above process? What is the relationship between them and the construction of their personal meaning?
2) From the perspective of public entrepreneurship education, what role does this education play in the above stages? What role should educators play? How to better play the educational function of public entrepreneurship? What factors in the university will affect the moral development of students? How do the university culture and environment relate students to ethical outcomes?

This study aims to: identify the development stages of moral leaders by case analysis based on the Meaning Making theory and identify key factors influencing the moral development of college students receiving education on social entrepreneurship.

# Literature review

## Public entrepreneurship and "moral leaders"

Social entrepreneurship is usually motivated by a social mission. Individuals or organizations adopt business strategies in the social non-profit field, aiming at efficiency, innovation, and social value to build a sustainable and competitive organizational entity (Hu, 2006). This process has been described both as a combination of social mission, innovation, and business (Dees et al., 2001) and a response to a social need requiring an out-of-the-box solution (Martin and Osberg, 2007). Similar to business entrepreneurship, social entrepreneurship progresses from team establishment, organization and communication, system establishment, and normal operation from the transition stage to the transformation and stable stages (Dees et al., 2001). Most definitions focus on four major factors: the characteristics of the social entrepreneurs themselves, their operative domain, the processes or resources used, and the mission of the social entrepreneur (Dacin et al., 2011).

Compared to other entrepreneurs, social entrepreneurs prefer the sense of social achievement brought by being innovators, emphasize self-realization, and have personal feelings of non-material pursuit and altruism (Xue and Zhang, 2016). Altruism is the most important and core motivation of social entrepreneurs (Zahxa and Gedajlovie, 2009), which can be expressed from three dimensions of public service, fairness and justice, and dedication, while self-interested motivation can be explained by the two dimensions of achievement orientation and control orientation (Zeng, 2014). Recently, Wettermark and Berglund (2022) also considered what relationships are possible between social entrepreneurs and those whom they strive to assist, their "beneficiaries," and how dimensions of mutuality—integral to the idea of SE—may be expressed in interactions between entrepreneurs and beneficiaries.

Compassion and prosocial factors are also the core factors that distinguish social entrepreneurs from business entrepreneurs. Compassion can complement traditional self-orientation by encouraging increased integrative thinking, more pro-social forms of weighing costs and benefits, and a commitment to alleviate the suffering of others, ultimately resulting in self-orientation through social entrepreneurship (Miller et al., 2012). SE intentions are based on two complementary mechanisms: self-efficacy (an agentic mechanism), and social worth (a communal mechanism) (Bacqa and Altb, 2018).

Researchers have applied identity theory to explain social entrepreneurship (Stryker and Burke, 2000). By adopting an identity-based lens, entrepreneurs have been recast not simply as individuals who create a venture but also as individuals who fervently pursue entrepreneurial activities that provide significant self-meaning (Murnieks and Mosakowski, 2007). This identity perspective helps to explain the diverse motivations driving entrepreneurs, including their distinct decision-making and strategic actions. When salient or central, identity can predict an entrepreneur's behaviors (Fauchart and Gruber, 2011: 945).

Entrepreneurial self-efficacy affects socially motivated entrepreneurial activities (Austin et al., 2006; Zahra et al., 2009). Such self-motivation is relevant in social entrepreneurship because entrepreneurs need persistent motivations to overcome the conflict between social goals and entrepreneurship's economic functions (Harding, 2004). Thus, entrepreneurial self-efficacy can explain entrepreneurs' sources of motivation to enact their intentions even though circumstances may not fit the enactment (Newman et al., 2018; Hsu et al., 2019).

In addition, studies on public entrepreneurs have researched how compassion promotes collective ability (Kanov et al., 2004); how people promote others' interests by bearing material costs (Rabin, 2002; Camerer and Fehr, 2006); emotional factors in decision making (Cardon et al., 2009) considering that entrepreneur self-efficacy may be influenced by other people (Licht, 2010); the relationship between empathy, moral identity, and the altruistic tendency of college students (Wu et al., 2020); *etc.* The motivation factors of potential social entrepreneurs may include social organization experience, empathy, moral responsibility, self-efficacy, perceived social support, pride, mutual benefit, homesickness, *etc.* (Katre and Salipante, 2012; Hockerts, 2017).

In the process of social entrepreneurship, the philosophical bases of social entrepreneurs and "moral leaders" are consistent. From the perspective of oriental management philosophy, social entrepreneurs demonstrate "doing good" and "doing everything smoothly" (Xu and Shi, 2012), among which, "doing good" is the expression of "benevolence," while "doing everything smoothly" is the expression of "ability." In the Book of Rites, "people who get on well with both superiors and subordinates are benevolent." The Confucian "benevolent person" has good moral character, just as social entrepreneurs must "get on well with both superiors and subordinates," cherish the heart of heaven and Earth, and have the quality of benevolence. A "benevolent person" has no desire to compete for fame and profit. Social entrepreneurship must seize the opportunity, integrate resources, persuade the community, and even carry out institutional entrepreneurship, which incorporates the concept that "everything goes smoothly" (Dacin et al., 2011; Kent and Dacin, 2013).

Based on the classical and practical theory of wisdom, a moral person is one who develops certain virtues based on intellect, reasoning, knowledge, and positive emotions (such as love, care, and compassion). The integration of rationality and emotion plays a crucial role in promoting moral behavior and the willingness to act wisely, as well as realizing the highest interests not only for the self but also for the community (Zhu et al., 2016). Mencius also said that morality is developed from people's hearts

or emotional fields, in which compassion is the most important factor. He emphasized the practice of justice and the establishment of moral norms by externalizing moral values and virtues (for example, performing moral acts), thus integrating the seemingly competing inner and rational logic. Mencius also emphasized the importance of cultivating external morality and moral behavior to internalize moral emotion through constant self-reflection.

Through the practice of internalizing compassion and externalizing moral behavior, people can integrate the paradoxical values related to heart and reason, which is closely related to the logic of integrating business and public welfare. From this point of view, successful social entrepreneurs are "benevolent and capable people" who can be seen as the aggregation of schools of social innovation and social enterprise (Dees and Anderson, 2003). Groups that participate in social entrepreneurship have the characteristic of moral quality. Thus, the process of becoming a leader of a public service organization is the process of the practice and externalization of moral behavior, the process of individual self-realization, and the core factor for the development of organizations.

## Construction of individual meaning and "moral leader"

The Meaning Making theory, proposed by Robert Kegan in 1982, is a process of defining beliefs, understanding, and commitment. Baxter Magolda et al. (2012) believed that meaning making is a process in which individuals understand identity, give meaning to actions, and decide how to get along with people and society. The development of meaning making should go through three stages: following external procedures, wandering at crossroads, and self-leading (Cen, 2014). It is also a question of what we usually call "how I perceive," "who I am," and "how I construct relationships with others." The concept is quoted in the field of pedagogy. Cen (2016) used the theory of meaning making to construct a pyramid model through empirical research to describe the process of college students' learning and development. "Moral leaders" are described as honest, trustworthy, and fair, who treat followers with respect and care, maintain commitment, give followers input and share in decision-making, and clarify their expectations and responsibilities (Treviño et al., 2003; Brown and Treviño, 2006). Fehr et al. (2015) summarized the role of "moralized" leadership behavior in defining "ethical leadership." The moralizing view of a leader's behavior stems from the moral intuitions of the followers. Individuals will have typical evaluation models in social systems, such as moral commonness (fairness and dignity), family or social values, institutional logic, *etc.* (Boltanski and Thevenot, 2006; Thornton et al., 2012; Abend, 2014). Different researchers have reported consistent findings: social interaction bridges the micro level of moral leadership to the macro level of moral system organization, through interactions and exchanges between leaders and followers on issues (Hallett and Ventresca, 2006). Especially when an organization is facing specific problems and moments, members use the behavioral framework provided by the values, ideologies, and ethics to explain uncertain problems and gradually legitimize them (Boltanski and Thevenot, 2006; Thornton et al., 2012; McPherson and Sauder, 2013). The moral system is also a dynamic process. Leaders and followers seek to expand the moral system and actively reshape, dismantle or expand its boundaries, leading to its evolution (Ashforth et al., 2000; Zietsma and Lawrence, 2010).

The steps of moral leadership are like the process of constructing personal meaning; both begin with moral reconstruction. Through moral consciousness and moral courage behaviors, leaders become the focus and expand the problem of moral reconstruction, establish alliances, gain moral understanding with others, and enlarge the personal framework of leaders and followers into the common foundation of followers in the organization. Finally, a new moral order is established by regularizing the boundary of the moral system. Specifically, we propose that a moral leader is likely to be perceived as representing the core values of the group (that is, they will be perceived as prototypical)—more so than another leader who has other positive attributes. Evidence shows that group members' evaluations of their groups, and their choice of which groups they want to belong to, are driven primarily by the group's perceived morality (Leach et al., 2007).

## Social entrepreneurship education and "moral leaders"

Estrin et al. (2013) reported that the higher the rate of social entrepreneurship in a country, the greater the spillover effect in improving social capital at the national level. One question is if the talent goal of social entrepreneurship is taken as the educational content, to which social welfare issues are added, will it be beneficial to cultivate the empathy and sympathy of college students to increase their motivation to creatively solve complex social problems and, thus, improve the intention of social entrepreneurship? Dees and Anderson, 2003, a professor at Harvard University, proposed that social entrepreneurship education is a process of "cultivating social entrepreneurs who can identify opportunities, make full use of existing resources and create social value." Hence, it is an innovative way to cultivate talent with the goal of encouraging comprehensive and free development, arousing self-consciousness, and enhance their ontological significance, which embodies the unity of "survival" and "development" in Education (Yang, 2017).

From ancient times to the present, universities have acted as organizations that educate students to become "holistic." In

"playing a powerful role in the development of citizens who think and act morally" (Pascarella and Terenzini, 2005), the role of moral education in moral decision-making leads to moral efficacy, moral meaning, and moral courage (Pascarella and Terenzini, 2005; May et al., 2014). Education is carried out by setting courses, tutoring students (falls, 1991), directly imparting values (Moosmayer, 2012), and providing moral training for students and teachers (Kelley et al., 2006). Petriglieri and Petriglieri (2010) emphasize that the result of moral development is not purely for college life, but for life ambition, which adopts the epistemological standpoint of constructivism. Students' moral beliefs are created, changed, and affirmed by their daily experiences. Collective meaning is produced by interactions, which are largely influenced by the language, culture, and environment of the member organizations.

# Sum up

Our search revealed a relatively rich body of literature on social entrepreneurship, moral leaders, and meaning construction in public welfare entrepreneurship at home and abroad. Some studies have also researched the uniqueness of public welfare entrepreneurs, such as altruistic motivation, compassion, personal identity, self-efficacy, *etc.*, which show the differences between social entrepreneurs and ordinary entrepreneurs.

However, the previous studies had some limitations: first, these mainly focused on the personal characteristics and entrepreneurial motivation of public entrepreneurs from a micro perspective rather than leader behavior in formulating their business. Second, the interaction mechanism between public welfare entrepreneurs and start-up public welfare organizations is not yet clear. Third, studies are scarce regarding its application in higher education, particularly regarding helping college students to develop themselves as moral leaders.

# Research design

## Research methods and case selection

### Research methods

This study applied theory-driven case analysis to establish a framework based on existing theories and verified and developed the theory through case data. The research on the process of generating a "moral leader" in social entrepreneurship used the theory of personal meaning-making and compared the function and role of social entrepreneurship education. Therefore, we applied a double-case exploratory comparative research method. The main reasons were as follows:

① The theoretical basis of this study was the Sense-Making Theory, which is mature; moreover, research on "moral leaders" is not rare. However, this study is innovative in assessing social value through the behavior of public entrepreneurship. Therefore, the exploration of the growth process of "moral leader" in public entrepreneurship using the Sense-Making Theory is an exploratory study that applies mature theory to a new field.

② Research questions belong to the category of "how," which are suitable for case studies to refine the theory and law behind the phenomenon and to present the integrity and dynamics of the research process (Yin, 2003). Within-case analysis and cross-case comparison allow an in-depth understanding of the diversity of public interest practices, which can help to confirm and supplement the same practice phenomenon to obtain more accurate and universal research.

③ Regarding the similarities and differences in the role of social entrepreneurship education on different "moral leaders" to realize the construction of personal meaning, the double-case method is used to analyze the similarities and differences between the two cases from self to organizational morality and assesses the impact of social entrepreneurship education on "moral leaders."

### Case selection

This study selected the YinChao Pension Service Center in Yinzhou District, Ningbo City, and the Ant Public Welfare Service Center in Yuyao City and their leaders as the case study objects, according to the model principle and the principle of sampling theory (Eisenhard and Graebner, 2007). The selection criteria were as follows: 1) Principle of sampling theory. The two enterprises are start-up private non-enterprise organizations registered in the Civil Affairs Bureau. The recognition of the person in charge as a "moral leader," the process of participating in public entrepreneurship, the construction of their personal meaning, and the degree of social entrepreneurship education were used to explore the path of a "moral leader" in social entrepreneurship. 2) Model principle. Self-leading, key events, path choice, organizational interaction behavior, and social entrepreneurship education differed between the two leaders and were used for the comparative analysis of cooperation. 3) Convenience principle. The research team was familiar with the case objects and could observe the process of the case objects' participation in social entrepreneurship. The public welfare organizations were willing to cooperate with the research to provide detailed data and multiple rounds of interviews; they were also willing to provide enterprise information and opportunities for on-site observation. The organizations also maintained contact and verified data to ensure the implementation of methodological triangulation. The following is a brief introduction to the basic situations of the cases.

TABLE 1 "Moral leaders" and their organizational data collection.

| Data sources | Data sources | Data information statistics | | | | |
|---|---|---|---|---|---|---|
| First-hand data | In-depth interviews | Public welfare organizations | The recording time | Number of words in valid text of the recording | Number of interview | Interviewees |
| | | "YinChao Pension Service Center" | 325 min s | 39,206 | 4 (3 formal interviews; 1 supplementary interview) | Li*hui, members of the organization |
| | | "Ant Public Welfare" | 414 min s | 41,362 | 5 (4 formal interviews; 1 supplementary interview) | Xie*jie, members of the organization, colleagues, peers |
| Second-hand data | Network information, company files | Publicity of public welfare organizations on the Internet, newspapers, related information on interview reports, WeChat and microblog | | | | |
| Other data | Field visit and observation | Participate in the guidance process, office space and activity site of "moral leader" public welfare entrepreneurship, and listen to the on-site explanation of project leader | | | | |

Li Hui, a member of the all-China Youth Federation, a national outstanding member of the Communist Youth League, news person of the year of Zhejiang Education, Ningbo good man, and other honorary titles, was selected in the 2019 Forbes China under-30 elite list. In 2015, she set up "YinChao Pension Service Center," and in 2017, when she was a junior, she registered "Ningbo Yinzhou District YinChao Pension Service Center" in the Yinzhou District Civil Affairs Bureau, which is the first non-governmental pension institution registered by a university student in Zhejiang Province. In the past 5 years, Li Hui led the team to establish 46 community service bases for the elderly and more than 30 colleges for senior citizens. The total service time of the team was >750,000 h. The project was awarded a gold medal in the China Youth Volunteer Service Public Entrepreneurship Competition and a silver medal in the China College Students' Entrepreneurship Competition.

Xie Jie is a member of Yuyao CPPCC, general manager of Ningbo BoLizi Health Technology Co., Ltd., initiator of Ant Public Welfare, secretary general of the Leshan public welfare foundation, among the "good people in China," and "good people in Zhejiang," outstanding individual of Chinese youth volunteers, self-improvement model of Zhejiang Province, top-ten outstanding young people in Ningbo, Ningbo good man, one of "The Most Beautiful Ningbo People," *etc.* "Ant Public Welfare" was established in 2015, with the tenet of "small ants, micro public welfare, big energy" and with the main business of helping the poor, assisting students, and providing emergency rescue.

## Data collection

### Data sources and collection methods

To improve the validity and reliability of the cases, this study mainly included three types of data sources: interview data, network data, and organizational records and field observation (Table 1), forming a "data triangle." The interview data were mainly focused on the growth process of the founder of the public welfare organization. The interview process used the narrative history for reference to objectively describe the process. The public entrepreneurs' self-awareness, education experience, key events, *etc.* were the key interview topics. For the process of public entrepreneurship education, we mainly considered the teachers' process for cultivating public entrepreneurs, entrepreneurship education curriculum and environment in public schools, *etc.* The supplementary interviews focused on the partners, team members, and colleagues of "moral leaders" to describe the characteristics of entrepreneurs, the major events of behavior transformation, and the perception of participation in the educational process from a third-party perspective.

The network materials mainly included network propaganda, newspapers, and interview reports of the public welfare organizations. Combined with semi-participatory field observations, the research process mainly adopted a semi-structured interview method and used the interview framework to control the interview focus and rhythm. If new problems were identified, a supplementary interview link was added and the proposed additional questions were put forward to the interviewees who had been interviewed or other interviewees to avoid a disconnect in the interview outline due to the structural reality.

### Data coding and data analysis

The text was analyzed according to the Strauss programmed grounded theory, "open coding—spindle coding—selective coding" data processing method (Wang, 2019). First, the materials were coded. In case 1, the recording data from Li * hui, related recording data, and second-hand data were coded as L; in case 2, the recording data of Xie * jie, related recording data, and second-hand data were coded as X. A total of 25 concepts were obtained by open coding (Table 2). Second, spindle coding

TABLE 2 Key construction and measurement variables.

| Level 1 coding | Level 2 coding | Generative dimension |
|---|---|---|
| The family environment cultivates character and enlightens values; A11 | Building moral awarenessA1 | Conceptual construction stage A |
| Acquire knowledge through school education and determine internal norms; A12 | | |
| Key events are mainly self decision-making; A21 | Trying self-identity A2 | |
| Take the initiative to choose the entrepreneurial experience; A22 | | |
| Be aware of moral differences; A31 | Generating moral motivation A3 | |
| Show compassion; A32 | | |
| The conflict of multiple identities; B11 | Finding a value gap B1 | Moral conflict stage B |
| Critical event pressure; B12 | | |
| Self efficacy of public entrepreneurship; B13 | | |
| Live through moments of upheaval and build a new understanding; B21 | Going through a moment of upheaval B2 | |
| Have not experienced drastic change, and achieve balance through avoidance and adjustment; B22 | | |
| Observation, thinking and external situations trigger moral emotions; B31 | Building Moral Courage B3 | |
| Moral emotion promotes moral motivation and promotes action to solve problems; B32 | | |
| Moral courage is associated with a sense of responsibility to alleviate the suffering of others; B33 | | |
| Cognitive dimension, correct understanding of public welfare entrepreneurship; C11 | Forming self-dominance C1 | Relationship building stage C |
| Personal inner dimension, clarifying identity; C12 | | |
| Interpersonal dimension, build a framework for moral relationships from individuals to collectives; C13 | | |
| Enhance moral leadership and build an ethical framework from individual to collective; C21 | Communicating ethically C2 | |
| Strive for common ground and establish a win-win framework for ethical solutions; C22 | | |
| Interact with society and build a bridge of communication between moral beliefs; C23 | | |
| Build teamwork relationship within the organization; C31 | Establishing a partnership C3 | |
| Establish win-win business relationship with government, community and service object; C32 | | |
| Establish system, form culture, common values and public mission in the organization; D11 | Establishing formal rules D1 | Rule construction stage D |
| The transition of "moral leadership" from informal to procedural and formal form; D12 | | |
| Continue to make moral claims; D21 | Conducting moral defense D2 | |
| Act as guardian, protect the border and maintain the system; D22 | | |

was applied to refine and integrate the initial concepts, which resulted in 11 categories. Third, selective coding was applied. According to the relationship between different categories, four main categories were obtained, which formed the "storyline" of the grounded theoretical model. In the process of coding, the research team was divided into two groups to code independently back-to-back to ensure the reliability and validity of the results. Inconsistencies between groups were discussed to reach a consensus. During this process, if the information was not sufficient or the theoretical logic was not smooth, WeChat, e-mail, telephone, and other methods were used to quickly complete the supplement to revise and improve the research conclusion.

The results of the literature review and coding analysis identified the four stages of progression of the core categories in the emergence of "moral leaders" in public entrepreneurship: concept construction, moral conflict, relationship construction, and rule construction. Moreover, the meaning construction process moves from "following external procedures → wandering at crossroads → self-leading," during which the key driving factors and public entrepreneurship education strategies promote the common growth of individuals and organizations.

## Research findings

### Construction stage of the concept of "moral leader"

In the conception-building stage, social entrepreneurs, from growth to the beginning of their careers, follow external procedures, base their decisions on social conventions, or ignore their own needs to meet perceived expectations (Kegan, 1994) (Table 3). This period is the key stage of establishing moral cognition and receiving education to

TABLE 3 Examples of typical statements and related categories in the stage of concept construction.

| | | |
|---|---|---|
| Building moral awareness A1 | Family environment cultivates personality and enlightens values; A11<br>Acquiring knowledge through school education and determining internal norms; A12 | My parents never expected me to make much money when I grow up. Their biggest expectation for me is to be healthy and happy and do what I want to do. (Li Hui) there is a special name for parents and parents never quarrel. (Li Hui) when I was young, my parents taught me to do good deeds. (Xie Jie) I come from the countryside, and I have a younger brother at home. Because of my family conditions, although I was admitted to key No.1 middle school, I did not go to school. I Wanted to learn technology early to make money, and went to technical secondary school. My younger brother is now a doctor of Zhejiang University. (Xie Jie) |
| Trying self-identity A2 | The key events are mainly self decision-making; A21 The experience of actively choosing to start a business; A22 | My idea has always been that I want to start a business and do it by myself. All my choices from small to large are my own choice, and so are my college entrance examination volunteers. (Li Hui) When I was in high school, I did business with my friends and found something to do. Otherwise, it would be boring. I like Du Lala. She can implement her own ideas and has her own opinions. (Li Hui) I have a strong ability to execute. (Xie Jie) In 2008, the company encountered a bottleneck, so I went to learn English, so that I could not only understand the mold, but also communicate in English. Later, I really found foreign customers, and the business of the company was also developed. (Xie Jie) |
| Generating moral motivation A3 | Be aware of moral differences; A31 Generating compassion; A32 | My parents were on business all the year round, and my grandfather was my companion. My grandfather loved reading and learning during his childhood, but he dropped out of primary school because he was poor. He always cleans himself up like an intellectual. (Li Hui) When I saw the old people selling vegetables, I wanted to help them buy them. I was born with this idea. When I see the old people I can help, I try my best to help them. (Li Hui) I'm a disabled entrepreneur, and I get a lot of help in the process of entrepreneurship, so I donate a certain amount every year, which is to give back to the society. (Xie Jie) Yuyao was flooded in 13 years. Seeing that many enterprises and people were affected by the disaster, I went to the streets to provide disaster relief. Later, I got to know a group of people and set up Ant Public Welfare. Everyone helped others, and I was very happy. (Xie Jie) |

Proposition A1: in the stage of moral concept construction, "moral leaders" follow external procedures, form moral system construction through family environment and special experience, acquire their own knowledge construction through school education and social practice, and promote the process of self-meaning construction through independent concept.
Proposition A2: in the stage of moral construction, moral differences or compassion caused by any event will trigger moral motivation. Moral consciousness is embedded in the existing and systematic institutional contradictions, which provide raw materials for the subsequent meaning construction and are the hotbed for the emergence of moral leaders.

determine internal norms and self. It is also the stage of the germination of moral consciousness and the generation of moral motivation. The comparative analysis of the case data revealed similarities between cases L and X in the initial concept establishment stage. Traditional Chinese families, harmonious family relationships, and good school education make it easier to cultivate the compassion of "moral leaders" and the moral consciousness of doing good for others.

Trying self-identity. Li Hui's parents were busy with business and Xie Jie was the eldest son at home; therefore, both had more space for self-exploration while growing up. Since childhood, they had relatively strong subjective consciousnesses, were more active in doing things, and had strong executive abilities. Li Hui has had a business mind since childhood and liked to earn pocket money from her parents. She started doing business on WeChat when she was in high school. After an industrial injury in 2001, Xie Jie started his own business. When he encountered the bottleneck in 2008, he took the initiative to learn English and began to do foreign trade business. Both leaders showed entrepreneurial initiative. They also showed strong self-realization and a positive outlook on life, actively exploring the external world. However, the family environment and life experiences of Li Hui and Xie Jie differed, which influenced the formation of certain values; thus, their moral decisions were closely related to their futures. Li Hui had a good family background and a strong self-concept since childhood. The character "Du Lala" in the novel is independent, as her example and enlightening tutor, and the key events such as entering a higher school and starting a business are mainly self-decision-making. Because her parents were busy with work, she lived in the countryside when she was a child and was cared for by the old people in the village. Therefore, she has an innate sense of kindness toward old people. The experience of living with her grandfather as a child provided the raw materials for her moral motivation. Xie Jie's family is ordinary, and his younger brother had a heavy financial burden. He gave up the college entrance examinations and went to technical secondary school. At 19 years of age, he became the director of the workshop. However, an accident led to the amputation of his right hand. After that, he started his own business and trained his brother to become a doctor at a famous school (Table 4).

TABLE 4 Examples of typical statements in the stage of moral conflict and related categories.

| Category | Coding | Examples of typical quotations |
|---|---|---|
| Finding a value gap B1 | Conflict of multiple identities; B11<br>Critical event pressure; B12<br>Social entrepreneurship efficacy; B13 | I hesitated at that time. At that time, the business model was not clear and I was not sophisticated. Besides, it costed 30,000 yuan to register, which might be wasted. My family said to give it a try. For them, 30,000 yuan is called tuition. I considered a lot about whether or not to do this and whether it was meaningful. Finally, I thought I should try it. (Li Hui)<br>When I graduated from my senior year, the team left. And you find that when you're alone, other people do not agree with you. Some enterprises offered me a better salary. At that time, I thought about whether I would continue to do it, whether I had such ability and whether I could support the future of these people. (Li Hui)<br>Seeing some successful cases, I felt that public entrepreneurship and social innovation were feasible, which gave me some confidence and made me feel that others can do a good job. Why can't I? This made me put more energy into doing it. (Li Hui)<br>In the process of starting my own business, many people helped me. I wanted to give back and did some good deeds within my ability. Give back to the society and take responsibility. (Xie Jie)<br>Later, I worked with like-minded people to help poor students. For myself, I would be very happy if I could help others. (Xie Jie)<br>Ant Public Welfare, including myself, has won a lot of honors. Some people in the team quarreled for the honor, and others left the team. Because I am disabled, doing public welfare will be typical. Volunteers are all here to do good deeds. Everyone contributes to the public welfare of Yuyao, so the concept of those who stay is more unified. (Xie Jie) |
| Building moral courage B2 | Observation, thinking and external situations trigger moral emotions; B21<br>Moral emotion elevates moral motivation and causes action to resolve; B22<br>Moral courage is associated with a sense of duty to alleviate the suffering of others; B23 | The elderly not only need material support, but also lack spiritual companionship. Since I was a child, I felt very kind to the elderly, so when I finished my homework, I did this project with the theme of serving the elderly. (Li Hui)<br>When I went to the community service, I saw that although many old people had retired, they had many skills. They were healthy, but lonely, and I felt very sad and felt that I needed to do it well. (Li Hui)<br>At that time, there was a flood in Yuyao. I happened to have generators in my factory that were not affected. But when I saw that many residents were trapped, I went to the streets to provide relief to help my hometown. (Xie Jie)<br>At that time, we designed a student aid project to help children from poor families in Yuyao Mountains, and we also paired up with children from Guizhou Province to not only help students, but also help their families out of poverty. We have been working on this project for more than 10 years, and we feel a great sense of achievement. (Xie Jie) |
| Going through a moment of upheaval B3 | Go through a moment of upheaval and build a new understanding; B31<br>Balance is achieved by avoiding and adjusting before experiencing upheaval; B32 | The salary was very small and the work was very hard. Should I continue to do it? Did I have the ability to support the future of these people? These were my biggest consideration at that time. (Li Hui)<br>A teacher reminded me that the people I was most responsible for were those who accompanied me in my career. I should guarantee them, they trusted me, so I should guarantee their basic life. (Li Hui)<br>We (members of the organization) have deep emotional ties. We spend almost all of our work and spare time together. I also realize that I am responsible not only for the elderly, but also for them. They are my motivation to continue. (Li Hui)<br>Our organization began to operate formally in 2014 until 2019. We were short of professionals. We once hired a full-time employee. Later, we found that there were many difficulties, and his salary became my personal payment. Although we are all part-time, we always insist on doing it. (Xie Jie)<br>Ant Public Welfare means that everyone contributes his own strength. Our WeChat group of 100 regular volunteers has a withdrawal mechanism. Every time there is volunteer service, there is always a response. As the organization became more and more famous, I invest more and more time in management. But the satisfaction we feel when we finish a commonweal together cannot be felt in other places. (Xie Jie)<br>At present, I spend more and more time on public welfare, about 50% or 60% of my time. The company is basically managed by the family. It's very busy. (Xie Jie) |

Proposition B1: Stage of moral conflict. Critical event stress, multiple identity conflicts and social entrepreneurship effectiveness are the driving factors of moral leaders' personal meaning construction, which marks the emergence of "crossroads" in personal meaning construction.

Proposition B2: Stage of moral conflict. Moral courage is the "moment of dramatic change" that "moral leaders" go through when they move from "crossroads" to "self-domination," and it is the key contributing factor to the emergence of moral leadership. The higher the moral courage, the more likely it is to take action.

Proposition B3: Stage of moral conflict. Philanthropist practice strengthens the emotional emphasis and connections of "moral leaders," and moral courage is enhanced when personal involvement in an issue is entangled with a sense of responsibility for the sake of others.

Generating moral motivation. From moral awareness to moral motivation, not all problems are experienced morally (Tenbrunsel and Smith Crowe, 2008; Hannah et al., 2011). Any event with certain moral differences will trigger moral motivation. Moral consciousness is embedded in existing and systematic institutional contradictions, which provide raw materials for the subsequent meaning construction and are the hotbed of moral leaders (Seo and Creed, 2002; Wright et al., 2017).

Li Hui's grandfather was eager to learn and accompany, so L later founded the YinChao Pension Service Center, hoping to help the elderly to have a richer and more high-quality life. Xie Jie's original intention in public welfare projects was to give back to society. As a disabled person, he received help from many people around him in the process of entrepreneurship. He also did what he could to give back to society. Especially in Yuyao's 2013 flood, he participated in the disaster relief team, which prompted him to start building a public welfare relief organization. This opportunity for him to set up a public welfare organization was a crisis event. Therefore, the gene of "Ant Public Welfare" is to give priority to the realization of social value. With the enthusiasm of "doing good," it builds a rescue platform as a volunteer to serve society.

### "Crossroads"—stage of moral conflict

When an individual enters the stage of moral conflict, their own purpose and meaning develop and conflict with the external authority, resulting in a tense relationship, between which they need to make a choice (Baxter Magolda, 2001). With the development of the practice of public welfare activities, there are new challenges and dilemmas for "moral leaders," such as personal career choice (Li Hui), turnover of core team members (Li Hui), project implementation (Li Hui), project sustainability (Xie Jie), new platform (Xie Jie), *etc.* The emergence of differences or conflicts means the initiation of meaning generation. In the process of facing the key events, "moral leaders" identify the value gap, generate moral emotions, build moral courage, and finally realize relationship construction. "Moral leaders" first face the conflict of multiple identities and develop moral emotions and conflicts in the practice of public welfare. However, they cannot find a balance point in the relationship; therefore, they need to rebuild the relationship or find a new balance. Second, the key event is stress. Emotion can evaluate the stress event (Crystal and George, 2013) and the meaning construction process will be re-expressed to accept this situation in different ways (Folkman and Moskowitz, 2007). Third, "moral leaders" require entrepreneurial efficacy. For example, in 2017, the "YinChao Pension Service Center" faced organization registration, and L needed to determine whether it was worth investing money and time to continue to support the moral choice. In 2018, L was faced with graduation, while members of the organization were faced with breaking up. For L, on the one hand, it is her own conflict—the choice of career direction, support of physical problems, strong opposition and from parents; on the other hand, it is an assessment of the future of the organization—the project itself and the way out for team members.

The examples of Li Hui and Xie Jie show that the motivation to trigger moral consciousness and change the current situation is not only a simple observation but also abstract thinking. The external situation can also trigger strong moral emotions. "Emotion is an individual's goal, motivation, or concern in response to an important event." For example, sympathy, guilt, shame, pride, disgust, *etc.* these emotions, in turn, make individuals redefine as "wrong" moral problems, which must be solved by action. Moral motivation becomes stronger and individuals are motivated to change the current situation and solve their inner discomfort (Meyerson and Scully, 1995; Creed et al., 2010; Gutierrez et al., 2010; Voronov and Yorks, 2015). For example, when Li Hui saw the lonely old life of "Granny Xue," she wanted to continue her cause for the elderly, establish a public welfare organization concerned about the spiritual life of the elderly, and promote the concept of active pension. When Xie Jie encountered the flood disaster in his hometown, he joined the rescue and later established a public welfare assistance project. Unexpected events stimulated his sense of responsibility to give back to society, and also balanced his internal conflicts.

"Crossroads" refers to the tense relationship between the outside and individuals, who must develop their own beliefs or reconstruct their identities in response (Baxter Magolda, 2001). "Crossroads" is the key period to promote self-leadership during which individuals address the challenges in their growth process and conflict with the construction established in the past. They need to consider multiple perspectives to choose their real inner construction. Under critical pressure events, "moral leaders" begin to seriously consider what kind of people they want to be and what kind of life they want to live. They walk out of the development stage of "following the external program" and enter the "crossroads" to stimulate moral emotions and rebuild self-identity. For example, after Xie Jie was disabled due to work, he gave up the Taiwan-funded enterprises that he originally depended on to survive and took the initiative to start his own business. After receiving help from the outside society, he actively fed back the society. The Yuyao flood in 2013 inspired him to register Ant Public Welfare, while the support of the government and the Bank of Agriculture and Commerce prompted him to join the LeShan Commonwealth College.

Not all people who go through the "crossroads" will achieve self-leading. The "cataclysmic moment" is a critical moment for the emergence of self-leading (Pizzolato, 2003). This kind of experience can promote individuals to seek inner self-definitions to solve the cognition imbalance and establish a new cognition with behavior (Pizzolato, 2005). Self-leading achieves a kind of cognitive balance, which some people achieve by avoiding or compensating (Table 5,6).

TABLE 5 Examples of typical statements and related categories in the stage of relation construction.

| Category | Coding | Examples of typical quotations |
|---|---|---|
| Forming self-dominance C1 | Cognitive dimension, correct understanding of public welfare entrepreneurship; C11 | I do not use very traditional public service methods...Because this cannot achieve the autonomy of development. (L)<br>The meaning of social entrepreneurship itself, namely social value and public value, is what drives us to do this all the time. (L)<br>Seeing some successful cases, I felt that social entrepreneurship and social innovation were feasible, which gave me some confidence and made me feel that others can do well, so can I, which made me put more energy into doing it. (L)<br>Charity, I hope to do it as my career. (X)<br>Two people changed my understanding of public welfare: a radio reporter who taught me that public welfare can be done in the form of self-haematopoiesis, and a teacher from the Red Cross who taught me how to cooperate with the government on projects. (X) |
| | Personal inner dimension, clarifying identity; C12 | But I'm most afraid of becoming a mediocre person. I do not allow myself to be mediocre. I hope to show myself in every corner, field or somewhere. (L)<br>It is rare for a man to come to the world, so he must leave something behind. When he comes, he should do something, whether for himself or for the society. (L)<br>I think I'm still a rational person. I'm not too emotional when dealing with affairs. I have to grow up. As a person in charge, it's not appropriate to be emotional. (L)<br>The first is feelings. I think it's very meaningful. It's in line with my personality and value pursuit. We are doing business, reflecting social responsibility and reflecting the needs of people in society . . . Want to be respected by society and to reflect personal value. It's natural. (X)<br>I am an activist because I have been designing projects before and then implementing them. (X)<br>I spend a lot of time and energy, and I have a certain typicality. Because I am disabled and do public welfare, the radiation will drive more social forces. (X) |
| | Interpersonal dimension, build a framework for moral relationships from individuals to collectives; C13 | They also get their own wages. Private non enterprise units are not allowed to pay dividends, and now we are in common. It's not because I'm in charge that I need to take more. Absolutely not. Because I have been advocating with them all the time that we start our business together. (L)<br>The team is the biggest motivation. they are willing to support you, trust you, accompany you, and willing to follow your footsteps to go forward. (L)<br>Why should hundreds of people listen to you. Why are they willing to spend this time with you? For people who have different purposes to join the team, we pursue the greatest common divisor, a sense of united front. (X) |
| Communicating ethically C2 | Enhance moral leadership and build an ethical framework from individual to collective; C21<br>Strive for common ground and establish a win-win framework for ethical solution; C22<br>Interact with society and build a bridge of communication between moral beliefs; C23 | I've been responsible for the elderly in society, but I'm not responsible for my own team. They work so hard with me. I can't guarantee their basic life and quality of life. If they stay with me for 10 years, can they buy a house? (L)<br>At most, I am a beacon. My own belief is always there, but it should be them who support me. (L)<br>In the process of work, we will even shed tears together and be moved. There is a soft part in everyone's heart. It's interesting to work together in this way. (X)<br>There are no heroic words. We are where we need to be. Well, then a little bit of you and a little bit of me will converge into a great force. No matter who you are. When we do public welfare together, you show your best and most beautiful side to our clients. People are relatively honest. (X) |
| Establishing a partnership C3 | Build teamwork relationship within the organization; C31<br>Establish win-win business relationship with government, community and service object; C32 | We built up a strong bond and ate together on average three times a week. They were my motivation to keep going. (Li Hui)<br>Our projects often participate in bidding and have established good communication with the community and Civil Affairs Bureau. (Li Hui)<br>As a member of the Chinese People's Political Consultative Conference (CPPCC), I pay more attention to public welfare. I have been calling on our public welfare organizations to invest in society and ask for the support of government departments. (Xie Jie)<br>Use exciting and successful activities to rally internal minds and attract external talents. (Xie Jie) |

Proposition C1: In the stage of relationship construction, "moral leader" obtains self leadership from cognitive, internal and interpersonal dimensions, and public entrepreneurship is accompanied by the process of personal meaning construction of "moral leader."

Proposition C2: In the stage of relationship construction, "moral leaders" conduct moral communication, establish cooperative relationship, strive for common position within the internal organization, interact with the society externally, and build a communication bridge of moral beliefs.

TABLE 6 Examples of typical statements and related categories in the stage of rule construction.

| Category | Coding | Examples of typical quotations |
|---|---|---|
| Establishing formal rules D1 | Establish system, form culture, common values and public mission in the organization; D11<br>The transition of "moral leadership" from informal to procedural and formal form; D12 | I'm good at brainwashing myself. Pass on these ideas to them, and they all agree. It's hard to make thousands of yuan now, and the success of enterprises will come back in the future. (Li Hui)<br>We like our logo very much. The logo of YinChao Pension Service Center is very simple. The framework of a nest and a nest is constructed by the two words "YinChao". We often say, "we are family, YinChao family, YinChao youth. We do not use old age as an excuse for old age. (Li Hui)<br>We have a strict management system, the office is separate, like the project team. Now I am mainly engaged in organizational planning and external, less involved in the actual project implementation. (Li Hui)<br>Our concept is "small ants, great public welfare", with personal small power, into a great public welfare. (Xie Jie)<br>We used to employ a full-time staff to manage the financial and reporting projects, but the requirement of this job is too high and there are too few suitable ones. (Xie Jie)<br>At present, I mainly focus on design projects, and gradually hand over the internal management and implementation of the organization to others. (Xie Jie) |
| Conducting moral defense D2 | Continue to make moral claims; D21<br>Act as guardian, protect the border and maintain the system; D22 | Now if someone doubts us again, I'll ask him to check Baidu or tell him with the trophy on the wall. (Li Hui)<br>I often participate in public activities such as speeches and interviews, such as CCTV's "Voice", and maintain a certain exposure rate, and in fact, I also want to convey a kind of value proposition to the society. (Li Hui)<br>Sometimes I feel sad, especially when the bidding fails. Sometimes we suffer losses when competing with enterprises. But the next day, I will lead the team to go on. (Li Hui)<br>In fact, some people value honor, some people will be jealous, there will be a lot of this situation. Try to give the honor to the team and less to the individual. (Xie Jie)<br>We should try our best to seek common ground while reserving differences in the organization, and the personnel in the organization should have a strict advance and retreat mechanism, so that the people who stay in the organization now basically have the same idea. (Xie Jie) |

Proposition D1: In the rule construction stage, moral leaders establish systems within the organization to form an organizational moral system, and the organization transits from informal to procedural and formal forms, which can ensure the maximum support and sustainable maintenance of the established moral framework.
Proposition D2: Rule construction. A new moral framework is institutionalized into a moral system, and moral leadership becomes a focus of influence. They should not only widely express their moral opinions, but also act as "defenders" to protect the boundary and maintain the system.

The first conflict and contradiction Xie Jie encountered at the "crossroads" was the key event pressure. Multiple identity conflicts and self-efficacy of public entrepreneurship continued to appear in the process of entrepreneurship. For example, Xie Jie had a main business, and public welfare activities required half of his working time. How to balance them? The revenue and expenditure of "Ant Public Welfare" were not stable and it was unable to operate as an enterprise; how, then, to develop it sustainably? A kind of moral motivation urges "moral leaders" to adhere to special action tendencies even in the face of risk, opposition, and fear (Hannah et al., 2011). This is a tendency of action, which means that over time, people may change or may act as an interlude in the process, showing a lack of courage, or they may establish moral triggers in the individual and organizational environments. With increasing participation, moral courage will be entangled with the sense of responsibility to alleviate the suffering of others. Research shows that individuals are more likely to commit to an altruistic initiative. While personal pain may only be tolerated, the pain of others brings feelings of guilt. Individuals may choose to maintain their own moral standards to get rid of the guilt (Cormack, 2002; Bastian et al., 2011; Inbar, et al., 2013). The courage to take responsibility and think for others can enhance a person's positive self-image (Cormack, 2002; Oliner, 2003). When moral courage, moral motivation, and a sense of responsibility are established, others will follow and improve to a higher level of moral organization operation in an interactive process. The interaction with followers will also strengthen the determination of "moral leaders" to change the existing framework to resonate with followers, challenge the original framework, face risks together, share experiences, strengthen the courage of moral leadership, and avoid disappointing followers. While starting a business, Li Hui has repeatedly stressed that the team's partners are her driving force, in addition to her responsibility to the elderly and the team as the person in charge (Table 7). After the establishment of the organization, the strength of the

TABLE 7 Examples of typical statements regarding the roles of public welfare entrepreneurship education in different stages of meaning construction.

| Meaning construction stage | Educational role | Examples of typical quotations |
|---|---|---|
| Conceptual construction stage | Exciter, organizer | As a student, I did not think much about it at that time. I just did whatever the teacher asked me to do. I just took it into consideration and spent more time to do something. (Li Hui)<br>At the beginning, I did not feel much about the project book. Later, I began to do community service and participate in various competitions. I gradually realized that social entrepreneurship is such a thing, which also overturned many of my original ideas. (Li Hui)<br>During the operation of my project, I was greatly influenced by two people. One was a TV reporter, who made me realize that public welfare can be done as a cause, and the other was the president of the Red Cross Society, who taught me how to deal with the government and how to write project documents. (X) |
| Moral conflict stage | Motivator, promoter | When I first started competing, I could not do it either. Everyone did not agree with me. Later, my teacher and I modified the project a little bit and carried it over. (Li Hui)<br>The meaning of social entrepreneurship itself has pushed me to stick to it. I have come into contact with so many public welfare people. I think this can be done, which can satisfy my own feelings and realize some economic value. (Li Hui)<br>The state of being truly happy<br>In addition to difficulties and hardships, there will be affirmation. In fact, in the process, he also gets feedback and exercises his ability. (Xie Jie)<br>When you've made a name for yourself in the industry, some caring people will come to you, and the public will push you forward. (Xie Jie) |
| Relationship building stage | Consultant and guide | When I was in college, I participated in various competitions with project books. I put my practice on the stage and received guidance from various experts. I found the original idea was a little naive, so I gradually corrected it to make the project better and linked a lot of resources. (Li Hui)<br>Seeing some successful cases, I felt that social entrepreneurship and social innovation were feasible, which gave me some confidence and made me feel that others could do well. Why can't I do it? So I put more energy into it. (Li Hui)<br>Sometimes when I meet difficulties, I think I have so many experts and teachers behind me to support me. We often meet and chat with each other, which inspires me a lot. (Li Hui)<br>Lin Hong, from the TV station, has influenced me deeply about the public welfare cause. We should not do what we should do. We should make it meaningful. Not to put on a show. (Xie Jie)<br>Because of some things we have done, we have become a local celebrity. The government and enterprises support our work very much and help us a lot. (Xie Jie) |
| Rule construction stage | | Now I mainly focus on organizing and planning, and linking external resources. I often participate in some public events and lectures, *etc.* Public welfare projects are different, so I need to constantly convey my ideas to others, because this is a kind of innovation, and acceptance takes a process. (Li Hui)<br>We set up the LeShan Institute to extend the concept of Ant Philanthropy to the public welfare undertakings in Yuyao. There is such an ecosystem where more like-minded people can innovate in different ways to promote the development of public welfare undertakings. (Xie Jie) |

Proposition E1: meaning construction. Different stages of social entrepreneurship education have different functional strategies. The concept construction stage is the exciter and the organizer of educational activities, and the moral conflict stage is the motivator and the promoter, which promotes the self-dominated completion. The relationship building stage and the rule building stage are consultants and guides, cultivating new public welfare organizations and moral leaders to maintain the moral framework.

organization also bolsters Xie Jie's moral courage and X also invests more time in public welfare.

## The construction stage of the "moral leader" relationship

"Moral leaders" go through the crossroad and enter the relationship-building stage, in which their experiences and abilities improve and they are self-dominant and critically self-reflective. This is the moral development stage of "moral leaders" and the formation stage of "self-dominant." Self-leading calls for "moral leaders" to "get rid of external influence, build knowledgeability, build internal identity and effectively participate in social relations" (Baxter Magolda, 1999). Usually, three dimensions; namely, epistemological, individual inner, and interpersonal dimensions, are used to judge the formation of self-dominance, which is the goal of personal meaning construction (Kegan, 1994). The cognitive dimension refers to people's understanding of the essence of knowledge. The cognitive maturity required for decision-making by integrating different information needs a self-dominated belief system (Baxter Magolda, 2004) Table 8. In the dimension of epistemology, "moral leaders" truly realize the innovation,

TABLE 8 Comparative analysis of the case objects.

| Contrastive analysis | | Moral leaders | |
|---|---|---|---|
| | | YinChao pension service center Li Hui | Ant public welfare xie Jie |
| Conceptual construction stage | Typical characteristic | Superior environment, self-definition can fully express | Family constraints. Balancing strategies in self-definition |
| | Social entrepreneurship education | L began to accept course learning, community practice and competition polishing | nothing |
| Moral conflict stage | Typical characteristic | From the perspective of self-realization, experiencing the moment of upheaval, realizing self-dominance and realizing the dual value model of organization | From the perspective of giving back to society. Find inner balance after going through a critical event. Follow the traditional model |
| | Social entrepreneurship education | L continued to be encouraged to participate in project practice and link to platform resources, so as to gain moral emotional reinforcement | nothing |
| Relationship building stage | Typical characteristic | Business value and social value are realized, personal morality is transformed into organizational morality, and organizational sustainable development has great potential | Realization of social value. Personal morality as the core of the organization<br>Relatively loosely organized<br>Transferring to other platforms to deliver personal moral systems |
| | Social entrepreneurship education | Help her to participate in all kinds of professional platform communication, using high-level thinking to analyze, integrate and innovate | To build awareness of social entrepreneurship, re-examine public welfare organizations, and face organizational reform |
| Rule construction stage | Typical characteristic | Focusing on the establishment of organizational system and long-term planning and development<br>Institutionalized internal management systems and symbolic spiritual constructs<br>Establishing a system of self-hematopoietic tissue | It is operated by project and mainly managed by the volunteer team. Rely on the appeal of personal morality. At present, there are no full-time staff, and its operation mode is between civilian and volunteer organizations |
| | Social entrepreneurship education | Companionship and support. Discuss learning partnerships together | Give play to his personal moral influence. Encourage and support him in the new platform to establish and maintain organizational ethics |

Proposition F1: Systematic social entrepreneurship education in colleges and universities is helpful to trigger college students to explore their personal meaning, thus generating moral courage to engage in social entrepreneurship. In addition, systematic theoretical training and simulation practice can help "moral leaders" establish public welfare organizations and maintain their ethical system continuously.

dual value, and future prospects of public entrepreneurship, and form a self dominated cognitive system. When Li Hui was in university, she learned the theoretical knowledge of public entrepreneurship. Through her participation in competitions and community services, she clarified the understanding of the value of public entrepreneurship and evaluated the feasibility of the cause by linking resources. Xie Jie's public welfare activities began with volunteer activities. Through contact with social public welfare platforms, governments, and professionals, Xie Jie gradually understood public welfare entrepreneurship.

The internal dimension of individuals is the use of cognition to construct beliefs and identities (Abes et al., 2007). Self-dominated people determine lasting values through reflection and build stable identities, which are not affected by external expectations. In the internal dimension of individuals, "moral leaders" clarify identity, the leaders of public welfare organizations, the participants of social problems, and the leaders of innovative problem-solving frameworks. Li Hui has a strong sense of self-leadership. After engaging in public welfare entrepreneurship, her sense of self-efficacy has also enhanced its confidence. Moreover, her entrepreneurial mindset enables her to rationally evaluate the feasibility of public welfare projects. In the practice of public welfare, Xie Jie found a sense of harmony that reflected his own values and used his previous experience in business entrepreneurship to execute projects and lead a team.

The interpersonal dimension is the ability to live in harmony with oneself, others, and other social relationships (Kegan, 1994). Regarding the interpersonal dimension, "moral leaders" promote moral leadership and build the framework of moral relationships from the individual to the collective. "Moral leaders" begin to build teams as social entrepreneurs and accumulate social network connections in the process of building personal meaning. "Moral leaders" adjust their beliefs and other people's moral concepts

according to the substantial moral foundation. Combining the views of different followers, they strive for preliminary common positions and establish a new moral solution as a common definition of "collective moral framework." Moral leaders must successfully bridge their own moral beliefs with those of others, which depends on their communication and persuasion skills and how they interact with society.

The moral foundation of Ant Public Welfare is that "little ants are the great energy of public welfare." Everyone contributes a little to become a collective great energy and make a great cause of public welfare. The volunteers who participate in the project have different intentions and purposes, and there will be contradictions and conflicts such as the distribution of personal honor, the embodiment of team value, etc. While Xie Jie constantly emphasizes the concept and value of the team, he also seeks common ground while setting aside differences to maximize support. Common experiences are another way to build links.

We find it difficult to build a strong enough following system with a single and self-frame. They will accommodate part of the framework into their own framework or present a more abstract framework (Gray et al., 2015). This creative fusion and pre-existing meaning become part of the attractive overall framework, creating a win-win situation. The new moral framework is not only worthy of the support of followers but also widely spread by followers. For example, in the initial stage of designing "YinChao caring for the old," Li Hui proposed to actively provide for the aged, promote the value, and provide an employment platform for the elderly. After integrating the framework including the needs for living, learning, and dignity, such as the transformation of the environment suitable for the elderly and YinChao University for the elderly, Li Hui upgraded the concept of "YinChao caring for the old" to "YinChao future." Caring for the old is positive; however, our common yearning for the elderly life may attract more social forces and partners to join in old-age care. However, the new framework also has the risk of being considered a compromise. If it is loosely coupled in daily practice, it lacks behavior integrity and moral consistency in people's eyes, thus challenging the moral authority of leaders and maintaining the moral framework (Ramus et al., 2017). For example, although "Ant Public Welfare" was founded in 2015, its organizational form has been relatively loose. It is mainly based on project operation and volunteer management and has not formed an enterprise-oriented management system and organizational form. Therefore, it still lacks full-time staff and the flow of volunteers is relatively large.

## Rule construction stage of "moral leaders"

The solidification stage of the new moral framework of "moral leader" involves reaching an agreed vision, establishing an organizational system, forming an organizational culture, sharing common values and public missions, and providing sustainable development. This stage is the construction of the moral framework of the "moral leader" from the individual to the collective. Emerging moral leaders need to continue to express, embody and symbolize shared values as a new moral framework, actively weaving invisible "moral structures." Followers can identify, relate, and then form experiences and behaviors in themselves to interact with others.

In addition to building a vision within the organization, establishing an organizational system, forming an organizational culture, and recruiting talents suitable for the characteristics of the organization, Li Hui also extensively participates in various influential public activities, such as CCTV's "Voice" program, and also participates in the evaluation of the Forbes youth list and lectures and forums within universities and community organizations to establish contacts and resonate through a wider range of social discourse. For example, in terms of organizational vision, Li Hui conveys sustainable and social values and opens a window for elderly life services in an aging society, thus showing huge market potential. It also widely accepts the emerging moral framework for the government and society and is willing to invest resources. In the construction of organizational culture, the YinChao Pension Service Center uses a unified logo and slogan to emphasize its significance. In the construction of Ant Public Welfare, Xie Jie has not yet formed a sustainable enterprise operation; however, the expansion of its moral framework is more reflected in its connection with government, foundation, and other resources. Yuyao Leshan Public Welfare Class is an upgrade on the original public welfare framework, training public welfare talents in the Yuyao area and forming a public welfare ecosystem. It is an extension of his moral framework to gain more followers.

Change leadership also eventually becomes traditional and rationalized, which means that moral leadership also transitions from informal to more procedural and formalized forms (DeRue and Ashford, 2010). Leaders and followers in the organization work together on formalization, rule-making, incentive schemes, *etc.* (Smith-Crowe et al., 2015). For example, the "YinChao Pension Service Center" specialized the office as an independent department responsible for internal system formulation, personnel assessment, *etc.* This allowed the organization to reduce unnecessary burdens and focus on self-development and running the business. Without institutionalization or formalization, it is difficult to ensure that members of an organization maintain the same level of moral awareness; thus, they may lose interest or invest less time.

Moral leadership can be defined as a process in which a person becomes a focus of influence. After a new moral framework is established and institutionalized into a moral system, "moral leadership" acts as a guardian, maintaining the boundaries around the moral system (Maak and Pless, 2006). The purpose is to ensure the integrity of its newly established moral framework and the stable moral identity of a group. The

framework will still be unstable, requiring moral leadership for intermittent behaviors; otherwise, the moral system may erode due to followers' selfishness and other manifestations of motivation. When the system is in danger, moral leadership must serve as a beacon of recognition that allows followers to continue to pledge their own shared values and existing moral systems. At the same time, moral leaders must also strike a balance between development and maintaining control. Whether they keep in mind moral values and forget to build relationships, or they are too easily swayed by current developments and not sufficiently rooted in moral beliefs, both can affect the development of moral systems. Moral leaders protect and maintain the newly established moral framework and support others' voluntary participation in the moral system to develop and articulate their own subjective experiences and actions. Moral systems are not tools for propaganda or persuasion but rather are used by followers as a medium for personal moral development. Thus, a moral leader must act as a manager of the character development process, engaging in a fair exchange of values with others, and sometimes as a "guardian" willing to maintain the boundaries of the moral system after interacting with others. This self-perpetuation is a key feature of the institutionalization of moral systems and has always been rooted in the interactions between leaders and followers.

## The function and strategy of public entrepreneurship education

Both cases in this study received social entrepreneurship education. Effective social entrepreneurship education can influence the attitude and behavior of "moral leaders," toward a strong desire for social entrepreneurship and the ability to act. Combined with the process of constructing personal meaning and from the perspective of cultivating "moral leaders," we discuss the role of social entrepreneurship education for college students for each stage of the generation of "moral leaders" and what strategies to adopt for further discussion.

In the conceptual construction stage, the behavioral strategies of educators are organizers and motivators, helping leaders to create organizations and obtain innovative solutions, providing cases to follow, and committing themselves to innovative solutions to various social problems. In the concept-building stage, Li Hui was exposed to the concept of social entrepreneurship in courses after entering college. She wrote the first project book on social entrepreneurship through course assignments and formed the initial team for the "YinChao Pension Service Center" project. At that time, the goal of social entrepreneurship was not clear. At the very beginning of her participation in social entrepreneurship, she was also passively required to complete her homework. Her moral awareness at a young age provided a fertile ground for her project direction. The social entrepreneurship education curriculum of the school provided a good entrepreneurial knowledge system, which made her design of the initial project double-oriented with commercial and social values, and enabled her to see the long-term development. In the process of knowledge construction, Li Hui also participated in various competitions and projects. "We must practice." Li Hui's practice was a crucial step for her to understand public welfare and develop moral awareness. The entrepreneurship competitions provided a platform for her to open her mind and broaden her resources. Thus, the construction of identity was closely related to the belief constructed by knowledge (Abes et al., 2007).

In contrast, Xie Jie was exposed to social entrepreneurship education in the relationship-building stage. Xie Jie first implemented the project with a volunteer team and registered a private non-enterprise organization with the support of the government and foundations. He learned about social entrepreneurship mainly from social resources such as the Red Cross and news media, and then systematically learned more after receiving training in a public welfare talent class. It has been said that practice precedes theory. His organization, which is oriented toward the realization of social values, is having difficulties in hiring full-time staff and advancing as an enterprise.

At the stage of moral conflict at the crossroads, educators become the motivators, facilitators, and external positive forces of "moral leaders" to complete their self-dominance. Students gradually develop an identity. On the one hand, they can learn from typical characters and imitate their identities to become social entrepreneurs with a sense of social responsibility and innovative ability. On the other hand, e can provide students with opportunities to practice social entrepreneurship. When ethical leaders engage in concrete, vivid social entrepreneurship practices, their underlying abilities are demonstrated, and their identity is strengthened. In the early stage of practice, students may be provided service work or simple public welfare projects, while the commercial link is relatively diluted. This is like the model of "service learning," which can help students understand the content of the course, improve their reflective cognitive ability, and strengthen their moral awareness. In the process of practice, "moral leaders" strengthen their identity, deepen their emotional involvement, invest time and experience, elevate their moral emotions to moral motivation, and further establish a strong will to solve social problems by participating in social entrepreneurship activities.

"Moral leaders" reconstruct social networks and acquire entrepreneurial ability through behavioral investments. With the deepening of practice, "moral leaders" begin to engage in moral input, including behavioral, cognitive, and emotional inputs. For example, Li Hui linked to various platforms and resources such as the government and foundations while participating in a public welfare competition. From the initiator of "Ant Public Welfare" to the secretary general of

"Leshan Foundation," Xie Jie has gradually changed his perception of public welfare during his public welfare practice. The organization and individuals have grown through this relationship reconstruction. "Moral leaders" gain a clearer self-awareness through emotional engagement, take public welfare as a cause, aim to be a public welfare entrepreneur, and experience the emotional changes in the early stages of entrepreneurship. For example, Li Hui gets confidence from the organization and feels frustrated when team members leave. When confronted with conflicting opinions within the organization and criticism of himself, Xie Jie seeks common ground while shelving differences, with negative and positive emotions mixed in the process, while also recognizing the spirit of social entrepreneurship.

The relationship-building and rule-building stages really enter the practice stage of social entrepreneurship, in which educators play roles as consultants and guides rather than authorities (Mezirow, 1997). "Moral leaders" take on the challenge of higher-order thinking in the entrepreneurial process to analyze, integrate, apply, evaluate and innovate, and develop new ideas to solve challenges. The most effective way to progress is to participate in various social entrepreneurship competitions.

Public welfare educators at this stage are like the team mechanism or mentor-led project forms of public interest institutes, which enable the mutual circulation of public interest resources within the platform. Social entrepreneurs and educators are more like collaborators and coaches. The teachers primarily act as mentors and positive role models, while university administrators and staff are seen as helpful supporters who perceive positive moral values and role models. In this stage, educators of these two stages mainly play the role of partners, discussing learning together and helping to link resources.

## Cross-case comparative analysis of the impact of public entrepreneurship education on "moral leaders"

The case objects in this study were college students who had received higher education. However, due to different growth environments, stages of receiving social entrepreneurship education, and environments for implementing social entrepreneurship, the students differed greatly. Before setting up the organization, Li Hui had received education on systematic theories and practices of social entrepreneurship, including course assignments, community practice, competitions on social entrepreneurship (registration and landing), and expert team guidance. She started social entrepreneurship in her junior year and set the dual goals of realizing business and social values at the very beginning of the organization. Xie Jie participated in volunteer service in the community after practicing business entrepreneurship before establishing an organization. He later received social entrepreneurship education, which was a process of exploring while practicing. His theoretical learning occurred in stages, including voluntary service, government recognition (registration and implementation), LeShan Charity Institute, expert guidance, *etc.* Therefore, the gene of Ant Public Welfare is a voluntary organization derived from voluntary service and charity activities. The organization was initially set with the priority of social values and had strong government guidance.

Among the four stages of constructing personal meaning, we further compared the impact of social entrepreneurship education on the construction of personal meaning for these "moral leaders." We found that the two "moral leaders" had the same experiences in establishing moral cognition and trying to define themselves in the concept construction stage. Li Hui grew up in a relatively superior environment and had greater autonomy to realize the path of self-definition. Xie Jie, restricted by his family environment, adopted a balanced strategy at the beginning. However, both had the same moral motivation for feeling empathy in critical situations. Li Hui received entrepreneurship education, as the organizer and excitation in her university stage provided the theory courses. In addition, she performed simulation projects in the community, which provided front-line practice opportunities and basic market data at a low cost. She also participated in public interest competitions, practiced expert projects, and learned about public welfare on a high platform, thus building a sound entrepreneurial knowledge system and social entrepreneurship concept. Although social entrepreneurship is a zero-to-one process, often starting from scratch, the low cost of theoretical and practical input provides a solid foundation for building a start-up organization and a good window for individuals and teams to build connections. In contrast, Xie Jie was driven by a moral motivation to establish a public welfare organization; however, his understanding of the concept of social entrepreneurship was limited. At the beginning of its establishment, the organization was entirely a volunteer activity that mainly relied on the government to support its operating costs. Such organizational genes are greatly uncertain as to whether they can be put into market operation as social entrepreneurship organizations in the future.

At the stage of moral conflict at the crossroads, the two "moral leaders" were conflicted by multiple identities. As a motivator and enabler, social entrepreneurship education serves as a mentor on the path of social entrepreneurs and continues to strengthen the realization of the higher personal meaning of "moral leaders" to promote moments of upheaval. Li Hui came to a crossroads when disbanding her team, experiencing health problems, and the lure of other perks. This phase emphasizes "moral leader" in the practice of the public and should establish and strengthen the sense of moral emotions such as responsibility and self-efficacy. At the same time, they should continue to provide high-quality professional materials in the field of social

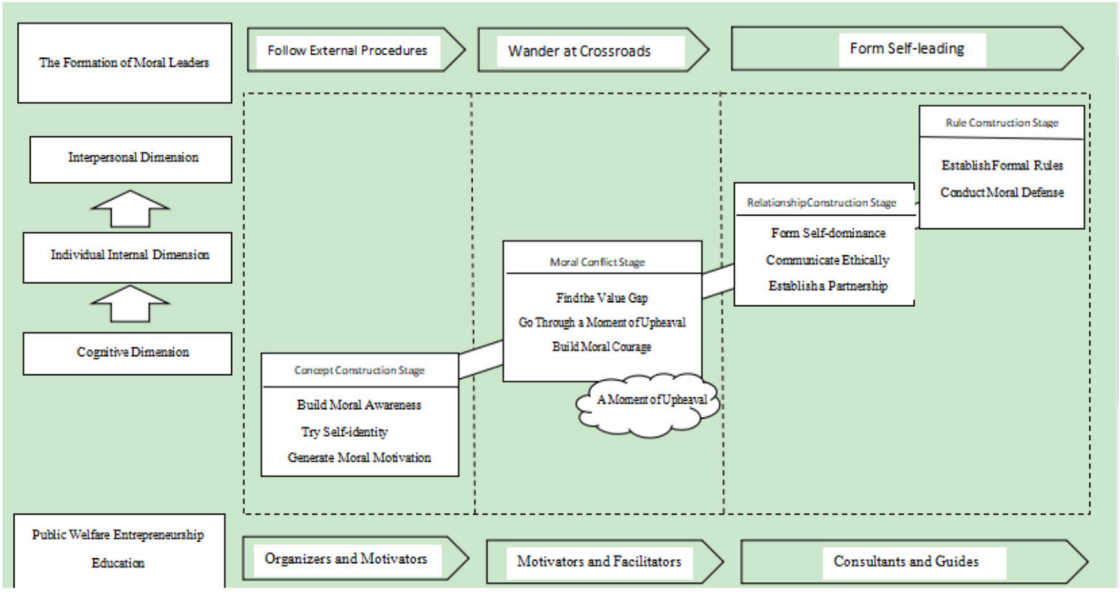


FIGURE 1
"Moral leader" development model based on personal meaning.

entrepreneurship and creative solutions to social problems and the link of personal meaning realization, thus eventually forming a firm inner moral system and complete self-guidance. In contrast, Xie Jie established a public welfare organization mainly from the perspective of rewarding society. When public welfare projects conflicted with work and family, Xie Jie mainly adopted the traditional model, which required negotiation with family members and even funding the public welfare projects with his own salary. He was exhausted as he tried to balance his work with public welfare projects. Moreover, the participants of the volunteer projects came from complex sources with different goals and they eventually left the team because of the unfair distribution of personal honors. From the perspective of social entrepreneurship, X has not established an effective organizational ethics system but is seeking balance.

In the relationship-building stage, "moral leaders" continuously communicate with themselves, the organization, and the society morally to establish cooperative relationships. Li Hui set the goal of the enterprise operation of the "YinChao Pension Service Center" to establish customer relationships with the government and service objects, constantly output moral beliefs, and innovate project models to allow for a greater development space for the organization. Li Hui has also started to run a public welfare organization independently, using high-level thinking to analyze, integrate, and innovate. At this stage, social entrepreneurship education is just a relationship between cooperation and coaching, a teacher to answer questions and doubts, and a gas station for career promotion. However, for Xie Jie, it was during the relationship-building stage that he really became familiar with social entrepreneurship. Previously, "Ant Public Welfare" was largely dependent on government funding and had good social benefits. It focused on establishing relationships between the government and the media and was managed loosely by volunteers. As a "moral leader," Xie Jie could not complete the transition from "personal ethics" to "organizational ethics" in "Ant Public Welfare." It was not until he joined the larger public welfare platform "LeShan Charity Foundation" that he had the platform to continue to give play to his moral beliefs and participate in social public welfare innovation.

In the rule construction stage, "moral leaders" exert moral leadership within the organization; however, the internal construction of public interest organizations may differ. Li Hui continues to dig deep into the operational mechanism of public welfare organizations. The YinChao Pension Service Center focuses on establishing an organizational system and long-term planning and development toward a consistent moral identity, institutionalized internal management system, and symbolic spiritual constructs within the organization. With nearly 20 full-time employees, it has completed the transformation from personal to organizational ethics and has established a self-hematopoietic organizational system. Currently, the educator is a partner and companion, and Li Hui is fully capable of independently carrying out social

entrepreneurship. She gradually became an expert in this field, expressing her views on various platforms, and guiding and influencing other people in the same industry. In contrast, Xie Jie's "Ant Public Welfare" is run as a project, mainly relying on the management of volunteer teams and project design and implementation, while the "moral leader" relies more on the appeal of personal morality. At present, "Ant Public Welfare" has no full-time staff and its operation mode is between non-government and volunteer organizations; thus, its development has encountered serious bottlenecks. Although Xie Jie has become the head of another public welfare organization, Ant Charity faces many difficulties and a bumpy road ahead.

# Conclusion

From the theoretical perspective of constructing personal meaning, through field interviews and relevant data collection of the founders and organizations of two public welfare organizations, this studies applied grounded theory to conduct a double-case study to explain the process of the emergence of "moral leaders," reveal the internal relationship and mechanism between moral leaders and public welfare organizations, and discuss the role and strategy of social entrepreneurship education at various stages.

The results showed that the development of a "moral leader" can be divided into four stages, namely, concept construction, moral conflict, relationship construction, and rule construction. In the first stage, the "moral leader" follows the external program, which is the process of an individual acquiring knowledge, defining self, and generating moral motivation to realize the concept construction as a theorist. Second, when "moral leaders" are at a crossroads, they find the value gap at the individual level, build moral courage, and experience a moment of drastic change. This is also the stage of conflict at the individual level. The final stage involves the construction of self-leadership and rules. Externally consistent modes or forms of self-leading, as well as cooperative relationships, are established in this stage, in addition to conducting moral communication and formalization and institutionalization within the organization. "Moral leaders" as practitioners establish formal rules at the organizational level, carry out moral maintenance, achieve individual leadership of the cognitive, individual internal, and interpersonal dimensions, develop "personal morality" into "organizational morality," and become "moral leaders" in the organization. This study also discussed the functions and educational strategies of public entrepreneurship education in the context of the four stages of "moral leader" development (concept construction, moral conflict, relationship construction, and rule construction), public entrepreneurship education takes on the roles of motivator, inspiration, consultant, and guide, respectively, to promote awareness of public welfare by the "moral leader" and put it into action. The results of the above analysis informed our development of a "moral leader development model based on personal meaning," as shown in Figure 1.

## Theoretical contribution

Through the systematic analysis of the stages and elements of "moral leader" personal meaning construction, this study focuses on the process of "moral leader" development to reveal the process of "moral leader" personal growth to organizational transition. Specifically, this study 1) explains the driving and strategic factors in the process of constructing the personal meaning of "moral leaders." In the process of public welfare entrepreneurship, finding the value gap, building moral courage, and experiencing a "cataclysmic moment" coincide with the view of Pizzolato (2005) that self-leadership needs to experience a "cataclysmic moment," and is also the key stage in the emergence of "moral leaders." 2) This study explains the process of developing a "moral leader" from personal growth to organizational moral transition and from the three dimensions of self-leading and moral communication, to the establishment of formal rules and moral maintenance, which theoretically extends research on the relationship between "moral leader" from individual to organization. 3) Finally, this study explains the role and function of social entrepreneurship education in the process of constructing the personal meaning of "moral leaders" and elucidates the mechanism by which the education process affects students' ethical concepts and entrepreneurial ability. Thus, the multi-dimensional identity model provides examples of the construction of personal meaning in "moral leaders".

## Practical contribution

In addition to its theoretical contributions, this study also has significance as a reference for the personal growth of public entrepreneurs, the start-up of public organizations, and the practice of public entrepreneurship education. This article 1) provides a learning path for the self-exploration of personal growth, especially stimulating the self-realization of exploring inner meaning. Social entrepreneurship serves as a path for reference and choice. Thus, social entrepreneurship education, as a learning course to explore such meaning in college, can help individuals establish a good internal "moral system." 2) This article also addresses how social entrepreneurs can play the role of "moral leaders" in new public welfare organizations, how to develop personal ethics into organizational ethics, and how social entrepreneurs can become the driving force of social practice and innovation to help new public welfare organizations find a foothold in the market and enter sustainable development. 3) Finally, this article provides theoretical basis and method reference for the practice of social entrepreneurship education, proposes the content and method of education from the perspective of constructing personal meaning, and effectively improves the connotation and effects of social entrepreneurship education.

## Future research directions

This study can be further explored as follows: 1) Start-up social entrepreneurship projects can continue to be selected as samples to demonstrate the interaction mechanism between "moral leaders" and organizations. 2) A dynamic follow-up study can be performed on the cases to further study the deepening factors of the interaction between "moral leaders" and the organization and the interaction between "moral leaders" and the organization after the social entrepreneurship project enters the development period. 3) Further exploration of the educational strategies, analysis of the factors related to strategies, and exploration of effective paths for the growth of "moral leaders" could also be performed.

## Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and institutional requirements.

## Author contributions

SZ and JL wrote the original draft. JL supervised and reviewed the manuscript. HZ and ML collected and analyzed data.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Industrial structure optimization, population agglomeration, and carbon emissions—Empirical evidence from 30 provinces in China

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The sustainability of the ecological environment has been greatly threatened. Based on carbon emissions and combined with the panel data of 30 provinces in China from 2003 to 2020, this paper studied the various mechanisms of industrial structure optimization and population agglomeration on carbon emissions. The fixed effect model, panel threshold model and spatial spillover model are used to study the direct and indirect effects of industrial structure optimization and population agglomeration on carbon emissions, and the robustness of the results is tested in various ways. In terms of direct effects, the industrial structure optimization has a significant negative effect on carbon emissions, and the significance level is 1%. Population agglomeration has a significant positive effect on carbon emissions, with a significance level of 1%. In terms of indirect effects, 1) by adding the cross term of industrial structure optimization and population agglomeration, it is proved that population agglomeration can promote the carbon emission reduction effect of industrial structure optimization. 2) Population agglomeration was used as the threshold variable to verify the interval effect of industrial structure optimization on carbon emission reduction. The results show that the industrial structure optimization has a double threshold effect of population agglomeration on carbon emissions, and the threshold values are 2.1137 and 5.9263, respectively. And the larger the population agglomeration interval, the weaker the inhibition effect of industrial structure optimization on carbon emissions. 3) The industrial structure optimization, population agglomeration and carbon emissions have significant spatial spillover effects. The industrial structure optimization in neighboring areas has a significant inhibitory effect on carbon emissions, and the population agglomeration in neighboring areas has a significant promoting effect on carbon emissions.

KEYWORDS

**industrial structure optimization, province, mechanism, population agglomeration, carbon emissions**

# 1 Introduction

To address climate change and achieve carbon neutrality is a global trend and the call of The Times. It bears on the future survival and development of mankind. In 2020, energy-related carbon dioxide emissions accounted for about 87% of the total global carbon dioxide emissions (UNEP, 2021), and fossil energy combustion was the main source of global carbon dioxide emissions. Accelerating energy transformation and reducing energy consumption intensity are necessary measures to reduce carbon emissions and achieve the goal of "zero carbon" (ECIU, 2021). Industrial structure optimization is the fundamental way to reduce carbon emission. Carbon emissions mainly come from the massive use of fossil energy such as coal, oil and natural gas, which can cause desertification, greenhouse effect and global climate change. The rapid development of industrialization has a high demand for various energy sources, resulting in an increase in carbon emissions. As far as China's current post-industrialization development stage is concerned, the proportion of the secondary industry shows an obvious downward trend, replaced by the rapid development of the tertiary industry, which reflects the country's industrial structure gradually tends to be advanced and rationalization (Huang and Li, 2017). In contrast, the tertiary industry has a weak dependence on energy, which can greatly reduce the total consumption and consumption intensity of fossil energy caused by China's industrial development. This is also a realistic way for China to promote the development of low-carbon economy through structural adjustment and mode transformation (Zhao et al., 2022). However, the rapid development of the tertiary industry is often accompanied by a large number of population agglomeration (Yang, 2018). Take China as an example, more and more people are moving to large and medium-sized cities with higher tertiary industry development level, and some first-tier and second-tier cities have very rapid population growth. This is because the development of the tertiary industry is more dependent on population agglomeration than the manufacturing and agricultural sectors (Duranton and Puga, 2020). On the one hand, compared with the manufacturing industry, most of the products of the tertiary industry are non-tradable and conform to the production and sale model. Enterprises and consumers need close interaction. On the other hand, tertiary industry products have higher income elasticity (Ngai and Pissarides, 2007) and attract population. The unreasonable population density will lead to the increase of carbon emission and the structural imbalance of regional carbon emission (Sun et al., 2013; He et al., 2019). This conclusion has been confirmed by a large number of scholars. However, some scholars hold the opposite view, believing that population agglomeration has positive external effects and can improve economies of scale in the use of resources and energy (Edward and Matthew, 2009). In this case, the effect of simply relying on industrial structure optimization to promote carbon emission reduction could be complex and uncertain, and the effect of industrial structure optimization accompanied by population agglomeration on carbon emission needs to be further verified.

Accordingly, this paper aims to construct a theoretical analysis framework for industrial structure optimization, population agglomeration and carbon emission. And explore the following questions: 1) Under the coexistence of regional industrial structure optimization and population agglomeration, what are the direct action mechanisms of the two factors on regional carbon emissions? 2) What is the non-linear mechanism of regional carbon emission under the interaction of industrial structure optimization and population agglomeration? Is there an interval effect with the population agglomeration scale as the threshold? 3) Do industrial structure optimization, population agglomeration and carbon emissions have spatial spillover effects? What is the effect? In order to answer the above questions, based on the panel data of 30 provincial-level regions in China from 2003 to 2020, this paper comprehensively verifies the direct and indirect mechanisms of industrial structure optimization and population agglomeration on carbon emissions by using OLS estimation, intra-group interval estimation (fixed effect model), panel threshold effect model and spatial econometric model. It provides ideas for national and local governments to formulate reasonable industrial structure adjustment policies, population mobility and supporting policies in order to promote carbon emission reduction and achieve the goal of "carbon peak". Therefore, the adjustment and industrial structure optimization to reduce carbon emissions, promote high-quality economic development and regional coordinated development has been widely concerned by the government and academia.

# 2 Literature review

The industrial structure optimization not only reflects the advanced development of economic development of a country or region (Fu, 2010; Gan et al., 2011), but also brings important impact on the ecological environment of a country or region (Chang, 2015; Li, 2021). For more than a decade, the adjustment and industrial structure optimization to reduce carbon emissions, promote high-quality economic development and regional coordinated development has been widely concerned by the governments around the world and academia. Kaya's identity proves that the upgrading of industrial structure is the fundamental driving force for the low-carbon development of industrial system. Reducing the energy use intensity and carbon emissions of the industry is conducive to the realization of low-carbon development of the industry (Sheinbaum and Belizza, 2010). As for the impact of industrial structure upgrading on carbon emissions, the current academic opinion holds that industrial structure optimization and upgrading can reduce

carbon emissions through structural adjustment and technological effect. However, this influence has regional differences at different spatial scales, including different countries (Duro and Padilla, 2006; Yuan et al., 2016) and different regions in the same country (Pau and Bhattacharya, 2004; Zhao et al., 2022). Different industrial sectors also have different impacts on carbon emissions. Some empirical studies prove that almost all industrial scale growth will make a positive contribution to carbon emissions (Al-Ghandoor, 2010). However, the contribution of the tertiary industry is significantly smaller than that of the secondary industry (Liu and Lung, 2010). In addition, some scholars use the spatial econometric model to demonstrate the spatial spillover effect of industrial structure on carbon emissions. The results show that the upgrading of industrial structure can not only reduce the local carbon intensity, but also reduce the carbon intensity of the surrounding areas. However, the capacity to reduce varies with the level of economic development, technological innovation and urbanization (Yu, et al., 2022).

Population size is an important factor in environmental pollution and carbon emissions. Since Marshall (1890) first proposed the concept of agglomeration, the relationship between population agglomeration and energy consumption, carbon emission and environmental pollution has attracted the attention of scholars in demography, development economics, geographic economics and other related fields (Liddle, 2014). There are three main viewpoints in academic research on the relationship between population and environment. First, population density will bring a large amount of pollutants in a short time, beyond the load-carrying capacity of the environment (Fang and Lin, 2009). Secondly, population agglomeration will bring positive external effect to the environment, which is conducive to improving environmental pollution (Chen, et al., 2020; Wang, et al., 2021). Thirdly, the relationship between population agglomeration and environment presents temporal and interval heterogeneity. In the time dimension, population growth increases the carbon footprint and $CO_2$ emissions in the short term. But in the long run, the consumption of natural resources and renewable energy improves the quality of the environment in the long run, along with population growth (Khan et al., 2020). From the interval dimension, there is a U-shaped relationship between population agglomeration and environmental pollution. When the agglomeration level is low, population agglomeration plays a positive externality and has a positive impact on environmental pollution. Only when the concentration exceeds a certain level can it have a negative impact on the environment. (Wang, 2015). In recent years, studies have also shown that the impact of population agglomeration on carbon emissions has significant regional differences (Clark, 2010; Menz and Welsch, 2012; Li et al., 2019). The differences are not only between countries, but also between regions and cities within countries. And the conclusion accords with the environmental Kuznets curve theory (EKC) (Grossman and Kruege, 1995).

Regional economic development depends on agglomeration economy, and agglomeration includes both industrial agglomeration and population agglomeration. And the two have synergistic effect (Ahmad et al., 2021). Both types of agglomeration will inevitably put enormous pressure on energy consumption and environmental pollution (Kaya and Koc, 2019; Qin et al., 2022). Many scholars have comprehensively considered the impacts of population agglomeration and industrial agglomeration on the environment, but no consensus has been reached. With the deepening of the research, some scholars are concerned that there is a certain relationship between the development of industry and population itself, so they begin to explore the non-linear relationship between the three. The general result is that population density can positively regulate environmental efficiency by strengthening the spillover effect of industrial synergistic agglomeration (Zhu et al., 2021). In addition, some scholars have verified the spatial effects among the three by using spatial metrology. It is also confirmed that the industrial development and population in neighboring areas have spillover effects on local carbon emissions.

Based on the above literature review, fruitful results have been obtained in the research on the relationship between industrial structure and carbon emissions, but there are still three aspects that can be improved. First, most of the existing studies on carbon emission or environment by industrial structure optimization only consider the simple linear relationship between industrial structure and environment, and whether there is interval heterogeneity in the emission reduction effect of industrial structure optimization has not been thoroughly studied. Second, most existing studies have studied the pairwise relationship between industrial structure, population agglomeration and carbon emissions, and rarely put in the same framework. Despite the comprehensive consideration of the relationship between industrial agglomeration, population and carbon emissions, industrial agglomeration cannot measure the structural problems of industries. At the same time, the relationship between regional variables is mostly investigated in isolation, while the possible agglomeration and spillover effects between regions are ignored. Third, generally speaking, a certain conduction mechanism affecting carbon emissions may exist as a function of time from its occurrence to its effect. In terms of the impact time of industrial structure optimization and population agglomeration on regional carbon emissions, it may be reflected in a time lag of one or 2 months, or one or 2 years. However, there are few literature that consider both long-term and short-term time effects when conducting empirical studies.

Therefore, the marginal contribution of this paper is to comprehensively consider the direct and indirect effects, short-term effects and long-term effects of industrial structure

factors and population factors of carbon emissions. First, consider the general regulation effect and threshold effect of industrial structure optimization of population agglomeration on carbon emissions. Firstly, population agglomeration is included in the research framework of carbon emission effect of industrial structure optimization. The general regulating effect and threshold effect of industrial structure optimization of population agglomeration on carbon emission were explored respectively. Second, the long-term and short-term effects of industrial structure optimization and population agglomeration on carbon emissions were investigated from two time dimensions, namely, the same period and the lag period. Thirdly, from the perspective of spatial spillover, whether industrial structure optimization and population agglomeration have spatial effects on carbon emissions is investigated. Exploring the direct and indirect spatio-temporal relationships among the three has important theoretical significance and strategic value for realizing the two-carbon goal by optimizing the industrial structure and improving the population mobility policy.

## 3 Theoretical mechanism analysis

Mechanism analysis of industrial structure optimization on carbon emission. The energy demand of each industry is quite different, and the carbon emission coefficient of each energy is different, so the carbon emission generated in the process of burning energy is also different. The secondary industry includes most of the industries with high energy consumption coefficient, and has a large demand for a variety of energy sources. China is in the process of post-industrial development, and the tertiary industry is the leading industry in China at the present stage (Yu, 2015). With the increase of the proportion of service industry, low energy consumption industries form clusters, which gradually reduce the proportion of high energy consumption and high emission industries (Zhang et al., 2016). In addition, from the perspective of factor flow, the industrial structure optimization has realized the flow of important production factors to the tertiary industry. Capital or labor factors flow to higher-end industrial sectors faster, and technological progress indirectly promotes carbon emission reduction that drives the industrial structure optimization (Cai, 2013). Therefore, the optimization of the industrial structure is realized by means of the "structural dividend" released by the coordinated development of various departments between and within the industry. In this way, more economic benefits can be obtained and the energy efficiency of the whole industry can be improved (Ervural, et al., 2018). At the same time, the spillover effect exists in a certain distance (Liu and Ma, 2021).

Mechanism of population agglomeration on carbon emissions. There are three mechanisms of population agglomeration on carbon emissions. First, population agglomeration greatly reduces the actual travel distance of residents, and large-scale use of public transport will achieve scale efficiency of carbon emission reduction (Holden and Norland, 2005; Brownstone and Golob, 2009). At the same time, the aggregation of population can improve the utilization rate of various resources, reduce the occupation of various resources by repeated construction, especially conducive to the sharing of public facilities. In this way, enterprises or individuals can reduce the cost of obtaining and using resources and public facilities and improve the economies of scale in the use of resources (Glaeser, 2011). In addition, it can increase the matching between jobs and workers, reduce the cost of job searching and improve work efficiency. More importantly, it can accelerate the generation of new knowledge and technology, promote the renewal of production and environmental protection technology to a certain extent, which is conducive to the control of environmental pollution. Second, Population agglomeration has negative environmental externalities. The large-scale disordered agglomeration of population will lead to a significant increase in regional domestic energy consumption, especially in the energy consumption of buildings, transportation and household appliances. A large amount of energy consumption increases the emission of regional pollutants. The economic development mode, population flow and wind conditions in neighboring areas will also lead to the close-range diffusion of pollutants. Moreover, it has a positive spatial effect on carbon emissions in neighboring areas (Xia and Lu, 2015).

Mechanism of industrial structure optimization and population agglomeration on carbon emission. Labor supply and population size affect the industrial value-added structure of consumption and investment through the income channel and the price channel respectively, so as to bring about the adjustment of industrial structure. People's pursuit of life status and quality is gradually advanced, so it strongly promotes the development of service industry and the industrial structure optimization (Thorpe and Schmuller, 1958). When people's pursuit of higher living conditions and quality gradually promotes the development of service industry and reduces the proportion of secondary industry. The development of tertiary industry not only reflects the stage and level of regional economic development, but also represents the technical level of the region. The tertiary industry sector has a higher level of demand for labor force, so that labor force can learn through a variety of channels (Marshall, 1890). As a result, the labor tends to match high-end industrial sectors with better pay, better working conditions, more room for advancement and higher demand for skills. Thus promote the industrial structure optimization, and finally reduce regional energy consumption and carbon emissions. The tertiary industry sector is highly dependent on labor and energy, and migrants tend to flow to areas with better public services (Xia and Lu, 2015), resulting energy consumption of the population. But

population agglomeration can also have positive externalities, reducing travel distances and sharing regional facilities, thus achieving economies of scale in energy consumption (Liddle, 2004). At the same time, the labor force can improve the labor production efficiency of the tertiary industry and reduce the energy consumption by constantly applying their knowledge to the production services of the tertiary industry. Therefore, the impact of industrial structure optimization and population agglomeration on carbon emissions depends on the difference between the direct energy consumption brought about by industrial structure optimization and population agglomeration and the indirect energy consumption reduced by agglomeration through positive externalities, which is closely related to the level of population agglomeration.

# 4 Research design

## 4.1 Model setting and data

### 4.1.1 Baseline regression model

Cobb-Douglas production function describes the functional relationship between labor force, capital and other production factors and economic output, which can profoundly reflect the nature and characteristics of changes in the output of economic activities (Phelps Brown, 1957). With the continuous development of economic theory and social practice, the production function has been continuously developed (Samuelson, 1979; Mc Combie, 1991). This paper refers to the model derivation method of Cheng et al. (2019). In this paper, referring to the model derivation method of Cheng et al. (2019), a direct impact model of industrial structure optimization on carbon emissions was constructed for the direct transmission mechanism (Model 1). On this basis, it is considered that the industrial structure optimization and population agglomeration may have a non-linear indirect mechanism of action on carbon emissions, that is, the general regulation effect of population agglomeration on the industrial structure optimization. Population agglomeration influences the industrial structure optimization from two aspects: "Marshallian technology externality" and the expansion of consumption demand (Jia et al., 2022). Therefore, the carbon reduction adjustment effect model of population agglomeration on industrial structure optimization (Model 2) was established, that is, the interaction term between industrial structure optimization and population agglomeration was added on the basis of Model 1.

**Model 1:** Direct impact model of industrial structure optimization on carbon emissions

$$\ln CETO_{it} = \alpha_0 + \alpha_1 MS_{it} + \alpha_2 \ln TP_{it} + \alpha_3 \ln PA_{it} + \alpha_4 \ln FDI_{it} + \alpha_5 \ln ER_{it} + \alpha_6 \ln GDP_{it} + \mu_i + \gamma_i + \varepsilon_{it} \quad (1)$$

**Model 2:** General moderating effect model of population agglomeration

$$\ln CETO_{it} = \alpha_0 + \alpha_1 MS_{it} + \alpha_2 \ln TP_{it} + \alpha_3 MS_{it} * \ln TP_{it} + \alpha_4 \ln PA_{it} + \alpha_5 \ln FDI_{it} + \alpha_6 \ln ER_{it} + \alpha_7 \ln GDP_{it} + \mu_i + \gamma_i + \varepsilon_{it} \quad (2)$$

In Eqs 1, 2, $CETO$ represents carbon emission, $MS$ represents industrial optimization level, $TP$ represents population density, $PA$ represents technological innovation, $FDI$ represents foreign direct investment, $ER$ represents the intensity of environmental regulation, $GDP$ represents the level of regional economic development. $i$ represents the province, $t$ represents the year. $\alpha_0$ denotes constants, $\alpha_1$ until $\alpha_7$ denote regression coefficients of each variable. $\mu_i$ and $\gamma_i$ are the non-observed effects of provinces and time, and $\varepsilon_{it}$ represent the random disturbance term.

### 4.1.2 Panel threshold regression model

In order to further clarify the non-linear mechanism of population aggregation, the panel threshold model was established by reference to Hansen (1999) method to verify whether there is complex interval effect in the regulating effect of population aggregation. Firstly, a single threshold effect model (Model 3) was established:

**Model 3:** Xxx.

$$\ln CETO_{it} = \beta_1 MS_{it} I(\tau_{it} \le \gamma) + \beta_2 MS_{it} I(\tau_{it} > \gamma) + \ln \gamma_x X_{it} + \mu_i + \varepsilon_{it} \quad (3)$$

Secondly, a double threshold effect model (Model 4) was established:

**Model 4:** Xxx.

$$\ln CETO_{it} = \beta_1 MS_{it} I(\tau_{it} \le \gamma) + \beta_2 MS_{it} I(\gamma_1 < \tau_{it} \le \gamma_2) + \beta_2 MS_{it} I(\tau_{it} > \gamma_2) + \ln \gamma_x X_{it} + \mu_i + \varepsilon_{it} \quad (4)$$

$I(\cdot)$ is an indicative function, The inequality in parentheses is one if it is true, and 0 if it is not. A represents the industrial specialization. $\tau_{it}$ is the threshold variable, namely, the population aggregation degree index. $\gamma_1$ and $\gamma_2$ are variable threshold values, $\mu_i$ is the individual fixed effect, $\varepsilon_{it}$ is the random interference term, $X_{it}$ represents the remaining variables in model 1 above and will not be repeated.

### 4.1.3 Spatial effect model

Industrial structure optimization, population agglomeration and carbon emission are likely to show certain spatial aggregation characteristics. Therefore, in order to further discuss the spatial spillover effect of industrial structure optimization and population agglomeration on carbon emissions, the spatial interaction term with the spatial weight matrix is introduced

into Model 1, which is further expanded into a general spatial econometric model (Anselin and Florax 1995; Shao et al., 2016). Spatial econometric models generally include spatial auto regressive model (SAR), spatial error model (SEM) and spatial Dubin model (SDM) (Ma and Zhang, 2014). Due to uncertainty in model selection, general spatial econometric model is adopted for verification (see Model 5):

**Model 5:** Xxx.

$$\begin{aligned}\ln CETO_{it} &= \tau \ln CETO_{i,t-1} + \rho\varpi \ln CETO_t + \alpha_1 X_{it} + d_t^{'} X_t \delta + \mu_i + \gamma_i + \varepsilon_{it}\varepsilon_{it} \\ &= \lambda\omega\varepsilon_t + \upsilon_{it}\end{aligned} \tag{5}$$

In Eq. 5, $\varpi$ is the space weight matrix, $\ln CETO_{i,t-1}$ is the first-order lag of the explained variable, $d_t^{'} X_t \delta$ represents the spatial lag term of the explanatory variable. $\omega$ is the row of the corresponding spatial weight matrix, $\gamma_t$ is the time effect, $\varepsilon_{it}$ is the random perturbation terms.

## 4.2 Data selection and processing

### 4.2.1 Data sources

Carbon Emission (ceto). The carbon emission in this paper refers to the carbon emission *per capita*, because the carbon emission is the carbon emission caused by various energy consumption, but the official institution has not given this series of data. Therefore, in accordance with IPCC emission guidelines (IPCC, 2006) and various energy data statistics of various provinces, this paper uses the following formula to calculate carbon emissions:

$$EC_i = \sum_{j=1}^{8} a_j{}^{*} b_j i = 1, 2, \ldots\ldots 30 j = 1, 2, \ldots\ldots 8 \tag{6}$$

$$AEC_i = \frac{EC_i}{POP_i} i = 1, 2, \ldots\ldots 30 \tag{7}$$

Where, $i$ represents the province, $j$ represents the selected energy type. A total of 30 provincial-level regions were selected (excluding Tibet, Hong Kong, Macao and Taiwan). Eight major energy sources were selected, namely raw coal, coke, gasoline, kerosene, diesel, fuel oil and natural gas. $EC_i$ represents the province $i$'s carbon emissions in 10,000 tons. $AEC_i$ represents carbon emissions *per capita*. $POP_i$ represents the total population. $a_j$ represents carbon emission coefficient of energy sources $j$. $b_j$ represents annual consumption of energy sources $j$, calculated as the standard coal consumption, the unit of ten thousand tons. The carbon emission coefficient of main consumption energy is derived from the default value of IPCC carbon emission calculation guide. The conversion standard coal coefficient and carbon emission coefficient of each energy are shown in Table 1 respectively.

Industrial Structure Optimization (ms). Petti-clark theorem points out that with the continuous development of economy, the industrial center will gradually transfer from tangible property production to intangible service production, and the proportion of non-agricultural industry is higher and higher, while the proportion of agriculture is continuously lower, which also reflects the upgrading of industrial structure (Clark, 1940). Therefore, many scholars use the proportion of output value of the secondary and tertiary industries in the total output value to measure the upgrading of industrial structure (Wu and Liu, 2013). At the different stages of national development, suitable leading industries are needed to promote economic development. In the middle and late stage of industrialization, the leading industries are capital intensive heavy industry and technology intensive industry respectively. In the late stage of industrialization, the public's demand for consumer services and social services rose sharply, and the leading industry began to transform into the service industry based on information economy and knowledge economy, which greatly increased the development volume of the "tertiary industry". Therefore, this paper follows the method of previous scholars and uses the ratio of output value of tertiary industry and secondary industry to measure the optimization level of industrial structure.

Population Agglomeration (tp). In this paper, population density is used as a proxy index of population agglomeration, which is equal to the ratio of the total population of the current year to the area of the administrative region (Yang and Ren, 2018). Generally speaking, the greater the regional population density, the stronger the population agglomeration.

Spatial weight matrix ($\varpi$). The construction of appropriate spatial weight matrix is the premise of accurately measuring the spatial correlation of carbon emissions. This paper chooses the geographical distance weight matrix to study. Elements in the matrix represent the inverse of the distance between the region $i$ and $j$.

Control variables. Technological innovation, environmental regulation, regional economic growth and foreign direct investment have important effects on regional carbon emissions. On the basis of determining the core explanatory variables, environmental regulation (ER) (Xu, 2016), technological innovation (PA) (Wang and Wei, 2019), regional economic development (GDP) (Teixeira and Queiros, 2016; Liu et al., 2018) and foreign direct investment (FDI) (Sarkodie and Strezov, 2019) were further selected as control variables. The total investment amount of industrial pollution control, the number of patent applications, *per capita* GDP and the total investment of foreign enterprises in each region are respectively used to express. Among them, pollution control investment, *per capita* GDP and foreign enterprise investment are based on 2002 and converted into constant prices.

**TABLE 1 Standard coal coefficient and carbon emission coefficient of energy conversion.**

| Energy category | Raw coal | Hard coke | Crude oil | Gasoline | Kerosene | Diesel | Fuel oil | Natural gas |
|---|---|---|---|---|---|---|---|---|
| Convert standard coal coefficient (Per million tons/million tons) | 0.7143 | 0.9714 | 1.4286 | 1.4714 | 1.4714 | 1.4571 | 1.4286 | 1.3300 |
| Carbon emission factor (Per million tons/million tons) | 0.7559 | 0.8555 | 0.5857 | 0.5538 | 0.5714 | 0.5921 | 0.6185 | 0.4483 |

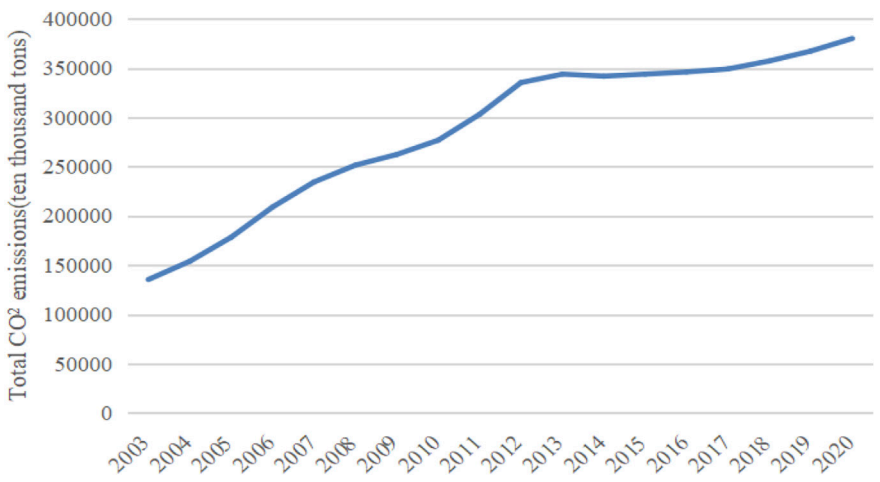


FIGURE 1
Total carbon emissions in China from 2003 to 2020.

# 5 Mechanism test and discussion

## 5.1 Carbon emission level analysis

In order to understand the carbon emission level of each provincial region in China from 2003 to 2020, a broken line chart of China's total carbon emission from 2003 to 2020 was drawn (see Figure 1). As can be seen from Figure 1, in recent 20 years, the total carbon emissions in China have been on the rise. However, after 2012, the rising speed and amplitude of the total carbon emissions decreased to a large extent, and the rising amplitude of the total carbon emissions tended to be gentle. This is because before 2011, China was in the stage of rapid industrial development, the development of the secondary and tertiary industries will inevitably promote the increase of energy consumption as the input factor, while after the 12th Five-Year Plan, China began to enter the post-industrial era, the demand for coal resources is constantly decreasing.

The emissions of each region in 2003, 2012 and 2020 were selected for analysis. According to the carbon emissions of each region in the 3 years, the emissions were divided into four ranges from small to large, which were named as low emission region, moderate emission region, high emission region and ultra-high emission region (see Figure 2). From 2003 to 2020, the number of regions with high emission and ultra-high emission also showed an increasing trend. The number of high-emission areas increased from zero in 2003 to six in 2012 and eight in 2020, while the number of ultra-high-emission areas increased from zero in 2003 to two in 2012 and three in 2020. The regions with the highest emissions in 2012 were Shandong and Hebei. Shandong is a major manufacturing center along China's east coast, and its energy, industrial and agricultural sectors are also strong. Hebei, in northern China that surrounds Beijing, is the country's largest steel-producing province. In 2020, the regions with ultra-high emissions were Inner Mongolia, Shandong and Shanxi. Among them, Inner Mongolia and Shanxi are large provinces with rich coal resources and high total carbon emission. This is partly evidence of the "resource curse" effect (Wu, et al., 2018).

In order to fully understand the change trend of carbon emissions in 30 provincial-level regions in China during the 3 years, the column chart of carbon emissions in 30 provincial-level regions in 3 years was drawn (see Figure 3). Specifically, from 2012 to 2020, carbon emissions in most provincial-level regions showed a continuous rise

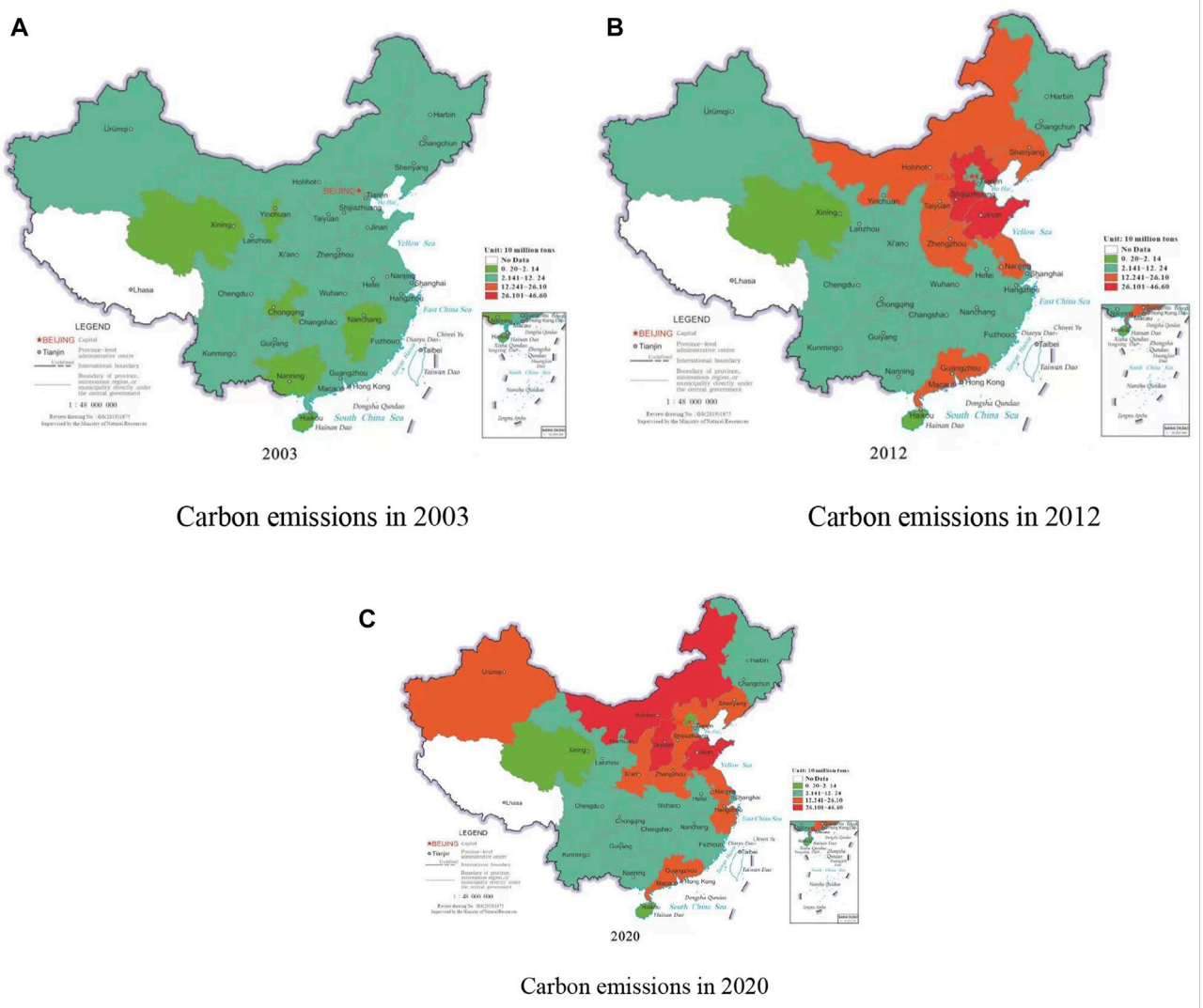


FIGURE 2
**(A)** Carbon emissions in 2003, **(B)** Carbon emissions in 2012, **(C)** Carbon emissions in 2020.

trend, while the rise trend tended to be flat in the past decade. In addition, the total carbon emissions of a considerable number of provincial-level regions, such as Beijing, Tianjin, Jilin, Henan and Chongqing, have shown considerable reductions. Although the number of high emission and ultra-high emission areas has increased in China, as far as the structure of carbon emission is concerned, there are different directions and different degrees of carbon emission change trends in various regions, and the "Matthew effect" of carbon emission between regions is also vaguely presented. This is because each region becomes more dependent on its own comparative advantage, and the comparative advantage of factor endowment further strengthens the changes of regional industrial structure and energy consumption.

## 5.2 Direct impact test

The least squares (OLS) estimation method is used to estimate the relationship between them. The mixed estimation model assumes that all individuals have exactly the same regression equation, so that all the data can be put together and OLS regression can be performed just like cross-sectional data, so it is called mixed regression. Before regression, descriptive statistical analysis was carried out on variables. In this paper, indicators of 30 provincial-level regions in China from 2003 to 2020 were used, and the total number of observation samples was 540 (see Table 2). The specific results of the mixed estimation are shown in Table 3.

According to Table 3, without considering individual effects, industrial structure optimization has a significant negative effect

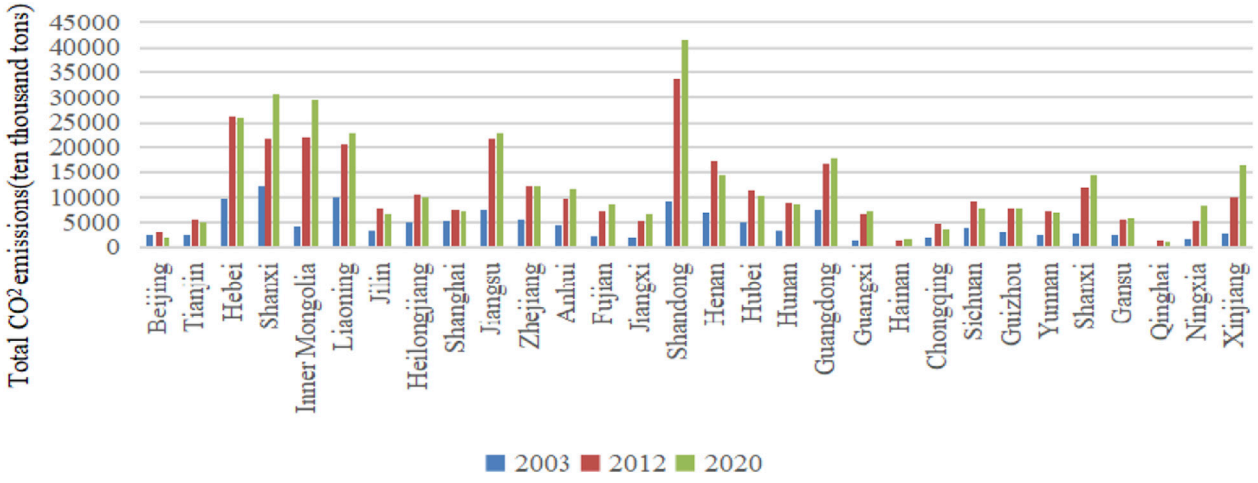


FIGURE 3
Three-year carbon emissions of 30 provincial-level regions in China.

**TABLE 2 Descriptive statistical analysis of each variable.**

| Variable | Obs | Mean | Std. Dev | Min | Max |
|---|---|---|---|---|---|
| Ceto | 540 | 8.8567 | 0.8427 | 5.4553 | 10.6335 |
| Ms | 540 | 1.0250 | 0.5606 | 0.4944 | 5.1692 |
| Tp | 540 | 5.4323 | 1.2714 | 1.9911 | 8.2569 |
| Fdi | 540 | 1.7955 | 2.9171 | 0.0408 | 22.2882 |
| Er | 540 | 3.4649 | 0.8833 | 0.2258 | 6.0218 |
| Pa | 540 | 1.5459 | 1.4075 | −1.4694 | 4.6537 |
| Gdp | 540 | 3.7189 | 2.7255 | 0.3088 | 16.4212 |

on carbon emissions, with a significance level of 1%.Population agglomeration has a significant positive effect on carbon emissions at a significant level of 10%.It can be seen that the industrial structure optimization can reduce carbon emissions on the whole, and regional carbon emissions also increase with the increase of population agglomeration level.

Since the basic assumption of mixed regression is that there are no individual effects, it is also known as' Population-averaged estimator' (PA), because the individual effects are averaged out. This hypothesis must be tested statistically. The null hypothesis that there is no individual effect is rejected by testing the mixed estimates. At the same time, the fixed effects model with cluster robust standard error (between-group estimator) was used to investigate the relationship between the two. The specific results are shown in Table 4.

In order to further prove the robustness of the estimation within the group and clarify the possible long-term time effect among the three, the data with the dependent variable lagging for 2 years were selected for the robustness test of the model. The test

**TABLE 3 Mixed estimation of industrial structure optimization, population agglomeration and carbon emissions.**

| ceto | Coef | Std. Err | T | *p*> t | [95% Conf.Interval] | |
|---|---|---|---|---|---|---|
| Ms | −0.6923*** | 0.1700 | −4.0700 | 0.0000 | −1.0401 | −0.3446 |
| Tp | 0.2680* | 0.1540 | 1.7400 | 0.0920 | −0.0470 | 0.5829 |
| Fdi | −0.1273** | 0.0435 | −2.9300 | 0.0070 | −0.2162 | −0.0384 |
| Er | 0.2369* | 0.1079 | 2.2000 | 0.0360 | 0.0163 | 0.4575 |
| Pa | −0.0027 | 0.1265 | −0.0200 | 0.9830 | −0.2615 | 0.2561 |
| Gdp | 0.1462** | 0.0659 | 2.2200 | 0.0350 | 0.0114 | 0.2810 |
| _cons | 7.0635*** | 0.9871 | 7.1600 | 0.0000 | 5.0446 | 9.0824 |
| $R^2$ | 0.4701 | | | | | |

***, ** and * indicate significance levels o%, 5%, and 10%, respectively.

**TABLE 4 Fixed effect model estimation of carbon emissions from industrial structure optimization and population agglomeration.**

| ceto | Coef | Std. Err | t | *p*> t | [95% conf. Interval] | |
|---|---|---|---|---|---|---|
| Ms | −0.7005*** | 0.0958 | −7.3200 | 0.0000 | −0.9047 | −0.4964 |
| Tp | 0.2893*** | 0.0109 | 26.6400 | 0.0000 | 0.2661 | 0.3124 |
| Fdi | −0.1327*** | 0.0220 | −6.0300 | 0.0000 | −0.1795 | −0.0858 |
| Er | 0.2627*** | 0.0449 | 5.8600 | 0.0000 | 0.1671 | 0.3583 |
| Pa | −0.0266 | 0.0257 | −1.0400 | 0.3170 | −0.0813 | 0.0281 |
| Gdp | 0.1443*** | 0.0364 | 3.9700 | 0.0010 | 0.0668 | 0.2219 |
| _cons | 6.9145*** | 0.1339 | 51.6500 | 0.0000 | 6.6292 | 7.1998 |
| $R^2$ | 0.4516 | | | | | |

***,**, and * indicate significance levels o%, 5%, and 10%, respectively.

**TABLE 5 Fixed-effects model estimates of the dependent variable with a lag of 2 years.**

| Robust | | | | | | |
|---|---|---|---|---|---|---|
| f2ceto | Coef | Std. Err | T | *p*>\|t\| | [95% Conf. | Interval] |
| Ms | −0.5754*** | 0.0940 | −6.1200 | 0.0000 | −0.7737 | −0.3771 |
| Tp | 0.2944*** | 0.0104 | 28.3800 | 0.0000 | 0.2725 | 0.3162 |
| Fdi | −0.1241*** | 0.0153 | −8.1300 | 0.0000 | −0.1564 | −0.0919 |
| Er | 0.2788*** | 0.0394 | 7.0800 | 0.0000 | 0.1957 | 0.3620 |
| Pa | −0.0115 | 0.0262 | −0.4400 | 0.6670 | −0.0668 | 0.0439 |
| gdp | 0.1136*** | 0.0252 | 4.5000 | 0.0000 | 0.0604 | 0.1668 |
| _cons | 6.6995*** | 0.1379 | 48.5700 | 0.0000 | 6.4085 | 6.9905 |
| $R^2$ | 0.4422 | | | | | |

***,**, and * indicate significance levels o%, 5%, and 10%, respectively.

results are shown in Table 5. Compared with Table 5, the results of the dependent variable taking the current year's amount and the lag of 2 years are very close. Meanwhile, the impact of industrial structure optimization and population agglomeration on the dependent variable is similar to that of the mixed estimation results, which further indicates the robustness of the results. It can be seen that industrial structure optimization has a significant inhibitory effect on carbon emissions at the level of 1%, and population agglomeration has a significant promoting effect on carbon emissions at the level of 1%.

## 5.3 General moderating effect test

It can be seen from the above that industrial structure optimization and population agglomeration have a significant direct effect on carbon emissions. In view of the causal relationship between industrial structure and population agglomeration, the panel fixed effect model is used to estimate the moderating effect of population agglomeration on the relationship between industrial structure optimization and carbon emissions. Meanwhile, the results of the same period and the two lag periods were compared. On the one hand, the

**TABLE 6 General adjustment effect analysis of population agglomeration on emission reduction effect of industrial structure optimization.**

| ceto | Coef | *p*>\|t\| | f2ceto | Coef | *p*>\|t\| |
|---|---|---|---|---|---|
| Ms | −0.3775*** | 0.0040 | ms1 | −0.5415* | 0.0630 |
| Tp | 1.7658*** | 0.0000 | tp | 1.6759*** | 0.0040 |
| Mstp | −0.1210*** | 0.0000 | ms1tp | −0.1508*** | 0.0070 |
| Pa | 0.2244*** | 0.0000 | pa | 0.1383*** | 0.0000 |
| Fdi | 0.0064 | 0.4730 | fdi | 0.0069 | 0.6520 |
| Er | 0.1291*** | 0.0000 | er | 0.1213*** | 0.0000 |
| _cons | −1.2309 | 0.2590 | _cons | −0.4815 | 0.8680 |
| $R^2$ | 0.7580 | | $R^2$ | 0.6534 | |

***,** and * indicate significance levels of 1%, 5%, and 10%, respectively.

**TABLE 7** Double threshold estimates.

| | f2ceto | Ceto |
|---|---|---|
| Threshold | Coef | Coef |
| Single | 2.1137***(0.000) | 2.1303***(0.000) |
| Double | 5.9263***(0.000) | 5.9487***(0.000) |

***, ** and * indicate significance levels of 1%, 5%, and 10%, respectively.

**TABLE 8** Results of double threshold estimation.

| | f2ceto | | Ceto | |
|---|---|---|---|---|
| _cat#c.ms1 | Coef | $p > t$ | Coef | $p > t$ |
| 0.0000 | −3.8700*** | 0.0000 | −3.6314*** | 0.0000 |
| 1.0000 | −1.2000*** | 0.0000 | −1.0737*** | 0.0000 |
| 2.0000 | −0.5696*** | 0.0000 | −0.4856*** | 0.0000 |
| _cons | 9.3437*** | 0.0000 | 9.2134*** | 0.0000 |
| $R^2$ | 0.1997 | | 0.3352 | |

***,** and * indicate significance levels of 1%, 5%, and 10%, respectively.

robustness of the results is proved. On the other hand, the differences of the long-term and short-term effects of industrial structure optimization and population agglomeration on carbon emissions are compared. The estimated results are shown in Table 6. As can be seen from Table 6, the model fit degrees were 0.7580 and 0.6534, respectively, indicating a high degree of fit. The estimated coefficient of the interaction term of industrial structure optimization and population agglomeration is −0.1210, which is significant at the 1% level. This indicates that the effect of industrial structure optimization on carbon emission will be moderated by population agglomeration. That is, with the increase of population agglomeration level, the inhibition effect of industrial structure optimization on carbon emission is enhanced. By comparing the results of two lag periods, it is found that industrial structure optimization, population agglomeration and their cross terms have the same direction of action on carbon emissions, and their influence coefficients are very close, which proves the robustness of the results. However, in the long run, the carbon emission reduction effect of industrial structure optimization is stronger, while the carbon emission effect of population agglomeration is weaker, and the synergistic effect of the two is also stronger.

## 5.4 Threshold effect test

To further verify the non-linear action mechanism of industrial structure optimization and population agglomeration on carbon emissions, and explore whether population agglomeration has a threshold effect on carbon emission reduction caused by the upgrading of industrial structure. The existence of threshold effect was tested based on the method of hansen (1999), and repeated sampling was conducted for 300 times through the “self-help method”. The results of the independent variable lagging for two periods were also used as comparative analysis and robustness test. The sampling results show that both the simultaneous threshold effect and the lag two periods are tested by single threshold and double threshold, but not by triple threshold. The test results and estimates of the double threshold model are shown in Tables 7, 8.

Figures 4A, B of the likelihood ratio function with a lag of two periods were drawn. The 95% confidence intervals of the threshold estimators 2.1137 and 5.9963 are the critical value estimators under the significance level of all LR statistics less than 1%, which is in the acceptance domain of the null hypothesis that the threshold estimate is equal to the true value, that is, the acceptance threshold estimate is equal to the true value.

Combining Figures 4A, B with Tables 7, 8, it can be seen that, The industrial structure optimization has a threshold effect of population aggregation on carbon emissions, and there is a double threshold effect, the threshold values are 2.1137 and 5.9963, respectively, and both of them are significant at the level of 1%.According to the estimation results in Table 8, in the first interval, the influence coefficient of industrial structure optimization on carbon emission is −3.87, which is significant at the level of 1%.This indicates that when the population concentration degree is less than 2.1137, the industrial structure optimization has a significant inhibitory effect on carbon emissions. In the second interval, the influence coefficient of industrial structure optimization on carbon emission reduction is −1.2, which is significant at 1% level. When the population concentration level is greater than 5.9963, the industrial structure optimization has a significant negative effect on carbon emissions, and the influence coefficient is −0.5696. From the above results, it can be seen that the industrial structure optimization has an interval effect on regional carbon emissions with the population concentration level as the threshold. The carbon emission reduction effect of industrial structure optimization will be weakened with the increase of population concentration level. Comparing the estimation results of the same period, it is found that the direction of the estimation coefficients is the same, and the estimation coefficients are very close, which proves the robustness of the interval effect of population agglomeration on the industrial structure optimization. However, the interval effect of industrial structure optimization on carbon emissions is stronger than the inhibition effect in each interval.

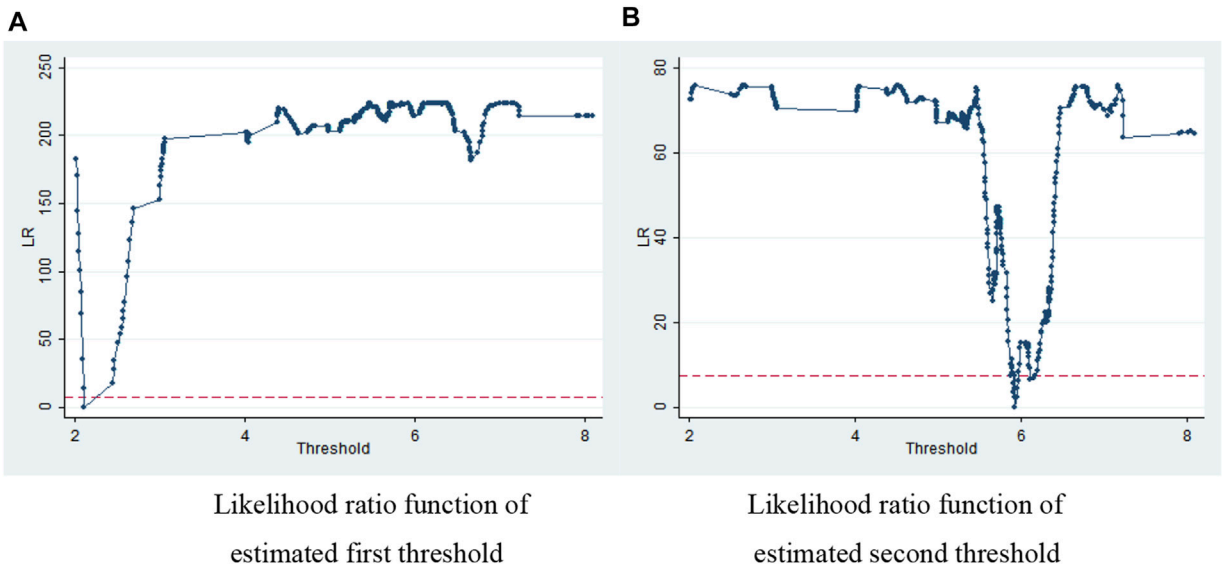


FIGURE 4
**(A)** Likelihood ratio function of estimated first threshold **(B)** Likelihood ratio function of estimated second threshold.

## 5.5 Spatial spillover effect test

Spatial econometric models generally include SAR, SEM and SDM, each of which has its own applicable situation. In order to avoid model selection bias, this paper uses the general spatial panel econometric model to verify the spatial effects among the three. Before the spatial econometric analysis, the existence of spatial effect is tested first, that is, the spatial auto correlation test is conducted on the optimization level of industrial structure, population agglomeration and carbon emissions. The Moran 'i index method was used to calculate the spatial effect from 2003 to 2020 under the geographical distance matrix. The results showed that the Moran 'i index reached the significance level of 1% in each year. This indicates that there is a significant spatial auto correlation between industrial structure optimization, population agglomeration and carbon emission in 30 provinces from 2003 to 2020, which means that there is spillover effect in spatial distribution between them (the results are omitted).

Based on the spatial weight matrix of geographical distance, the general spatial panel model is used to verify the spatial spillover effects of industrial optimization and population agglomeration on carbon emissions. The results are shown in Table 9. According to Table 9 , the total effect of industrial structure optimization on carbon emission is 3.4551, and the significance level is 1%.The total impact coefficient of population agglomeration on carbon emissions is −0.5317, and the significance level is 1%.In addition, the direct and indirect effects of industrial structure optimization and population agglomeration are also significant in the partial differential interpretation results of variable changes. The industrial structure optimization and population agglomeration have significant indirect effects on carbon emissions, and the industrial structure optimization in neighboring provinces has a significant negative spatial spillover effect on carbon emissions in their own province, and the influence coefficient of −0.1483 is significant at 10% level. However, the population agglomeration of neighboring provinces has a positive spatial spillover effect on the carbon emission of the province, and the coefficient is estimated to be 2.7024, which is significant at the level of 1%.According to the above results, industrial structure optimization can reduce carbon emissions of neighboring provinces through spatial spillover effect, while population agglomeration can increase carbon emissions of neighboring provinces through spatial spillover effect.

Since the Spatial Dubin Model (SDM) combines the advantages of the spatial lag model and the spatial error model, it can investigate the spatial effects of the main variables and unobservable random shocks at the same time. Therefore, the SDM model is used to test the robustness of the relationship between the three. The test results are shown in Table 10. According to the results in Table 10, the test results of the SDM model are very close to the results of the general spatial panel model, indicating the robustness of the spatial spillover effect of industrial structure optimization and population agglomeration on carbon emissions.

**TABLE 9 Regression results of general spatial panel model.**

| Variables | Coef. | Std. Err. | Z | $p > z$ | [95% conf. | Interval] |
|---|---|---|---|---|---|---|
| Main | | | | | | |
| Tp | 0.8919*** | 0.1866 | 4.7800 | 0.0000 | 0.5262 | 1.2576 |
| Ms | −0.3891*** | 0.0425 | −9.1500 | 0.0000 | −0.4725 | −0.3057 |
| Wx | | | | | | |
| Tp | 5.4354*** | 1.2366 | 4.4000 | 0.0000 | 3.0117 | 7.8592 |
| Ms | −0.5716** | 0.2514 | −2.2700 | 0.0230 | −1.0643 | −0.0790 |
| $\rho$ | −0.8369*** | 0.2089 | −4.0100 | 0.0000 | −1.2464 | −0.4275 |
| sigma2_e | 0.0183*** | 0.0011 | 16.1000 | 0.0000 | 0.0160 | 0.0205 |
| Direcet | | | | | | |
| Tp | 0.7528*** | 0.2006 | 3.7500 | 0.0000 | 0.3596 | 1.1459 |
| Ms | −0.3834*** | 0.0391 | −9.8000 | 0.0000 | −0.4601 | −0.3068 |
| Indirect | | | | | | |
| Tp | 2.7024*** | 0.7878 | 3.4300 | 0.0010 | 1.1582 | 4.2465 |
| Ms | −0.1483* | 0.1248 | −1.1900 | 0.0635 | −0.3930 | 0.0964 |
| Total | | | | | | |
| Tp | 3.4551*** | 0.7533 | 4.5900 | 0.0000 | 1.9786 | 4.9316 |
| Ms | −0.5317*** | 0.1415 | −3.7600 | 0.0000 | −0.8091 | −0.2544 |
| $R^2$ | 0.2919 | | | | | |

***,** and * indicate significance levels of 1%, 5%, and 10%, respectively.

**TABLE 10 Regression results of SDM with fixed effects.**

| <!--Col Count:>Robust | | | | | | |
|---|---|---|---|---|---|---|
| Ceto | Coef | Std. Err | z | $p>\|z\|$ | [95% Conf. | Interval] |
| Main | | | | | | |
| Tp | 0.4413** | 0.5894 | 2.7500 | 0.0454 | −0.7139 | 1.5965 |
| Ms | −0.2804*** | 0.0503 | −5.5800 | 0.0000 | −0.3789 | −0.1819 |
| Wx | | | | | | |
| Tp | 2.7668** | 1.3287 | 2.0800 | 0.0370 | 0.1626 | 5.3710 |
| $\rho$ | 0.5389*** | 0.0703 | 7.6700 | 0.0000 | 0.4011 | 0.6766 |
| Variance | | | | | | |
| sigma2_e | 0.0239*** | 0.0055 | 4.3200 | 0.0000 | 0.0131 | 0.0348 |
| $R^2$ | 0.7898 | | | | | |

***,** and * indicate significance levels of 1%, 5%, and 10%, respectively.

## 6 Discussion

The results of Tables 2–Tables 5 show that industrial structure optimization has a significant negative effect on regional carbon emissions. In the long run, it has a stronger inhibition effect on carbon emissions. This is due to the optimization and upgrading of industrial structure, which can weaken the influence of natural resources on the formation of resource-dependent industrial structure (Wang and Chen, 2020). The negative external effect of population agglomeration is obvious, because the consumption of daily energy brought by population increases greatly, such as transportation energy consumption and electricity consumption (Liddle and Lung, 2010). Thus, improving energy efficiency and lowering carbon emissions by providing or encouraging living in high-rise buildings and using public transport resources is not proven.

The results in Tables 7–Tables 9 show that population agglomeration has a significant positive moderating effect and a double threshold effect on carbon emissions from industrial structure optimization. From the perspective of population agglomeration promoting the industrial structure optimization, the cross-terms of the two have a significant inhibiting effect on carbon emission at the level of 1%.This means that when more people are matched into a more optimized industrial structure, carbon emissions can be effectively reduced (Wu et al., 2021). However, in terms of interval effect, there are significant interval differences in the effect of industrial structure optimization on carbon emissions, which are not reflected in the direction of the effect, but in the intensity of the effect. In the current period, when the population concentration level is lower than 2.1303, the industrial structure optimization has the strongest carbon emission reduction effect. However, when the concentration level is greater than 5.9487, the intensity of carbon emission reduction is the weakest. In the long run, when the population concentration level is less than 2.1137, the carbon emission reduction intensity is maximum, and when the population concentration level is greater than 5.9263, the carbon emission reduction intensity is minimum. This indicates that the carbon emission reduction effect of industrial structure optimization is limited by the population agglomeration level, and the lower the agglomeration level, the stronger the emission reduction effect. In the long run, the emission reduction effect of industrial structure optimization is better, but there is a more strict limit on the population concentration level. According to the above findings, it is necessary to find a reasonable match between regional population size and industrial structure (Khan et al., 2020).

Tables 9, 10 show that industrial structure optimization, population agglomeration and carbon emissions have significant spatial spillover effects. The spatial spillover effect of industrial structure optimization is significantly negative, while the spatial spillover effect of population agglomeration is significantly positive. Geographical proximity facilitates internal information exchange and the spread of green technologies through frequent interaction of professional and technical personnel, as well as the integration of development concepts and industrial synergies (Zeng et al., 2021).

## 7 Conclusion and policy implications

Nature is the basic condition for human survival and development. o actively yet prudently promote carbon peaking and carbon neutralization, and to carry out carbon peaking in planned steps, is a necessary measure for China to actively participate in global governance on climate change. Industrial structure adjustment is an effective path for our country to reduce carbon emissions and strive to achieve the peak target as soon as possible. However, the optimization of regional industrial structure is often accompanied by the accumulation of resources, especially the large-scale agglomeration of population. It has important practical significance and strategic value to explore how to reduce carbon emission under the coexistence of industrial structure optimization and regular population crowding.

This paper constructed a panel model to verify the various mechanisms of industrial structure optimization and population agglomeration on carbon emissions, based on the panel data of provincial regions from 2003 to 2020. 1) The fixed effects model was used to verify the direct effects and general moderating effects among the three. 2) Panel threshold model was used to further explore the heterogeneous effect of population agglomeration on emission reduction interval of industrial structure optimization. 3) The spatial weight matrix was introduced to construct a spatial econometric model to analyze the spatial spillover effects of industrial structure optimization, population agglomeration and carbon emissions. The specific conclusions are as follows:

First, considering the environmental regulation, the scale of opening to the outside world, regional economic development and technological progress, the improvement of industrial structure optimization level can effectively reduce regional carbon emissions, this conclusion is consistent with the mainstream conclusion of the academic circle (Zhao et al., 2022).

Second, population agglomeration plays an important role in the relationship between industrial structure optimization and carbon emission (Liu J. et al., 2021). First, population agglomeration can reduce regional carbon emissions by adjusting industrial structure optimization. Secondly, in terms of regional heterogeneity test, population agglomeration is taken as the threshold variable to verify that there is a significant double threshold effect in the carbon emission reduction of industrial structure optimization. With the increase of population agglomeration level, the carbon emission reduction effect of industrial structure optimization is gradually weakened.

Thirdly, industrial structure optimization, population agglomeration and carbon emissions have significant spatial spillover effects. Industrial structure optimization is conducive to carbon emission reduction in neighboring areas, while excessive population agglomeration contributes positively to carbon emissions in neighboring areas.

According to the above conclusions, some suggestions are put forward to promote the low-carbon development of 30 provincial-level regions in China. First, optimizing industrial structure is an effective way to reduce regional carbon emissions and realize the target of carbon peak soon in China. Therefore, we should continue to vigorously develop the tertiary industry and increase the proportion of tertiary industry output. Policymakers should give full play to their role in industrial development, and optimize and upgrade local industrial structure by improving regional infrastructure, building a good business environment and attracting a number of

high-quality large enterprises to settle in. At the same time, carbon reduction strategies can be optimized by developing energy-saving carbon pricing (Jiang et al., 2022) and promoting natural gas reform (Jiang et al., 2021). Second, population sprawl and unsustainable lifestyle are important reasons for the increase of regional carbon emissions. Therefore, policymakers should control the overuse of natural resources by the population and promote sustainable lifestyles, such as water and energy conservation and the use of renewable energy. We should give full play to the positive externalities of population agglomeration, strive to achieve economies of scale in the utilization of energy and resources, and improve the quality level of population and environmental awareness. Thirdly, formulate reasonable population mobility policies, especially to raise the population entry threshold in regions with a high level of industrial structure optimization, and maximize the green and low-carbon development effect of the regional industrial system. Fourthly, due to the obvious spatial effects of industrial structure optimization and population agglomeration on carbon emissions, good information sharing and economic sharing mechanisms should be established among regions. To avoid "beggar-thy-neighbor" phenomenon, we should build a platform for inter-regional interaction and cooperation of industrial factors and promote the rational inter-regional flow of innovative resources and technological factors. At the same time, we will give full play to the regional linkage mechanism and formulate and improve policies for coordinated socio-economic development to rationalize the spatial distribution of population.

## 8 Prospects

The mechanism of industrial structure optimization and population agglomeration on carbon emissions is based on the provincial data from 2003 to 2020. So, the action mechanism of urban industrial structure and population agglomeration on urban carbon emission is averaged out. The actual situation of industrial structure optimization, population agglomeration and carbon emissions may vary greatly among cities within provinces. Therefore, in the future, the industrial structure optimization, population agglomeration and carbon emissions of prefecture-level cities in China will be explored, and the relationship among them will be verified.

## Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: http://www.stats.gov.cn/.

## Author contributions

LL: Conceived and designed the study, Built the model and wrote the paper. CH: Built the model and revised the manuscript. ZH: Formal analysis, Revised the manuscript, All authors read and approved the manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Pro-environmental behavior, *green* HRM practices, and *green* psychological climate: Examining the underlying mechanism in Pakistan

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The success of an organization's environmental sustainability objectives is contingent on the environmental behavior of its personnel. The present study was conducted to observe how the green human resource management (GHRM) practice improves environmental performance (EP) through psychological green climate (PGC) and pro-environmental behavior (PEB). It also evaluates the moderating role of the individual green value (IGV). Data were collected from HR professionals and health officers directly engaged in human resource practices in private hospitals in Sialkot, Pakistan. To gather the responses, questionnaires were distributed and PLS analysis was used to analyze the data. The findings showed that GHRM explains that the PGC stimulates employees to perform pro-environmental behaviors for better environmental performance. Furthermore, the individual green value moderates the employee's behavior for better environmental performance. This research paper gives vital practical implications to the top management and regulators in assuring employee engagement in applying green human resource management practices.

KEYWORDS

**green human resource management (GHRM), environmental performance (EP), green psychological climate (GPC), green behavior (GB), green self-efficacy (GSE)**

## 1 Introduction

In recent times, irreparable changes in the environment, increase in environmental pollution, damage to the natural environment, and imposition of laws related to environmental organizations have the immense force to make efforts for the reduction of pessimistic effects on the environment (Ahmed et al., 2020). The healthcare sector is critical in a country because it influences related sectors and the environment (Javed et al., 2019). Developing a healthy workforce is one of the important tasks for the health sector. The hospital staff has been involved in the environmental sustainability (McMillan, 2014). Healthcare services are linked to water and energy, both extremely harmful and non-

harmful to the society. The healthcare sector has guided patients and staff with the value of quality service and environmental sustainability (Karlsson and Öhman, 2005). Growing environmental concerns have bound healthcare units to take up environmental practices at an escalating rate, which helps such companies to be green and competitive (Mostafa, 2013; Afsar et al., 2020).

The hospital environment profoundly relies on workers' pro-environmental behaviors (Robertson and Barling, 2013). As a result, the environmental performance of the healthcare sector is largely ensured by the pro-environmental behavior (Blok et al., 2015). As a result, the healthcare sector worldwide, particularly in Pakistan, has launched several pro-environmental measures (Ahmad and Umrani, 2019). Many hospitals in the healthcare sector are motivated to eliminate the waste produced during service delivery for the patient treatment, which would improve the environmental performance (Rawashdeh, 2018). According to previous research, an effective description of the organizational environment is highly trusting workers' pro-environmental behavior; as a result, pro-environmental behaviors help assure and drive the environmental performance (Vicente-Molina et al., 2013; Wesselink et al., 2017; Rawashdeh, 2018).

To supplement the findings of previous studies, this current study examines organizational environmental performance with GHRM practices. The GHRM practice is a concept that has acquired a lot of impetus in the debate over environmental management (Ahmed et al., 2021). Employees who spend much time at work will show sustainable action and aim for environmental success as catalytic agents of green human resource activities (Ruepert et al., 2016). As a result, organizational employees may substantially impact greening of the organization and improve the environmental performance by fetching them into a wide range of pro-environmental behaviors (Aboramadan, 2020). However, there has been a growing academic interest in the function of GHRM practices and environmental performance (EP); the latest studies emphasize more research on the employee pro-environmental behavior (Dumont et al., 2017; Hameed et al., 2020). Organizations can feel less socially responsible if they do not turn green when compared to employees so that it can be damaging to the environmental behavior and psychological environment (Whitmarsh et al., 2012). Therefore, organizations need to be clear to stakeholders, from job design to environmental management, which improve environmental performance (Saeed et al., 2019). There were many studies that emphasize on PEB and EP; in those studies, GHRM practices outline a worker's psychological climate, which stimulates them to exhibit pro-environmental behaviors in the workplace (Li et al., 2011; Kim S. H. et al., 2019). Organizational environmental management and its success depend upon pro-environmental behaviors. Individuals' work-related practices are influenced by their norms, values, and convictions (Chwialkowska et al., 2020). Human beliefs and environmentally sustainable activities have been linked in the literature. The truancy of individual values may intimidate the employees, which affects their pro-environmental behavior and environmental performance. For individuals who respect the atmosphere, it is supplementarily possible for them to connect to environmentally forthcoming actions (Chou, 2014; Ajitha and Sivakumar, 2017). Recent research asserts that green values influence human actions and that stipulation shows there is a match connecting individuals and corporate green values; hence, good environmental policies can be established (Saeed et al., 2019; Naz et al., 2021).

A decent amount of research has been conducted on the said variables. However, there is still the enquiry that GHRM practices play an intense role in nurturing environmental performance through psychological green climate and pro-environmental behavior (PEB) (Ojo et al., 2019). Psychological and individual values may be more appropriate for interpreting the impact of green human resource management practices on the pro-environmental behavior and environmental performance (Shen et al., 2018), and the current study investigates this relationship. This study included green human resource management practices as a predictor of pro-environmental behavior (Shen et al., 2018) to promote environmental performance in their model. According to a thorough investigation, GHRM practices and swaying pro-environmental behaviors are still lacking and should be investigated in a different business setting, such as the healthcare sector (Yong et al., 2019). Given that such a link has been overlooked (Saeed et al., 2019), researchers should further study the phenomenon to find other psychological and behavioral underpinnings. In addition, a recent study (Saeed, Afsar, Hafeez, Khan, Tahir, Afridi, et al., 2019) suggests that mediating and moderating roles between GHRM practices and pro-environmental behaviors should be developed to discover underlying processes. According to a more recent study, individual green values (IGVs) have been studied less in the context of GHRM practices (Ren et al., 2018).

A noticeable paucity of research has examined how GHRM enabled organizations to improve their performance in terms of environmental sustainability. To fill the research gaps described previously, this research aims to explore the green psychological climate as an antecedent of the pro-environmental action and investigate how individual green values act as a moderator in private healthcare hospitals between pro-environmental behavior and environmental performance. To respond to the recent study's call, the study goes above and beyond to assess the role of the green psychological climate as a mediator between the relationship of green human resource management and the pro-environmental behavior (Saeed et al., 2019). This paper consists of sections such as the literature review, methodology, results and discussion, practical implications, and future directions, and the end section is the paper's conclusion.

# 2 Literature

## 2.1 Theoretical background

The current research approach is focused on two models: the social cognitive theory and the norm activation model. People who engage in constructive actions look for self-management due to the socio-cognitive process and view (Dumont et al., 2017). A "person's convictions" are at the core of these theories. Individual beliefs and values inspire a person to engage in PEB, decreasing negative environmental impacts while positively affecting the environment (Ajitha and Sivakumar, 2017). The STC theory is based on subjective experiences, neural influences, and the surrounding environment. These hypothesis elements are linked and impact one another (Dace

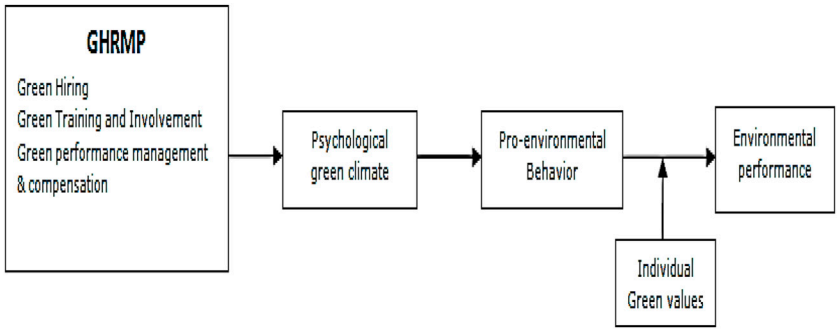


FIGURE 1
Conceptual framework.

et al., 2020). The norm activation model (NAM) is being considered for the current analysis. In the 1960s, Schwartz postulated the general activation model and began a series of papers to change it. Common model activation typically includes recycling and sustainability considerations (Xiao and Buhrmann, 2019). According to this report, GHRM practices improve the corporate environmental performance by developing a green psychological climate (GPC) and behavioral intentions with individual green values. People have associated more with pro-environmental behaviors due to the moderation effect (Chou, 2014).

## 2.2 Hypothesis development

### 2.2.1 Green human resource management practices and the psychological green climate

It is becoming increasingly important when the health sector is concerned about environmental protection and pollution prevention (Pinzone et al., 2016; Agrawal and Puri, 2020). Following the current scenario, organizational goals are related to environmental goals. Organizations are involved with enhancing and bringing social and environmental sustainability. HR managers can influence the adoption and implementation of environmental policies and procedures (Yusliza et al., 2017). Green human resource management has gained great consideration (De Stefano et al., 2018; Podgorodnichenko et al., 2020). Green human resource practices are based on the long-term sustainability of achieving a social and economic balance that aligns with long-term organizational goals (Dumont et al., 2017). Green human resource management practices place a premium on natural concerns to follow significant standards and speculations through human asset administration. The widespread adoption of green human resource practices has highlighted that this framework spans many dimensions (Tang et al., 2018). The term "psychological green climate" implies that firms want to achieve long-term objectives and priorities by enacting a wide variety of environmentally friendly policies (Chou, 2014). According to the most recent studies, the psychological green climate substantially impacts workers' green behavior on an interpersonal basis (Dumont et al., 2017). Similarly, the workplace encourages employees to seek information, and ecologically friendly practices may successfully generate a psychologically green climate (Nisar et al., 2021). The literature has shown that the climate affects employees' behaviors (Dumont et al., 2017; Pham et al., 2020). The betterment in environmental performance can constantly be achieved by taking into consideration the GHRM practices.

**H1:** Green human resource management (GHRM) practices are associated with the psychological green climate (PGC).

### 2.2.2 Psychological green climate and pro-environmental behaviors

The terms psychological green climate (Zhou et al., 2018), green organizational climate (Zientara and Zamojska, 2018), and green working climate (Norton et al., 2017) are used interchangeably. These constructs contribute to similar organizational outcomes, such as the green product development performance. Organizations can feel less socially responsible if they do not turn green when compared to employees; hence, it can be damaging to the environmental behavior and the psychological environment (Corner et al., 2012). Therefore, organizations need to be clear to stakeholders, from job design to environmental management, which improve the organizational environmental performance (Saeed et al., 2019). If organizations do not turn green, the workforce of an organization perceives that the company may be less conscientious in a social context and, as a result, may prejudice the pro-environmental behavior and psychological climate perception (Whitmarsh et al., 2012). Therefore, organizations must be clear to their stakeholders about the organizational environmental performance. As a result, workers become conscious of their role in engaging in pro-environmental behaviors (Pinzone et al., 2016).

**H2:** Psychological green climate is positively associated with the pro-environmental behavior.

### 2.2.3 Pro-environmental behavior and environmental performance

The terms "pro-environmental behavior," "environmentally responsible behaviors," or "green behavior" have been widely used to describe behaviors that protect the environment (Lee et al., 2013). The pro-environmental behavior encompasses any individual actions that minimize the depressing of human activities that harm the environmental quality and performance (Kim and

**TABLE 1 Convergent validity.**

| Construct | Item | Loading | Alpha | CR | AVE |
|---|---|---|---|---|---|
| Environmental performance | EP1 | 0.822 | 0.865 | 0.895 | 0.552 |
| | EP2 | 0.81 | | | |
| | EP3 | 0.727 | | | |
| | EP4 | 0.716 | | | |
| | EP5 | 0.613 | | | |
| | EP6 | 0.794 | | | |
| | EP7 | 0.697 | | | |
| Green hiring | GH1 | 0.896 | 0.907 | 0.935 | 0.783 |
| | GH2 | 0.903 | | | |
| | GH3 | 0.906 | | | |
| | GH5 | 0.833 | | | |
| "Green performance management and compensation" | GPM1 | 0.791 | 0.71 | 0.822 | 0.537 |
| | GPM2 | 0.728 | | | |
| | GPM3 | 0.655 | | | |
| | GPM4 | 0.75 | | | |
| "Green training and development" | GT1 | 0.824 | 0.783 | 0.854 | 0.544 |
| | GT3 | 0.8 | | | |
| | GT4 | 0.706 | | | |
| | GT7 | 0.778 | | | |
| | GT8 | 0.546 | | | |
| | GHRM | 0.933 | 0.933 | 0.942 | 0.507 |
| Individual green values | IGV2 | 0.772 | 0.733 | 0.85 | 0.654 |
| | IGV3 | 0.87 | | | |
| | IGV5 | 0.78 | | | |
| Pro-environmental behavior | PEB1 | 0.798 | 0.623 | 0.8 | 0.572 |
| | PEB3 | 0.774 | | | |
| | PEB5 | 0.693 | | | |
| | PGC1 | 0.824 | 0.728 | 0.845 | 0.646 |
| | PGC2 | 0.819 | | | |
| | PGC4 | 0.767 | | | |

Stepchenkova, 2020). The pro-environmental behavior is intended to promote the wellbeing of an individual, group, or organization (Bassi et al., 2007; Sawitri et al., 2015). Employees' pro-environmental behaviors have increased as they develop a greater awareness of the negative effect that human behaviors have on the environment (Sawitri et al., 2015). The environmental success is "a firm's effectiveness in fulfilling and overcoming society's standards of respect for the natural environment" (Judge and Douglas, 1998). Organizations are concerned about the environmental management and organizational performance (Suganthi, 2019). Specifically, significant signs for the environmental performance assessment are pollution preclusion and a disposal decline and reprocess actions. Similarly, another study found that organizations that see the protection of the environment as part of the HR process add value to environmental success by educating their workers, especially in the natural environment's shield (Sawitri et al., 2015).

**H3:** Pro-environmental behaviors are positively linked to the environmental performance.

### 2.2.4 Psychological green climate as a mediator

The psychological green climate is a shared organizational sense of environmental wellbeing (Chatelain et al., 2018). Through green

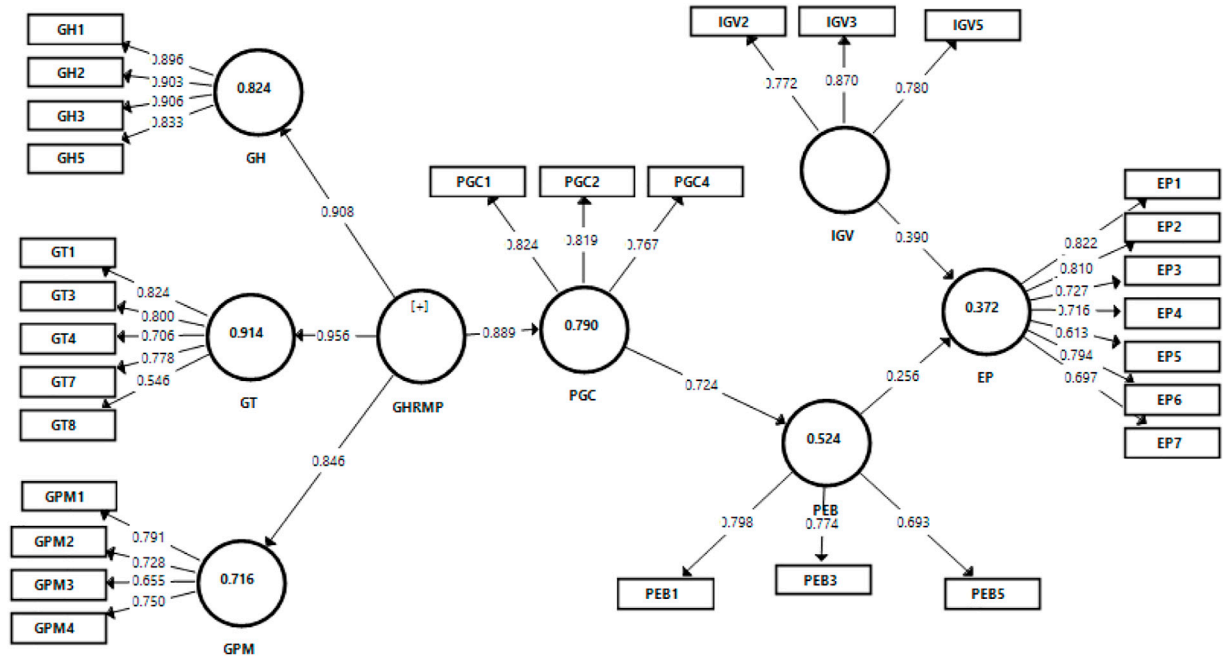


FIGURE 2
Measurement model.

human resource strategies and pro-environmental attitudes, employees' mutual opinions on environmental issues will be further reflected by the organization's laws, legislation, policies, and procedures. The psychological green climate is built on the process of social cognition (Dumont et al., 2017). The psychological environment strongly correlates with work fulfillment, burnout, position actions, and extra-role job success (Phillips and Dickie, 2015). Recent research has discovered a correlation between institutional environment policies, green environment activity, and successful green actions among employees (Norton et al., 2017). Employee interaction and management strategies form the psychological atmosphere if the goal is to help the organization. Green human resource management practices usually establish the requirements that workers must adhere to. Furthermore, by building a green psychological climate, green human resource management practices aid workers in addressing their anxiety about pro-environmental practices (Saeed et al., 2019). The psychological green climate encourages environmentally friendly behaviors (Capstick et al., 2019).

H4: Psychological green climate mediates the relationship between GHRM and pro-environmental behaviors.

### 2.2.5 Role of pro-environmental behaviors as a mediator

Employees' pro-environmental behaviors increase an organization's productivity and environmental performance. Green human resource policies and a positive psychological atmosphere boost environmental results (Naz Alt and Spitzeck, 2016). Typically, an organization's staff discovers this by monitoring others (Suganthi, 2019). Due to this, research has found that an organization's sustainability initiatives affect employee behaviors. The management identifies workers to respond in ways that are appreciated and desired in the workplace in a consistent approach to environmentally positive attitudes (Naz et al., 2021).

H5: The relationship between the psychological green climate and environmental performance mediated by pro-environmental behaviors.

### 2.2.6 Individual green values as a moderator

Karadag and Kayabasi, 2013 defined values as "what people believe to be fundamentally right or wrong." Therefore, they are "likened to 'building blocks of behavior by providing foundations for attitudes, which in turn, provide bases for action" (Schminke et al., 2015). Individuals' apprehension about the environment significantly influences their environmental behaviors (Chou, 2014). Previous research has established a momentous alliance between the green value of individuals and their behaviors toward the environment. Individuals with green values exhibit proof of green behavior; according to Chou (2014), individual green values have the potential to influence environmental efficiency. On the other hand, individual green values play a critical role in generating innovative ideas for business development (Esty and Winston, 2009) and innovative solutions aimed at corporate growth (Chou et al., 2012).

H6. Individual green values moderate the relationship between pro-environmental behaviors and environmental performance.

## 2.3 Control variable

Enormous studies have shown that some individual-level characteristics, including gender, organizational tenure, age,

and education, can also influence green behaviors in any business (Aljarah, 2020). Employee cognitive capacities can be influenced by years of experience and other socio-demographic factors. Controlling these components might be effective (Li et al., 2020). Moreover, with age, experience, and education, employees become more capable, skilled, and innovative, which may influence their green perspectives (Zhang, Xu, and Wang, 2020). In consistence with the previous research and the present theoretical model, this study employed the gender, age, experience, and education of current employees as control variables.

# 3 Methodology

## 3.1 Population and samples

In the present study, the population includes people from private hospitals located in the district of Sialkot, Pakistan; at the same time, these hospitals are following green practices. Convenience sampling was used for the collection of data from respondents. Data were gathered from the general managers and HR managers of private hospitals in Sialkot, Pakistan. To reduce the likelihood of bias, each responder was given specific instructions regarding their involvement (Tabachnick et al., 2007). The questionnaires were distributed among 160 private hospitals, out of which 120 responses were returned. After the screening of incomplete responses, 110 responses were found to be useful for the analysis.

## 3.2 Measures

This research included variables such as green human resource management practices, psychological green climate, pro-environmental behavior, individual green value, and environmental performance, all of which were measured using a five-point Likert scale to a rating scale from 1 (strongly disagree) to 5 (strongly agree). Green human resource management practices were measured, which consist of three dimensions. Mousa and Othman's (2020) six-item scale was adopted to measure green hiring, green training, and the involvement scale used by Yusoff et al., 2020, and the four-item scale of green performance management and compensation was used by Tang et al., 2018 in their study.

The seven-item scale of pro-environmental behaviors was developed by Robertson and Barling (2013). A total of three items from Chou's (2014) personal environmental scale were used to calculate an individual's green rating. The environmental performance eight-item scale was also used, which was developed by Kim Y. J. et al. (2019).

# 4 Results and data analysis

Researchers used a smart PLS for data analysis in Figure 1 since it is widely utilized as a modern evaluation method in business research. To evaluate the convergent validity by loading, Table 1 and Figure 2 explain loading, which was above .50 after deleting the items whose loading was below .50. Similarly, all constructs have a composite

TABLE 2 Discriminant validity (HTMT) (first-order).

| | EP | GH | GHRM | GPM | GT | IGV | PEB | PGC |
|---|---|---|---|---|---|---|---|---|
| EP | | | | | | | | |
| **GH** | 0.709 | | | | | | | |
| **GHRM** | 0.725 | 0.875 | | | | | | |
| **GPM** | 0.656 | 0.737 | 0.652 | | | | | |
| **GT** | 0.808 | 0.745 | 0.675 | 0.575 | | | | |
| **IGV** | 0.703 | 0.872 | 0.488 | 0.761 | 0.655 | | | |
| **PEB** | 0.724 | 0.805 | 0.467 | 0.544 | 0.776 | 0.702 | | |
| **PGC** | 0.629 | 0.833 | 0.679 | 0.736 | 0.697 | 0.638 | 0.735 | |

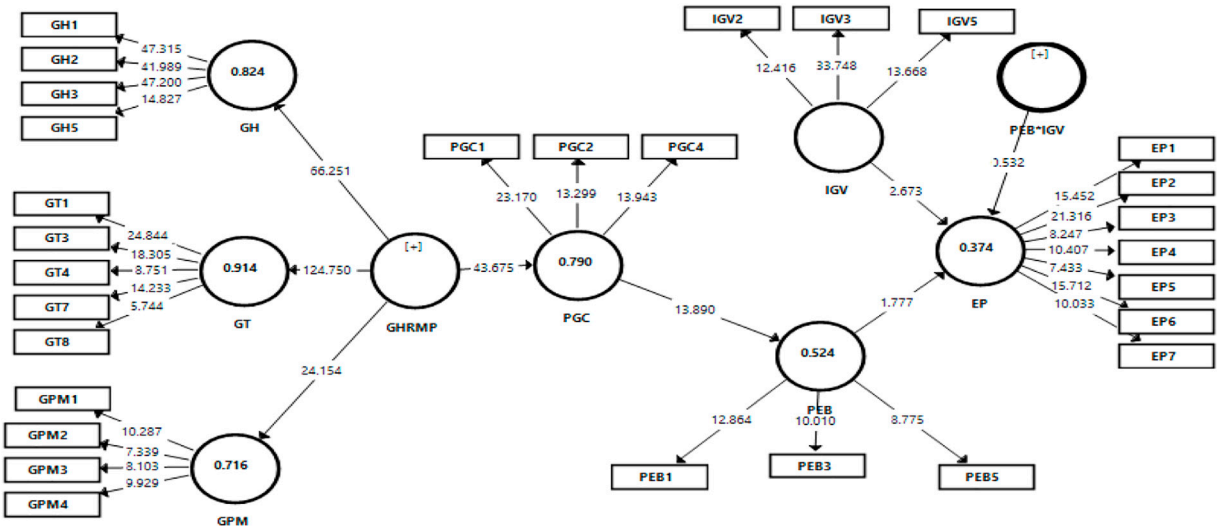


FIGURE 3
Structural model.

**TABLE 3** Path analysis.

| | "Relationships" | "Beta" | S.D | T-value | *p*-value | L.L | U.L | "Decision" |
|---|---|---|---|---|---|---|---|---|
| H1 | GHRM---> PGC | 0.89 | 0.021 | 42.755 | 0.000 | 0.85 | 0.917 | Supported |
| H2 | PGC-> PEB | 0.72 | 0.049 | 14.856 | 0.000 | 0.63 | 0.795 | Supported |
| H3 | PEB-----> EP | 0.26 | 0.156 | 1.692 | 0.046 | 0.02 | 0.524 | Supported |
| H4 | GHRM----> PGC--> PEB | 0.64 | 0.052 | 12.313 | 0.000 | 0.55 | 0.716 | Supported |
| H5 | PGC---> PEB---> EP | 0.19 | 0.118 | 1.618 | 0.053 | 0.01 | 0.395 | Not supported |
| H6 | Moderating effect---> EP | 0.05 | 0.098 | 0.483 | 0.315 | 0.12 | 0.223 | Not supported |

reliability above the recommended value of .70 and also all AVE values above the recommended value, which is .50. On the whole, there was no issue in the present study regarding the discriminant validity.

Table 2 and Figure 3 shows that there was an HTM, which validated the discriminant validity. The given values are less than the value of .85, as discussed by Kiline (2011).

## 4.1 Structural assessment models

Structural modeling was executed to test the hypothesis of this study. Path coefficients and T-values are computed to explain the relationships of the hypothesis. The bootstrapping procedure was adopted for the mediation and moderation effect.

Table 3 shows that H1 green HRM practices were significantly associated with the psychological green climate ($\beta$ = 0.122, t = 42.755, L.L = 0.85, U.L = 0.917, and *p*-value is 0.000). Therefore, H1 supported the results showing the H2 psychological green climate positive link with pro-environmental behaviors ($\beta$ = 0.72, t = 14.856, L.L = 0.63, U.L = 0.917, and *p*-value = 0.000), in the same way that this H3 pro-environmental behavior is the link to the environmental performance ($\beta$ = 0.26, t = 01.692, L.U = 0.02, U.U = 0.524, and *p*-value = 0.046). Therefore, H3 was supported besides the H4 psychological green climate, and it mediated the relationship of green HRM and pro-environmental behaviors ($\beta$ = 0.64, t = 12.313, L.L = 0.55, and U.L = 0.716). H4 is also supported. The H5 pro-environmental behavior mediated the association with the psychological green climate and environmental performance ($\beta$ = 0.19, t = 1.618, L.L = 0.01, and U.L = 0.395). H5 is not supported. Lastly, the H6 individual green value moderated the pro-environmental behavior ($\beta$ = 0.05, t = 0.483, L.L = 0.12, U.L = 0.223, and *p*-value = 0.315). H6 is not supported.

# 5 Discussion

The previous study has demonstrated that pro-environmental behavior among workers improves environmental performance (Robertson and Barling, 2013). However, the relevance of such activities is expanding in the present global period as nations make concentrated attempts to achieve organizational greening through acclimating workers to connect with pro-environmental proposals (Paillé et al., 2014; Norton et al., 2017). The psychological green climate as a predictor of pro-environmental behavior studied the degree of the individual green value influence on the relationship between pro-environmental behaviors (Dumont et al., 2017). According to the present study's results, green human resource

management practices have a significant relationship with the psychological green climate. According to previous studies, environmental workplace practices and the devotion to green human resource practices affect employee behaviors when operating in a psychological green environment (Dumont et al., 2017; Yusliza et al., 2017; Pham et al., 2020; Ali et al., 2022). The present study followed the hypotheses by collecting data from healthcare workers employed in the Hospital District of Sialkot, Pakistan, and analyzing the results. As a result, we investigated the function of the green psychological climate in mediating the link between green human resource management practices and pro-environmental activities. The green psychological environment is shown to be a valuable resource for enhancing the link between green human resource management practices and pro-environmental behaviors. Despite the significance of the green psychological climate for pro-environmental activities, there is a vacuum in comprehensive observational evidence linked with the proposed study paradigm; as a result, the authors of this study looked at the moderation of the individual green value with pro-environmental behaviors and environmental performance (Dumont et al., 2017; Naz et al., 2021). Empirical research does not support this moderating relationship, and it has been claimed that individual values for the environment do not affect the pro-environmental behavior or environmental performance.

## 5.1 Theoretical contributions

As previously stated, environmental sustainability has become a crucial study issue due to the growing apprehension for environmental protection. Despite the research that has been carried out in this area, it is still unclear how employees' behaviors toward the environment and green human resource management practices develop a system to improve environmental sustainability (Saeed et al., 2019; Naz et al., 2021). The current study potentially adds to the body of knowledge in various ways. To begin with, the current study theoretically contributes to bridging the research gap by studying linkages between study components in the context of the Pakistani healthcare business using the combined academic paradigms of the social cognitive theory and norm activation. It is still unknown despite the numerous works of research that have been undertaken on the topic, how environmental and personal elements boost the behavior of employees that contribute toward the fulfillment of green corporate goals to safeguard the environment. Second, when investigating rising research trends in Pakistan, the existing research is performed to cover the investigative gap and learn more about the multifaceted phenomena of the employee pro-environmental behavior and how it relates to the environmental performance. Finally, this study adds to the knowledge by including individual green values as a moderator with pro-environmental behaviors and environmental performance, thereby addressing a knowledge gap found in the prior research (Dumont et al., 2017; Naz et al., 2021).

## 5.2 Practical implications

The study has practical implications for company managers who want their staff to embrace pro-environmental behaviors and implement green human resource management practices for improved environmental performance at the organizational level. A previous study (Podsakoff and Organ, 1986; Saeed et al., 2019) indicated that organizations focus on GHRMP for efficient green policy implementation. Organizations should make a concerted effort to create a green psychological climate by using green human resource strategies. The managerial level's concern for the environment pushed them to be in charge of developing green HRM policies. As a result, managers must hold themselves accountable for implementing HRM practices for environmental sustainability. The study reveals that the presence of organizational green shared visions raises the beneficial influence of GHRMPs on employees' convictions so that they can effectively accomplish environmental objectives, address environmental difficulties, and carry out green missions. Therefore, the highest level of management should ensure that sustainable human resource management methods are supported by appropriate environmentally conscious visions. Finally, study findings point practitioners toward rewarding workers in financial and non-financial ways to incentivize them to engage in eco-friendly actions. Managers should solicit their ideas for resolving environmental challenges to encourage workers to engage in pro-environmental practices. Employees' interests grow as a result of participating in pro-environmental behavioral activities.

## 5.3 Limitations and future research

First, the current study has the limitation that the manufacturing sector has addressed; future studies need to address this model and framework in other sectors just as the pharmaceutical and chemical industries, which will ensure the present study results in other sectors. Second, the current research was conducted in a developing economy, such as Pakistan's; future research should be conducted in a country with a cultural difference in the developing world. Third, future researchers should consider different mediators in the present study model as corporate social responsibilities, job satisfaction, and moderator roles (organizational citizenship behavior, green creativity, and green self-efficacy) will make a greater contribution to the literature of green human resource management practices and environmental performance.

# Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

## Author contributions

ML and SUQ contributed equally as first author. SUQ: conceptualization. RQ : methodology and interpreted results. SUQ: formal analysis, investigation resources, and visualization. SUQ, ZM, RZUA, SQ, MKK, ML, HA, SM: validation, and writing original draft preparation, review and editing. SUQ and SM: data curation. ZM, HK and ML: project administration. All authors have read and agreed to the published version of the manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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# How to realize digital transformation in satellite communication industry? -- Configuration analysis based on the technology-organization-environment framework

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**Introduction:** Digital transformation is the key link of the prosperity and development of digital economy, and the successful digital transformation is the result of the synergy of multi-level factors.

**Methods:** Based on the theoretical framework of technology-organization-environment, this paper takes 27 satellite communication enterprises as samples and uses fuzzy set qualitative comparative analysis method to explore the configuration effect of six antecedent conditions at the level of technology, organization and environment on digital transformation of satellite communication enterprises.

**Results:** The results show that a single antecedent condition does not constitute a necessary condition for digital transformation. There are four configuration paths for digital transformation of satellite communication industry, which are technology-organization-oriented, technology-organization-environment collaboration-oriented, technology-organization-oriented environment collaboration, and organization-environment-oriented. Under certain conditions, there is substitution effect between antecedents.

**Discussion:** The complex causes of the digital transformation of Chinese satellite communication enterprises, and can provide beneficial enlightenment for the digital transformation of satellite communication enterprises.

KEYWORDS

**digital economy, technology-organization-environment framework (TOE), satellite communication industry, fuzzy-set qualitative comparative analysis (fsQCA), digital transformation**

# 1 Introduction

With the emergence of a new round of scientific and technological revolution and industrial transformation, the Internet, big data, cloud computing, artificial intelligence and other digital technologies are changing with each new day. The digital economy, with data resources as an important factor of production and total factor digital transformation as an important driving force, has developed vigorously (Pan et al., 2022). Under the new wave of scientific and technological revolution and industrial transformation, the Chinese government attaches great importance to the digital economy. In the 14th Five-Year Plan and the outline of 2035 vision goal, China has clearly proposed to promote the building of a space power and digital China (Zhang et al., 2018). Under the background of digital economy, satellite communication industry, as the main battlefield of China's development of digital economy, is the main direction and key breakthrough to promote the integration of digital economy and real economy (Ding et al., 2022). Especially in the international situation where the United States and other developed countries are vigorously implementing the "Star-link" strategy to further widen the gap with developing countries, the development of China's space industry will be under increasing pressure (Lee et al., 2021). How to realize the digital transformation of satellite communication industry with digital technology is an important topic for realizing smart spaceflight (Pagani, 2013), improving the development mode of China aerospace + China Service, and implementing the national strategy of "One Belt and One Road" spatial information corridor (Liu and Suk, 2022). Therefore, the digital transformation of satellite communication industry is not only an important way to promote the high-quality development of China's satellite communication industry (Wen et al., 2022), but also an important support to drive the development and growth of China's digital economy. At the same time, exploring the law of digital transformation of satellite communication industry has also become a theoretical issue of academic focus (Amankwah-Amoah et al., 2021).

Satellite communication industry is a kind of industry that uses radio communication technology, sophisticated materials and other production factors and uses artificial Earth satellites as relay stations to forward radio waves, so as to realize communication between two or more Earth stations (Faheem et al., 2018). China's 14th Five-year Plan calls for economic development to focus on the real economy, accelerating the development of China's space power and satellite communications industry (Suk-Ching Tang and Lee, 2003), and promoting the deep integration of the Internet, big data, artificial intelligence and the real economy (Allam and Dhunny, 2019). Against the backdrop of weakening momentum of the global economic cycle, promoting high-quality development of the satellite communication industry is the basic support for the formation of a new development pattern and an urgent need to meet the demand of China's huge domestic market. Under the tide of digital economy, China's satellite communication industry has a strong desire for digital transformation (Zaki, 2019). However, due to the widespread problems of resource rigidity, path dependence and innovation burnout in enterprises, artificial intelligence, industrial Internet, block chain and other digital technologies are difficult to organically integrate into the satellite communication industry in a short period of time, and ultimately, the role of digital technology in leading the high-quality transformation and upgrading of the satellite communication industry is not obvious (Wenzel, 2015). Moreover, there are huge differences in production capacity, technical level and number of employees among enterprises, and the countermeasures obtained through single path research cannot well guide China's satellite communication enterprises to realize digital transformation (Vergne and Durand, 2010). Therefore, this paper regards the digital transformation of satellite communication enterprises as a process of the organic integration of satellite communication industry and digital technology, in which the satellite communication industry applies digital technology to promote its own high-quality development (Birner et al., 2021). Based on this, this paper combines the technology-organization-environment (TOE) theoretical framework, which is suitable for the study of emerging technology transfer. This paper takes 27 Chinese satellite communication enterprises as cases, and uses the qualitative Comparative analysis (QCA) method. This paper discusses the configuration paths of digital transformation of satellite communication enterprises promoted by the pre-factors such as digital technology transition and management mode transformation, further explores the similarities and differences between the configuration paths of digital transformation of different satellite communication enterprises, and tries to open the "black box" of digital transformation of satellite communication enterprises. Combined with the results of empirical analysis, this paper puts forward management enlightenment to promote the digital transformation of satellite communication enterprises, and promote the "key minority" of China's space industry -- satellite communication industry under the background of digital economy. On the premise of maintaining high-quality development, we should take the lead in realizing digital transformation, give full play to the "head goose effect", stimulate the vitality of geese, provide guidance for other aerospace enterprises in digital transformation, and ensure the completion of high-quality transformation and upgrading of China's aerospace industry. In short, this study aims to accomplish two main objectives:

- Explain whether a single factor is a necessary condition for the digital transformation of satellite communication enterprises.
- To study the configuration effect of the T-O-E framework on the digital transformation of satellite communication enterprises.

# 2 Literature review and research model

## 2.1 Literature review

In recent years, scholars have found that the process of enterprise digital transformation is affected by many factors, such as the awareness of digital transformation (Hanelt et al., 2021); Technological transition (Rohracher, 2001); Infrastructure construction (Chang and Kendall, 2011); Management change (Jilte et al., 2021); Internal factors of enterprises (Chi et al., 2022); Policy promotion (Vu and Hartley, 2022); Enterprise cooperation (Zhang et al., 2022); Influence of external factors

such as government guidance (Llopis-Albert et al., 2021); Environmental factors (Feroz et al., 2021; Chen and Tian, 2022). In the context of China, the digital transformation of satellite communication enterprises needs to be considered comprehensively by combining their own characteristics and integrating various factors (Giua et al., 2022). Previous scholars have done a lot of research on the factors influencing the digital transformation of space enterprises from the technical, organizational and environmental levels, and relevant fruitful research results have important reference significance and inspiration for further discussion on the path of digital transformation of satellite communication enterprises (Lin and Yi, 2022). However, from the single level of technology, organization, only considering the single factors promote the net effect of the digital transformation, aerospace industry is difficult to reflect different dimensions of factors on the combined influence of the digital transformation, aerospace industry cannot explain system digital transformation of enterprises of different space complex multi-factor joint mechanism (Yaacoub et al., 2022). Are the driving factors for digital transformation of satellite communication enterprises necessary conditions? What is the difference in linkage matching effect between single factor and various factors? And what are the similarities and differences in driving paths? The relationship and difference between the factors influencing the digital transformation of satellite communication enterprises and whether different factors have a combination role in promoting the digital transformation of satellite communication enterprises still need to be further discussed.

## 2.2 Research model

This paper integrates the TOE theoretical framework and existing studies with the specific context of digital transformation of satellite communication enterprises in China, and identifies the condition variables driving digital transformation of satellite communication enterprises in terms of technology, organization, and environment, taking into account various factors such as research samples, research methods, and research feasibility.

The influencing factors of technological dimension are mainly reflected in digital technology transition and digital facilities construction, which are the important forces to promote the digital transformation of satellite communication enterprises (Zhao et al., 2018; Gangi et al., 2022; Gao and Yuan, 2022). In this paper, digital technology transition refers to that satellite communication enterprises rely on digital technology to meet users' expectations or change market standards by transforming technology orbit and providing new functional attributes (Ometov et al., 2021). Digital facility construction refers to the improvement of digital hardware level of satellite communication enterprises through digital infrastructure construction and industrial Internet supporting facilities construction in order to realize the organic integration of digital technology and itself (Yu and He, 2022). Digital technologies represented by artificial intelligence and industrial Internet have disruptive potential, which can help satellite communication enterprises meet users' expectations or change market standards by transforming technological track and providing new functional attributes (Alaimo, 2022), so as to realize technological transition and enhance technological innovation capability of enterprises (Ryu et al., 2021). Therefore, digital technology transition is an important guarantee for the digital transformation of satellite communication enterprises as a prerequisite for enhancing technological innovation capability of enterprises (AlNuaimi et al., 2022). In addition, existing studies have proved that the construction of digital facilities will significantly promote industrial digitization and promote the upgrading of aerospace industrial structure (Borowski, 2021). Therefore, digital technology transition and digital facilities construction are important prerequisites for the digital transformation of satellite communication enterprises.

The influencing factors of organizational dimension are mainly reflected in the reform of management mode and improvement of production process, which are important space for the digital transformation of satellite communication enterprises (Eito-Brun and Amescua-Seco, 2018; Chen et al., 2021; Li et al., 2022). Within the research scope of this paper, management mode reform refers to that satellite communication enterprises rely on intelligent execution systems such as ERP and MES to promote the realization of intelligent aerospace technology by eliminating "digital islands" and improving the quality of employees (Guo et al., 2021). Production process improvement refers to that satellite communication enterprises rely on intelligent processing equipment, intelligent execution system and other advanced production factors to achieve workshop production data transparency and improve their own production process with digital information feedback. The digital management information system with ERP as the typical representative is considered as one of the important foundations for the internal digital transformation of enterprises (Pizzi et al., 2021). Digital technology will also promote satellite communication enterprises to improve the production process with products and processes as the entry point and promote the digital transformation of manufacturing industry (Mushi et al., 2022; Wen et al., 2022). Therefore, management mode reform and production process improvement can effectively promote the formation of internal advantages of digital transformation of satellite communication enterprises.

The influencing factors of the environmental dimension are mainly reflected in the two aspects of industry development level and enterprise competitive pressure, which are important opportunities for satellite communication enterprises to speed up their digital transformation. In the scope of this paper, industry development level refers to the operation level, development level and industry cluster construction level of the industry in which satellite communication enterprises are located; enterprise competitive pressure refers to the pressure brought by regional performance assessment, enterprise efficiency evaluation, and inter-enterprise market scramble and other behaviors on satellite communication enterprises. The level of development of the aerospace industry is the basis and an important carrier for the digital transformation of satellite communication enterprises, and regions with good development bases in the aerospace industry can rely on industrial advantages to carry the rapid development of industry digitalization in the region (Pathak and Dhakate, 2022). In

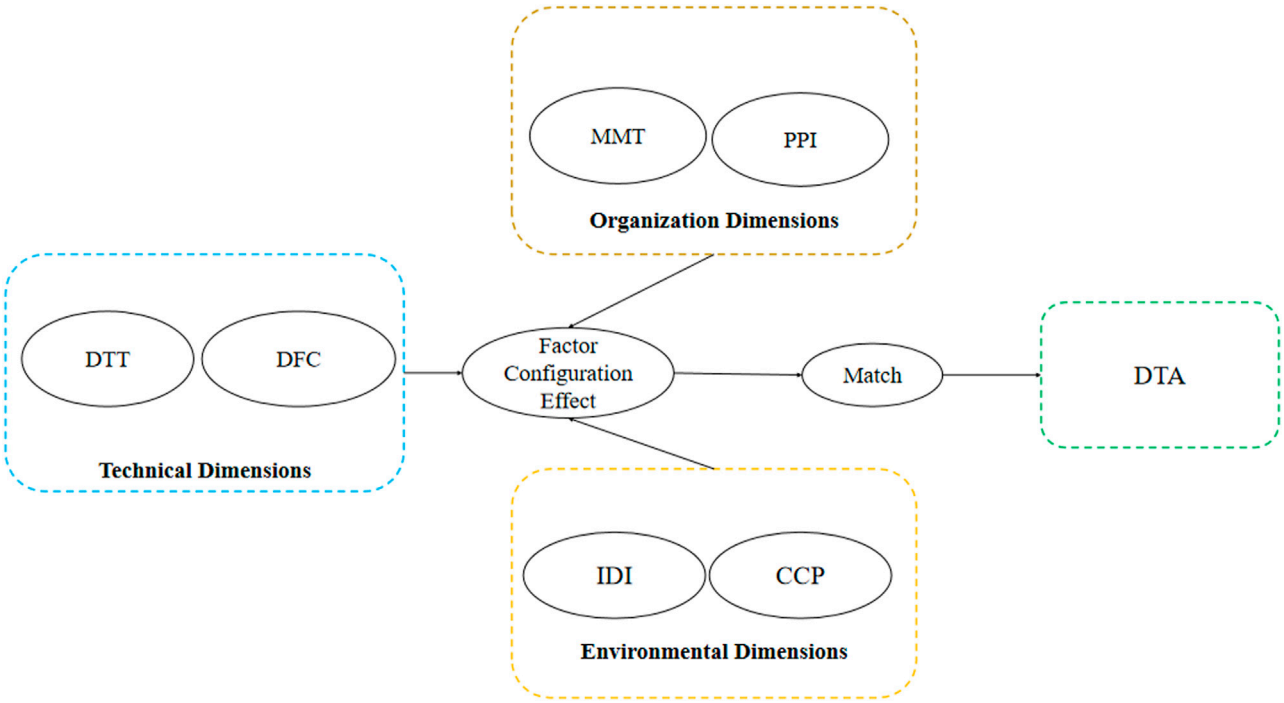


FIGURE 1
Research model.

the face of performance assessment each regional government must respond, so the competition between geographically close peer governments will inevitably affect the attention and behavior of local governments (Zhang et al., 2021). The digital transformation of the aerospace industry is the main pillar to promote the high-quality development of the digital economy, thus, when regional governments face competitive pressure from the digital high-quality development of the aerospace industry in neighboring regions, they will stimulate local governments to promote the digital development of the industry by means of digital transformation of satellite communication enterprises (Ganichev and Koshovets, 2019). The competitive pressure between regions is transmitted to satellite communication enterprises in each region through the government, which affects the digital transformation process of satellite communication enterprises. Therefore, the level of industry development and the competitive pressure of enterprises have an important impact on the advantages of digital transformation of satellite communication enterprises.

In summary, the digital transformation driver model of satellite communication enterprises constructed in this paper is shown in Figure 1.

# 3 Methodology

## 3.1 Sample

The reasons why satellite communication enterprises are selected as digital transformation research samples in this paper are as follows: One is satellite communications enterprises as digital technology and aerospace industry play in depth fusion, there was a significant difference between traditional price competition in digital economy as the main line of business model—satellite communications enterprises for the realization of the intelligent space, will actively seek digital core technology, intelligent management system and create a business model of rapid iteration. Therefore, satellite communication enterprises are the ideal objects to study the digital transformation of space industry. Second, compared with traditional aerospace enterprises, satellite communication enterprises integrate more high-tech achievements and apply more modern management experience, laying a good foundation for the realization of digital transformation of enterprises. It creates the possibility of value co-creation based on digital technologies such as industrial Internet and artificial intelligence, and provides a good soil for enterprises to connect with digital economy technologies such as artificial intelligence, industrial Internet and blockchain.

According to relevant studies on QCA model specifications, when the antecedent conditions of the model are six and the sample number is greater than 25, random data and real data can be distinguished to ensure the internal validity of configuration results (Fiss, 2011). On the basis of data collection principles such as typicality, richness and accessibility, combined with industry planning and think tank research reports such as “2021 China Unicorn Enterprise Research Report” and “2021 Space Industry Cluster White Paper”, this study finally selected 27 satellite communication enterprises for analysis.

**TABLE 1 Assignment criteria for digital transformation outcome variables for satellite communication enterprises.**

| Construct | Items | Score |
|---|---|---|
| Digital transformation advantage of satellite communication enterprises (DTA) | The company has complete digital transformation equipment and technical conditions, and is realizing the organic integration of digital technology and management mode and production process, with strong market influence | 1 |
| | The company has good digital transformation equipment and technology conditions, and is in the process of organic integration of digital technology and management mode, production process, and good market performance | 0.67 |
| | The company has sufficient digital transformation equipment, technical conditions, digital technology to promote the change of management mode, production processes, and faster growth in market share | 0.33 |
| | The company fail to has sufficient digital transformation equipment, technical conditions, digital technology has not yet driven the management model, production process changes, the market performance is general | 0 |

**TABLE 2 Assignment criteria for digital transformation condition variables of satellite communication enterprises.**

| Construct | Variable | Items | Assignment criteria | References |
|---|---|---|---|---|
| Technical Dimensions | Digital Technology Transition (DTT) | Nine criteria are measured in terms of digital technology sources, digital technology performance and digital technology development potential | In line with 7 or more criteria are met, the value is 1; In line with 4–6, the value is 0.67; In line with 2-3, the value is 0.33; If 1 or below is met, the value is 0 | Teixeira et al. (2022) |
| | Digital Facility Construction (DFC) | Nine criteria are measured in terms of infrastructure construction, industrial Internet and network security facilities construction | | Borowski (2021) |
| Organization Dimensions | Management Mode Transformation (MMT) | Nine criteria are measured in terms of digital information fluency and utilization capability, intelligent personnel quality trainingetc. | In line with 7 or more criteria are met, the value is 1; In line with 4–6, the value is 0.67; In line with 2-3, the value is 0.33; If 1 or below is met, the value is 0 | Zhao et al. (2017) |
| | Production Process Improvement (PPI) | Nine criteria are measured in terms of the degree of process intelligence and the degree of intelligent integration of logistics and supply chain | | Pizzi et al. (2021) |
| Environmental Dimensions | Industry Development Level (IDI) | Eleven criteria are measured in terms of industry operation overview, carrier construction situation and industry development status | In line with 9 or more criteria are met, the value is 1; In line with 6–8, the value is 0.67; In line with 3–5, the value is 0.33; If 2 or below is met, the value is 0 | Li et al. (2022) |
| | Corporate Competitive Pressure (CCP) | Eleven criteria are measured in terms of corporate partnerships, product market recognition, and government support | | Gangi et al. (2022) |

## 3.2 Data analysis technique

Based on set theory and Boolean operation, fsQCA deeply mines the interaction between antecedent conditions and their joint effect on results through configuration analysis (Chen and Tian, 2022). The reasons for applying fsQCA method in this paper are as follows: 1) fsQCA method integrates the advantages of quantitative and qualitative analysis, and can solve the problems of complex causality and common path in management research (Afonso et al., 2018). 2) fsQCA method is suitable for digital transformation research with "combination" characteristics (Mikalef and Pateli, 2017), which can explore how the collaborative interaction between variables successfully drives digital transformation from the perspective of configuration. 3) fsQCA method can be used to study small and medium-sized samples. Since there are only a few listed satellite communication enterprises at present, there are only 27 sample cases in this paper, which does not meet the requirements of multiple regression on sample size; 4) fsQCA method does not require special treatment of cross-level antecedent conditions, which is suitable for the multi-level analysis framework of this paper (Ragin, 2014).

## 3.3 Variable measurement and calibration

This study carried out the investigation according to the process of designing the scale, conducting small-scale investigation, improving the scale and issuing questionnaires, and then collected relevant data. In order to ensure that the scale has good reliability and validity, this study tries to draw lessons from previous research assumptions and research results, and tries to design the scale by adopting the items in the mature scale of existing literature. At the initial stage of designing the scale, we discussed several times

**TABLE 3 Test the necessity and sufficiency of conditional variables.**

| Condition | Consistency | Coverage |
|---|---|---|
| DTT | 0.810 | 0.979 |
| ~ DTT | 0.032 | 1.000 |
| DFC | 0.788 | 0.979 |
| ~ DFC | 0.287 | 0.988 |
| MMT | 0.713 | 0.988 |
| ~ MMT | 0.371 | 1.000 |
| PPI | 0.730 | 0.988 |
| ~ PPI | 0.354 | 0.993 |
| IDI | 0.784 | 0.989 |
| ~ IDI | 0.300 | 1.000 |
| CCP | 0.814 | 1.000 |
| ~ CCP | 0.278 | 1.000 |

with doctors who conducted relevant industry researches and middle and senior management personnel of enterprises to get the initial scale. In the middle stage, a small scale survey was carried out combined with the initial scale. In the later stage, the questionnaire items were repeatedly improved based on the survey feedback data, and the final scale was obtained.

For scholars from the production process, enterprise network characteristics, design a variety of external environment such as dimension index to depict the multidimensional characteristics of satellite communication enterprises digital transformation, give the inspirations of this study are as follows: one is the digital technology although plays an important role in the process of enterprise digital transformation, but rely on digital technology is not well realize satellite communication enterprises digital transformation. Enterprises need to apply digital technology science to all production links and make intelligent decisions based on data in combination with corresponding digital technology, so as to better accumulate the advantages of digital transformation of satellite communication enterprises. Second, if satellite communication enterprises do not pay attention to the importance of digital transformation, they will gradually lose their original advantages in resources, technology and management, increasing the difficulty for enterprises to break through the development bottleneck. Therefore, satellite communication enterprises also need to actively transition to digital transformation, give full play to their own advantages, combined with digital technology to promote their own better industrial upgrading.

In this paper, the digital transformation advantage of satellite communication enterprises (DTA) is taken as the result variable of the configuration model of digital transformation of satellite communication enterprises. Considering that the research data came from 27 case materials of satellite communication enterprises, the anchor points of the result variables were set as 0, 0.33, 0.67 and 1, among which "1" and "0" stand for complete membership and non-membership, and "0.67" and "0.33" are intersection points, that is, partial membership and partial non-membership (Fiss, 2007). The assignment criteria are shown in Table 1. Since the digital transformation of satellite communication enterprises is a fuzzy construct, this study, on the basis of integrating previous studies, takes the influencing factors at different levels such as digital technology level, management and production mode and external environment adaptability as conditional variables. The influence of its combined configuration on the digital transformation of satellite communication enterprises is discussed. The questionnaire measurement and evaluation criteria are shown in Table 2.

**TABLE 4 Configuration for high DTA.**

| Configuration | Solution | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| DTT | ● | ● | ● | ⊗ |
| DFC | ● | ● | | ● |
| MMT | ● | | ● | ● |
| PPI | ⊗ | ● | ● | ● |
| IDI | | ● | ● | ● |
| CCP | ● | ● | ● | ⊗ |
| Consistency | 1.000 | 0.980 | 0.990 | 0.970 |
| Raw Coverage | 0.310 | 0.490 | 0.430 | 0.170 |
| Unique Coverage | 0.120 | 0.100 | 0.040 | 0.040 |
| Overall solution consistency | 0.990 | | | |
| Overall solution coverage | 0.700 | | | |

Note: ● Core causal condition (presence). ● Peripheral causal condition (presence). ⊗Core causal condition (absence). ⊗Peripheral causal condition (absence). The blank cells represent do not care conditions.

# 4 Result

## 4.1 Necessity conditions analysis

Firstly, the necessity analysis of all the preconditions and their anti-conditions is carried out to judge the necessity of each condition in the realization of the result variable. The analysis results are shown in Table 3. If there is a single factor consistency rate higher than 0.9, it should be considered as a necessary condition. In this study, no single factor consistency rate is higher than 0.9, indicating that a single precondition is weak in explaining the digital transformation of satellite communication enterprises and should not be discussed as a necessary condition. Configuration matching is required to affect the digital transformation of satellite communication enterprises (The symbol "~" in the text represents the lack of antecedent elements or the opposite state).

## 4.2 Sufficient solutions

We used fsQCA3.0 software to analyze the standardized data. In line with established research, we conducted a sufficiency analysis by using a minimum case frequency benchmark ≥1. We also applied PRI (proportional reduction in inconsistency) to further filter the truth table rows that are reliably linked to the outcome. As the configurations with a PRI score below 0.5 may show inconsistency (Greckhamer et al., 2018), we adjusted four rows of data to 0 based on comprehensive analysis of case details and data distribution. Using these comprehensive standards, we obtained the truth table rows that meet the requirements and obtained the configurational paths by running the data. The results are given in Table 4. We identified four pathways that can lead to high levels of digital maturity. The overall solution consistency is 0.99, which explains the significance level of all configurations as a whole. The results show that the five configurations captured 70% of high-level digital maturity.

Configuration path 1: technology-organization-oriented (DTECT × DFC × MSC × ~PPI × CCP). This path shows that satellite communication enterprises with high degree of digital technology transition and management mode transformation, better digital facilities construction, less competitive pressure of enterprises and less investment in production process improvement can realize digital transformation faster. Digital technology transition (technology) and management mode transformation (organization) are the core conditions, while digital facility construction (technology), production process improvement (organization) and enterprise competitive pressure (environment) are the marginal conditions. This configuration path can explain about 31% of high-quality digital transformation cases in satellite communication enterprises, and 12% of them can be explained by this path alone.

Configuration path 2: technology-organization-environment collaboration-oriented (DTECT × DFC × PPI × IDI × CCP). This path shows that satellite communication enterprises with high digital technology transition degree, production process improvement degree and industry development level, better digital facilities construction and less competitive pressure can realize digital transformation faster. Among them, digital technology transition (technology), production process improvement (organization), industry development level (environment) are the core conditions, digital facility construction (technology), enterprise competitive pressure (environment) are the edge conditions. This configuration path can explain about 49% of high-quality digital transformation cases in satellite communication enterprises, and 10% of them are explained by this path alone.

Configuration path 3: technology-organization-oriented environment collaboration (DTECT × MSC × PPI × IDI × CCP). This path shows that satellite communication enterprises with high degree of digital technology transition and management mode transformation, better improvement of production process, less competitive pressure of enterprises and higher level of industry development can realize digital transformation faster. Among them, digital technology transition (technology) and management mode change (organization) are the core conditions, while production process improvement (organization), industry development level (environment) and enterprise competitive pressure (environment) are the marginal conditions. This configuration path can explain about 43% of high-quality digital transformation cases in satellite communication enterprises, and 4% of them can be explained by this path alone.

Configuration path 4: organization-environment-oriented (~DTECT × DFC × MSC × PPI × IDI × ~ CCP). This path shows that the satellite communication enterprises with high level of development and high degree of management mode transformation, good situation of digital facilities construction and production process improvement, and the satellite communication enterprises with no excessive investment in technological transition and high competitive pressure can realize digital transformation faster. The core conditions are management mode change (organization) and industry development level (environment), while the edge conditions are digital technology transition (technology), digital facility construction (technology), production process improvement (organization) and enterprise competitive pressure (environment). This configuration path can explain about 17% of high-quality digital transformation cases in satellite communication enterprises, and 4% of them are explained by this path alone.

## 4.3 Analysis of overlapping paths and potential alternatives

This study finds that there may be overlapping paths and potential substitutions among the preconditions of configuration paths for digital transformation of satellite communication enterprises. In order to intuitively reflect the connection between each path, this study made a Venn diagram (see Figure 2) combining configuration analysis data to show the block and coverage of each path in the fuzzy set.

This study focuses on the overlapping paths among paths 1, 2 and 3 and the potential substitution of factors. As the original coverage of path 4 is much lower than the other three paths, it is not included in the research scope. According to the visualization results of the original coverage and unique coverage of the three paths on the Venn diagram of configuration path connection, it can be seen

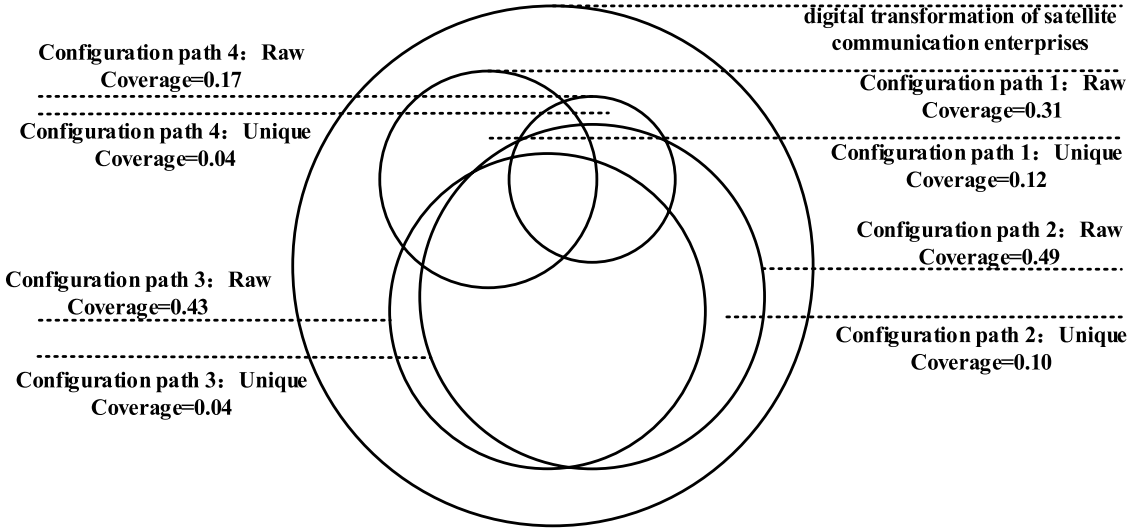


FIGURE 2
Configuration path connection status.

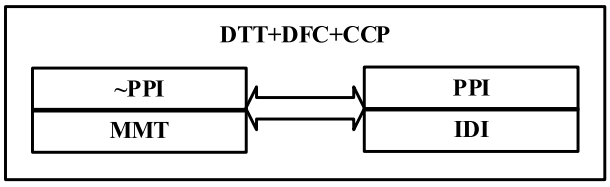


FIGURE 3
Overlapping paths and substitution relationships between path 1 and path 2.

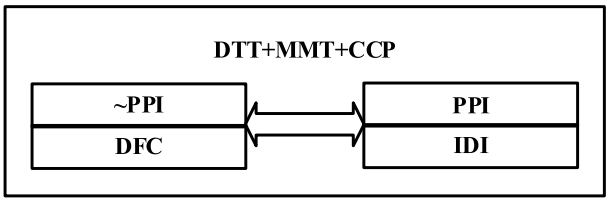


FIGURE 5
Overlapping paths and substitution relationships between path 1 and path 3.

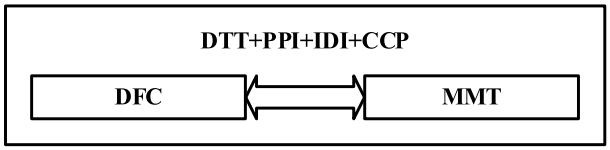


FIGURE 4
Overlapping paths and substitution relationships between path 2 and path 3.

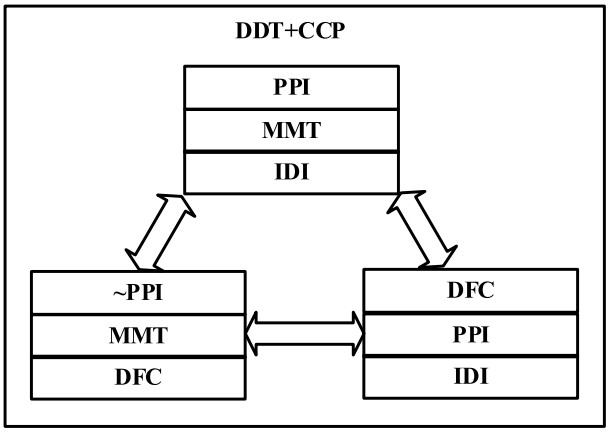


FIGURE 6
Overlapping paths and substitution relationships among path 1, path 2, and path 3.

that the three paths are not completely isolated, and there is a strong connection between paths. Therefore, on the premise that the three paths overlap, this study attempts to explore the possible substitution relationship among the three configuration paths of the digital transformation of satellite communication enterprises.

Firstly, there are overlapping paths between path 1 and Path 2, which are composed of digital technology transition, digital infrastructure construction and enterprise competitive pressure. Under this premise, there is a substitution relationship between ~ production process improvement, management mode change, industry development level and production process improvement, as shown in Figure 3. Secondly, there are overlapping paths between path 2 and path 3, which consist of digital technology transition,

production process improvement, industry development level and enterprise competitive pressure. Under this premise, there is a substitution relationship between digital facility construction and management mode reform, as shown in Figure 4. Thirdly, there are overlapping paths between path 1 and path 3, which consist of digital technology transition, management mode transformation and enterprise competitive pressure. On this basis, there is a substitution relationship between ~ production process improvement, digital facility construction, production process improvement and industry development level, as shown in Figure 5. Finally, the three paths are further analyzed. There are overlapping paths composed of digital technology transition and enterprise competitive pressure between paths 1, 2 and 3. On this basis, there is a substitution relationship between ~ production process improvement, digital facility construction, management mode change and production process improvement, digital facility construction, industry development level and management mode change, production process improvement and industry development level, as shown in Figure 6.

# 5 Conclusion

Based on the sample data of 27 satellite communication enterprises, this study combined TOE theoretical framework and fsQCA method to explore the configuration path of digital transformation of satellite communication enterprises, and explored the overlapping paths among the configuration paths and the potential substitution relationship of pre-factors. The research conclusion of this paper mainly includes the following two points: First, any single antecedent condition in the dimensions of technology, environment and organization cannot constitute the necessary condition for digital transformation of satellite communication enterprises, and antecedent condition needs configuration matching to promote digital transformation of satellite communication enterprises. There are four driving paths for digital transformation of satellite communication enterprises, which are technology-organization-oriented (path 1), technology-organization-environment collaboration-oriented (path 2), technology-organization-oriented environment collaboration (path 3) and organization-environment-oriented (path 4). Second, there are overlapping paths and potential substitution relationships between path 1 and path 2, path 2 and path 3, and path 1 and path 3. Further research finds that there are also overlapping paths and potential substitution relationships between path 1, path 2 and path 3.

# 6 Discussion and implication

## 6.1 Implication

From the perspective of configuration path, enterprise managers should realize the superiority of configuration path development strategy in digital transformation strategy and attach importance to the application of configuration coordination thinking. The results show that although digital technology transition and management mode transformation are the core conditions in the configuration path of digital transformation of satellite communication enterprises, a single precondition cannot guide them to realize digital transformation. In terms of the results of guiding the digital transformation of satellite communication enterprises, the multi-factor combination driven strategy is obviously better than the single factor driven strategy (Zhao et al., 2018; Gangi et al., 2022). Therefore, satellite communication enterprise managers should pay attention to the combined utility of technology, organization, environment and other factors, attach great importance to the coordination of various conditions on the premise of clarifying the technical conditions, management ability and environmental advantages of the enterprise, and formulate the configuration path of digital transformation in line with the current enterprise situation (van Grootel et al., 2020; Li et al., 2022).

From the perspective of overlapping paths and alternative factors, enterprise managers should clarify the relationship between overlapping paths and alternative factors and make the optimal decision of digital transformation of satellite communication enterprises in a short time (Eito-Brun and Amescua-Seco, 2018; Pathak and Dhakate, 2022). The results show that the combination of "digital technology transition + enterprise competitive pressure" is the most universal; On the premise that the enterprise improves the combination of such factors, managers can make optimal development decisions at each key node of digital transformation by combining the characteristics of the enterprise and the substitution relationship of factors. When an enterprise wants to realize its digital transformation through the technology-organization oriented path, the optimal strategy at the key nodes is to prioritize the construction of digital facilities or reform management mode on the premise of improving the combination of "technological transition + enterprise competitive pressure" elements. The development path can be adjusted at any time according to the status of enterprise digital transformation while realizing digital transformation according to technology-organization oriented path. Therefore, managers should give full consideration to overlapping paths and alternative factors when making short-term decisions at key nodes of digital transformation, so as to improve the fault tolerance rate of decisions while ensuring correct decisions.

From the perspective of influencing factors, enterprise managers should pay attention to the characteristics of the preconditions and formulate the corresponding long-term cultivation strategy of factors combined with the enterprise's own conditions. The results show that digital technology transition and management mode transformation are the core conditions in the configuration path of digital transformation of satellite communication enterprises. Production process improvement, industry development level of core conditions and edge conditions; Digital facility construction and enterprise competitive pressure are mostly marginal conditions. First of all, enterprise managers should attach great importance to the positive effect of digital technology transition and management mode reform on the digital transformation of satellite communication enterprises; Secondly, enterprise managers need to realize that production process improvement and industry development level are also important factors in the process of digital transformation. Finally, enterprise managers need to understand that the construction of digital facilities and the competitive pressure of enterprises are the keys to promote the digital transformation of satellite communication enterprises. Therefore, enterprise managers need to combine the characteristics of the pre-conditions and the characteristics of the enterprise itself to develop the corresponding factor training program, to complement the shortcomings of the pre-factors of the enterprise and relieve the dependence on single advantage, and drive the high-quality transformation and upgrading of the enterprise.

### 6.2 Limitations and future research

Since there are few maturity scales in the field of digital transformation of satellite communication enterprises and data collection principles such as typicality, richness and accessibility are taken into account, the questionnaire is designed in the form of scoring scale in this study, and likert scale can be used to design the questionnaire later. In addition, in the empirical analysis of this study, different characteristics are found in digital transformation paths of satellite communication enterprises in different fields. Subsequent attempts can be made to analyze the connection and difference between configuration paths of digital transformation of satellite communication enterprises in different fields.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

Ethical approval was not required for this study as per local and institutional guidelines.

## Author contributions

Methodology and software, LW and LJ.; formal analysis, LW and JH; resources and data curation, HZ, LJ and QW; investigation, LW; writing-original draft preparation, LW; writing-review and editing, LS and KD; supervision and project administration, PL and JH; All authors have read and agreed to the published version of the manuscript.

## Conflict of interest

LW, KD, PL, and JH were employed by Xi'an Aerors Data Technology Co., Ltd.; HZ, LJ, QW, and LS were employed by Space Star Technology Co., Ltd.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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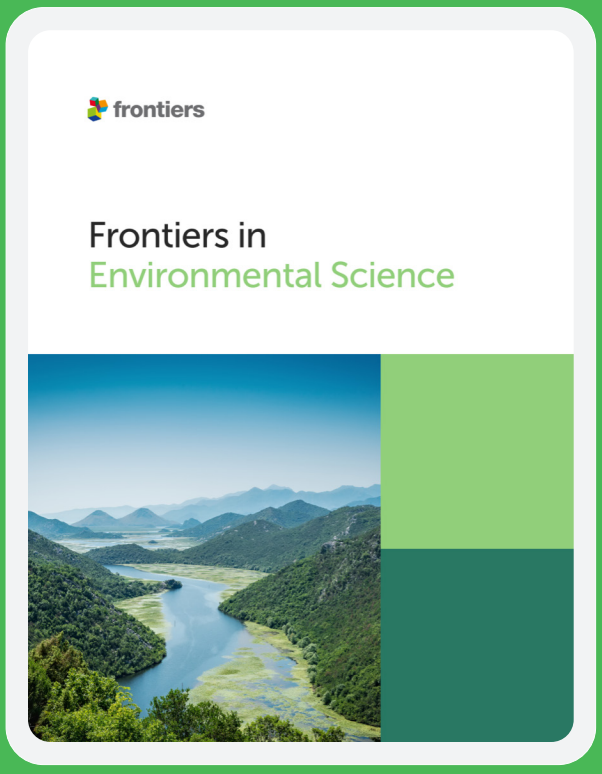


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