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# A comprehensive review of the soil health status for enhancing agricultural sustainability

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Sustainable agricultural practices have become more crucial than ever as the world grapples with food insecurity and environmental degradation. Soil health, a fundamental attribute of agricultural productivity and ecosystem stability, plays a pivotal role in achieving global sustainability targets. Despite its importance, comprehensive analyses of soil health initiatives remain limited. This systematic review addresses this gap through a dual objective: first, to contextualize the critical role of soil health in advancing the Sustainable Development Goals (SDGs); and second, to critically evaluate the implementation, impact, and policy relevance of India's Soil Health Card (SHC) scheme launched in 2015 to enhance soil fertility through site-specific assessments and tailored fertilizer recommendations. Global research highlights the crucial role of soil health in promoting sustainable agriculture, and the SHC scheme has yielded notable results, including a 5%–6% increase in crop yields and an 8%–10% decrease in chemical fertilizer usage. Grounded in the framework of the SDGs, this paper highlights the SHC scheme's contributions to enhancing farm productivity, lowering input costs, and advancing environmental objectives. It further explores the policy landscape, identifies institutional gaps, and examines the potential for scaling and adapting these practices in other regions. This review offers evidence-based insights into the interplay between soil health, agricultural sustainability, and policy innovation, aiming to inform future interventions and promote international collaborations in sustainable land management.

KEYWORDS

**soil health, soil health cards, agricultural sustainability, sustainable development goals, soil management practices, climate change mitigation, food security and poverty reduction**

## 1 Introduction

Sustainable agriculture has become a crucial area of focus for policymakers and researchers, given the growing challenges of environmental degradation and food insecurity. A central element of sustainable agriculture is soil health, which is essential for maintaining agricultural productivity, ecological balance, and climate resilience. Despite the commitments outlined in the Sustainable Development Goals (SDGs) to address environmental and socio-economic issues, soil health has received limited attention. This is notable because soil quality has a direct influence on food security, environmental sustainability, and the livelihoods of billions of people worldwide.

Currently, only about 1.4 billion hectares, or roughly 10% of the global land area, is classified as arable (Food and Agriculture Organization (FAO), 2023) and approximately 33% is already degraded due to unsustainable land management, overuse of chemical inputs, and climate change (FAO, 2015; Lal, 2015). The average *per capita* cropland has halved over the past six decades, and further declines are projected due to rapid urbanization and population growth. By 2050, 68% of the global population is expected to live in urban areas, contributing to the annual loss of 1.8%–2.4% of cropland (Bren d'Amour et al., 2016; United NationsDepartment of Economic and Social AffairsPopulation Division, 2019). These dynamics place enormous pressure on agricultural systems to produce more food from shrinking and degraded land. Projections suggest that food production must increase by 59%–102% by 2050 to meet global demand (Pawlak and Kołodziejczak, 2020). Given the urgency in meeting the food demand, this challenge concerns the pressure on crop land and in this context, preserving and restoring soil health is not merely an agronomic concern but a strategic imperative for ensuring long-term food security, climate adaptation, and sustainable land management.

In response, several global initiatives have emerged to promote sustainable soil management. The Global Soil Partnership (GSP), led by the FAO, and the Land Degradation Neutrality (LDN) framework of the United Nations Convention to Combat Desertification (UNCCD) aim to foster cooperation and improve governance of soil resources. Projects such as Global Soil Organic Carbon Sequestration (GSOCseq) promote soil carbon sequestration to enhance fertility and mitigate climate change. Additionally, the recognition of World Soil Day and the inclusion of soil-related targets in the SDGs reflect growing, though still insufficient, attention to this foundational issue.

In the Indian context, the challenges of soil degradation are acute. With 16.8 crore hectares of farmland, India has the largest area under cultivation globally (FAO, 2023). Yet nearly 32% of Indian land is degraded, and 25% faces desertification (FAO, 2024). Agriculture supports nearly half of the Indian population and contributes 14.5% to GDP (Gulati and Juneja, 2022). Declining soil health not only threatens food security and farmer livelihoods, but also risks derailing national sustainability goals. To address this, the Government of India launched the Soil Health Card (SHC) scheme in 2015. The SHC program provides farmers with individualized soil assessments and nutrient recommendations, aiming to optimize fertilizer use, enhance productivity, and promote long-term soil stewardship. Early assessments suggest that the scheme has improved yield efficiency and contributed to more sustainable input use (Ministry of Agriculture and Farmers' Welfare, 2020; Ministry of Agriculture and Farmers' Welfare, 2021).

This review paper seeks to evaluate the SHC scheme within the broader context of sustainable agriculture and global soil governance. Specifically, it aims to: (1) contextualize the importance of soil health in meeting the SDGs, and (2) assess the implementation, impact, and policy relevance of the SHC initiative in India. This paper examine the drivers of soil degradation and the design of targeted policy responses, and offers insights for researchers, policymakers, and development practitioners seeking to enhance agricultural sustainability through soil health interventions.

## 2 Methodology

In order to deliver an in-depth examination of the soil health issue at globally and the impact of SHC scheme on promoting agricultural sustainability in India, we employed a systematic approach to collect and evaluate relevant literature (Figure 1). We conducted a thorough search of academic databases such as PubMed, Web of Science, Scopus, Science Direct, and Google Scholar, focusing on peer-reviewed journals, conference papers, and official reports. Aligned with the study's objectives, our study centers on soil health issues through the lens of social sciences, sustainability frameworks, and farmer-cantered practices. Therefore, the keywords used in the search included "soil health," "soil health cards," "agricultural sustainability," "sustainable agriculture," "soil health management," "sustainable farming practice," "nutrient management," "climate resilient agriculture," "India agriculture policy," "soil quality assessment," and "fertilizer use efficiently." The implementation of the soil health card in 2015 prompts an examination of strategies employed 15 years prior and the subsequent progress following its introduction. Therefore, the study encompasses a timeframe of about three decades, spanning from 1990 to 2024.

A screening process was conducted following the identification of relevant studies to ensure quality and relevance. This entailed reviewing abstracts, analysing the methodology of each study, and assessing the results and conclusions. Specifically, we initially considered 250 studies and excluded 30 duplicates resulting from overlaps across multiple databases accessed via the Publish or Perish software. The entries exhibited uniformity regarding title, authorship, and publication metadata. The removal of duplicates ensured that each study included in the review was unique and not counted multiple times. In the title screening phase, 80 studies were excluded due to irrelevance to the review's focus. Many studies addressed unrelated fields, including forestry, soil microbiology without agricultural relevance, and water resource management. The studies failed to consider soil health, sustainable agriculture, or the policy mechanisms related to soil health interventions. During the abstract screening phase, 54 studies were excluded according to the predetermined criteria. Those excluded from consideration were studies not written in English, those lacking empirical material, geographically inappropriate studies for SHC-specific analysis, studies focused solely on technical soil science without relevance to agricultural sustainability, and publications prior to 1990 that did not present significant findings.

In the global context, we identified 58 research articles that offered insights into diverse aspects of soil health and sustainable agricultural practices worldwide (Figure 2). The selected studies exhibit methodological rigor, relevance to soil health and sustainability, and contribute significantly to the understanding of global agricultural practices. The selected articles were further categorized according to their focus areas, including knowledge of soil quality, climate resilience, technology adoption for sustainability, precision farming and management, and soil health and nutrient management (Figure 2).

In the context of the soil health card scheme, 28 articles were selected that specifically examined its impact on agriculture in India (Figure 3). Due to the limited availability of studies, we incorporated research that presented both quantitative and qualitative data regarding the impacts of the SHC scheme on crop yields, chemical fertilizer usage, soil fertility, and wider socio-economic

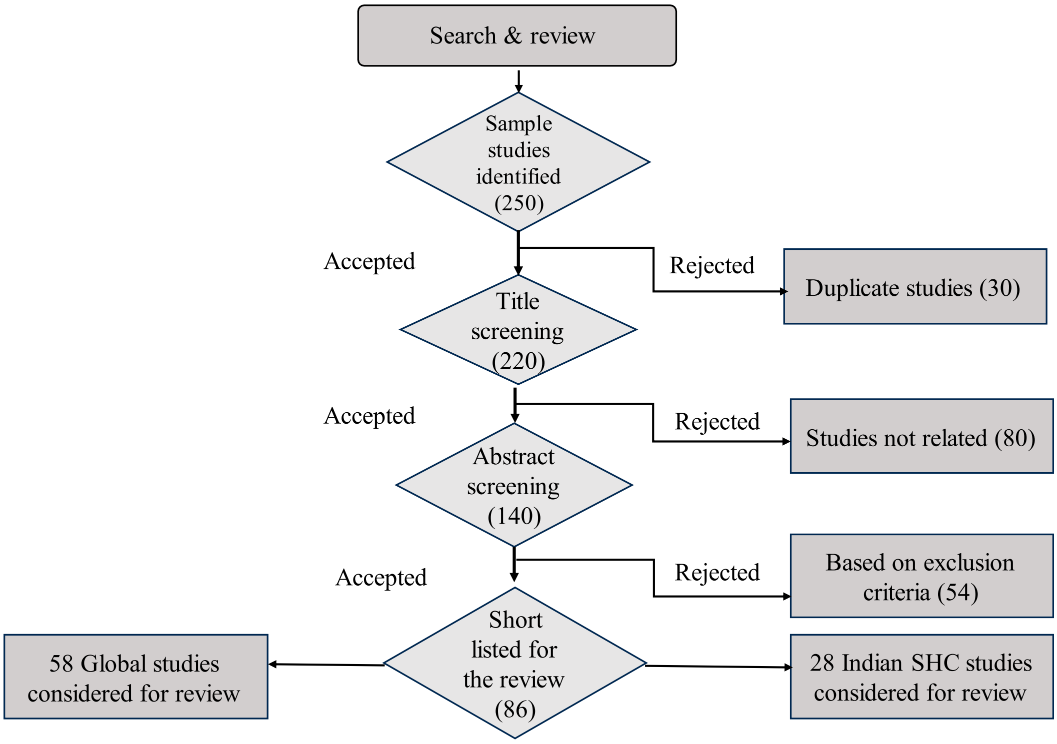


FIGURE 1
Systematic approach for literature survey. Source: Authors' illustration.

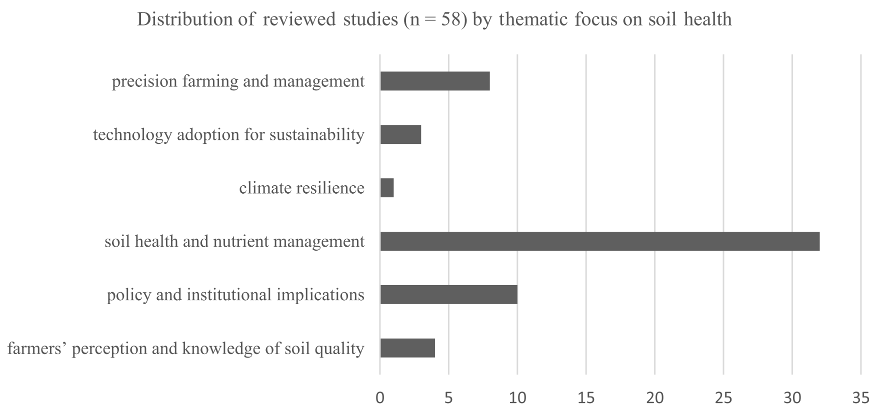


FIGURE 2
Distribution of reviewed studies (n = 58) by thematic focus on soil health. Source: Authors' compilation based on reviewed studies.

outcomes. We also examined official reports and government publications to enhance academic research and offer a thorough understanding of the policy implications and practical outcomes of the SHC scheme. The selected studies were categorized into four distinct groups: awareness and perception of soil health cards, their utilization, impact, and the constraints faced by farmers (Figure 3).

The conceptual framework illustrated in Figure 4 highlights the multifaceted impact of the SHC scheme on agricultural sustainability in India. Central to this framework is the SHC scheme, which plays a pivotal role in enhancing soil health through detailed soil analysis and crop-specific fertilizer recommendations. The improved soil fertility resulting from the SHC scheme leads to increased crop yields, contributing directly to the achievement of SDGs. Specifically, the SHC scheme aligns with SDG-2 (Zero Hunger) and SDG-15 (Life on Land) by promoting sustainable agricultural practices that enhance food security and environmental health.

One of the significant economic benefits of the SHC scheme is the doubling of farmers' income. By providing precise fertilizer recommendations, the SHC scheme reduces the overuse of chemical fertilizers, leading to an 8%–10% reduction in chemical fertilizer use (Ministry of Agriculture and Farmers' Welfare, 2020;

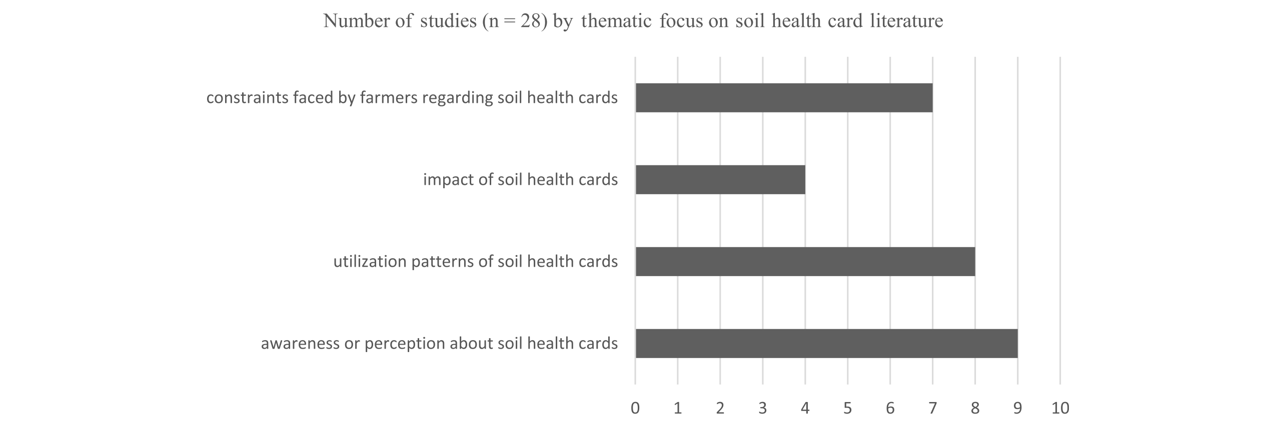


FIGURE 3
Number of studies (n = 28) by thematic focus on soil health card literature. Source: Authors' compilation based on reviewed studies.

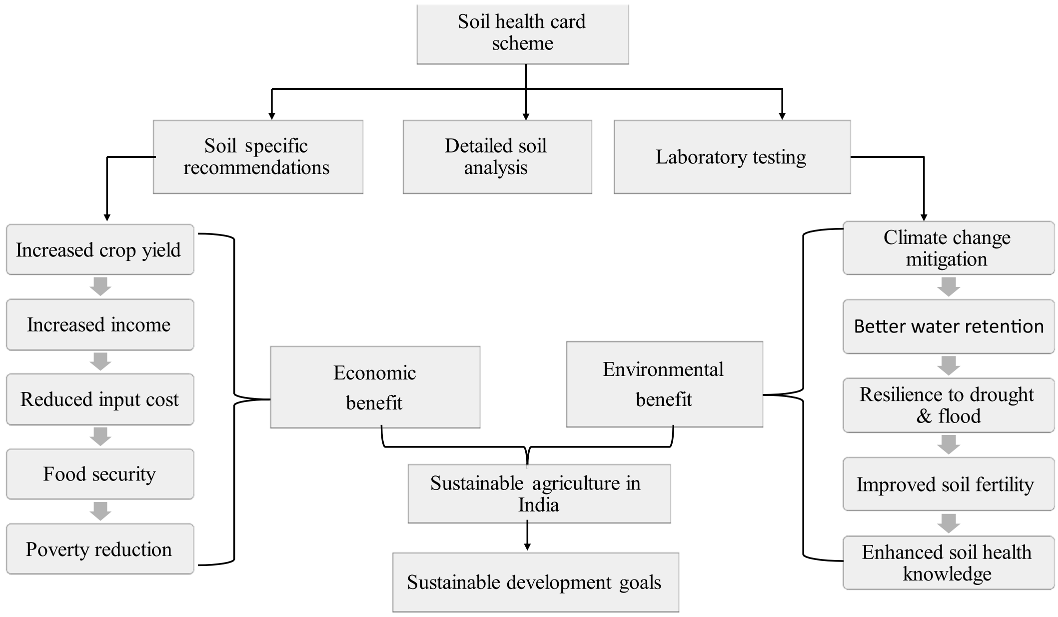


FIGURE 4
Conceptual framework: Integrating Soil Health Cards for Sustainable Agriculture in India. Source: Authors' design.

Ministry of Agriculture and Farmers' Welfare, 2021). This reduction not only lowers input costs for farmers but also mitigates the environmental impact of excessive fertilizer application. The SHC scheme also plays a crucial role in climate change mitigation by enhancing water retention in soils and improving the resilience of crops to droughts and floods.

## 3 Driving mechanisms of soil health

The concept of soil health emerged in the 1990s, evolving from the earlier notion of soil quality. This paradigm shift reflects a broader, more integrated understanding of soil as a dynamic, living system essential to ecosystem functioning. Soil quality emphasized the soil's capacity to sustain productivity and environmental integrity, later soil health extends this focus to include biological vitality, resilience, and the soil's role in supporting broader ecological processes. Recognizing this expanded scope, our review is organized into two strands: global initiatives advancing soil health and sustainable agriculture, and the specific challenges and policy responses within India's agricultural landscape because India plays major role as food basket to the World.

### 3.1 Global initiatives and strategies for promoting soil health and sustainable agriculture

Soil health is critical for the attainment of the SDGs, acting as a fundamental basis for sustainable agriculture and environmental resilience. Improved soil health increases crop productivity and food security, thereby directly contributing to SDG 2 (Zero Hunger) through enhanced nutrient cycling, as evidenced by Han et al. (2023). This also contributes to SDG 13 (Climate Action) by sequestering carbon, as reported by Kumar et al. (2025) who observed an increase in soil carbon stocks through regenerative and climate smart agricultural practices. SDG 15 (Life on Land) is enhanced by decreased erosion and increased biodiversity, as highlighted by Asefa et al. (2025) in the context of climate-smart land management in Ethiopia. Furthermore, SDG 1 (No Poverty) is enhanced by increased farmer incomes, as evidenced by Khonje et al. (2022) regarding subsidy-driven soil fertility adoption in Malawi. Similarly, SDG 6 (Clean Water and Sanitation) is improved through enhanced water filtration, as illustrated by Jian et al. (2020). The global literature on soil health can be broadly classified into six thematic domains. First, studies on farmers' perceptions and knowledge provide critical insights into grassroots-level constraints and engagement with soil management. Second, policy and institutional analyses underscore the influence of governance structures on soil health outcomes. Third, research on soil nutrient management focuses on practices that enhance fertility and long-term productivity. The fourth strand examines the role of soil health in strengthening climate resilience, particularly in mitigating the effects of climate variability. Fifth, the literature on technological innovations highlights emerging tools that advance sustainable soil practices. Finally, precision agriculture research demonstrates the potential of data-driven approaches to optimize soil use and ensure ecological sustainability (The synthesized results are detailed in Table 1).

### 3.1.1 Farmers' perception and knowledge of soil quality

Farmers' perception and knowledge of soil quality are shaped by cultural, economic, and informational factors, which significantly influence the adoption of sustainable soil health practices. Bennett and Cattle (2013), in a study of Australian landholders, found generally positive attitudes toward soil health, yet observed a gap between awareness and the consistent implementation of soil management programs attributed largely to communication shortcomings among stakeholders. Recent research emphasizes the importance of targeted and credible messaging in improving knowledge uptake. For instance, Wen and Ma (2024) and Mathanda et al. (2025) highlight how social capital, such as trust in leadership and community participation facilitates the adoption of conservation-oriented practices. In the United States, Bagnall et al. (2020) found that profitability, peer learning, and the complexity of soil health-promoting practices (SHPPs) significantly shape farmer decisions, with soil health often prioritized only after land acquisition suggesting a need for early-stage, tailored education efforts.

In developing regions, integrating traditional knowledge with scientific tools remains essential. Asthana and Kumar (2008), evaluating a world bank-supported initiative in Uttar Pradesh, stressed the importance of promoting soil testing through awareness and institutional support. Similarly, Abera et al. (2021) in Ethiopia demonstrated that farmers' experiential knowledge closely aligns with scientific indicators, underscoring the value of participatory approaches in soil management. Together, these studies reinforce that enhancing farmers' understanding and engagement with soil health requires culturally relevant, trust-based communication, institutional backing, and alignment between local knowledge and formal agronomic practices.

### 3.1.2 Policy and institutional implications

The intersection between soil health and policy frameworks is widely recognized as central to achieving environmental sustainability. Gopikrishna (2012), for example, critiques India's continued reliance on chemical fertilizers and advocates for a shift toward holistic ecological fertilization supported by investment in grassroots institutions and research. Similarly, Salvati (2014), using Italy's Environmental Sensitive Area Index (ESAI), underscores the need for policy interventions targeting land vulnerability driven by soil and vegetation degradation.

Several studies emphasize that soil degradation carries broader social and ecological consequences. Berdesheva et al. (2014) link environmental pollution to negative child health outcomes, reinforcing the importance of soil quality in public health. Expanding the conceptual scope, Koch et al. (2013) propose a "soil security" framework to integrate ecological, economic, and social dimensions into soil policy. Programs like the Environmental Quality Incentives Program (EQIP) and the Conservation Stewardship Program (CSP) in the United States demonstrate the effectiveness of participatory conservation mechanisms in promoting sustainable practices such as no-tillage and cover cropping (Bowman and Lynch, 2019).

Innovative approaches continue to reshape the policy landscape. Keenor et al. (2021) highlight the potential of carbon farming to sequester soil carbon while enhancing productivity, though they call for stronger political frameworks to scale such efforts. Arrouays et al. (2021) similarly emphasize the role of digital tools, such as soil mapping and monitoring systems in supporting evidence-based policy decisions aligned with the dimensions of soil security. Meanwhile, studies like Maroušek et al. (2022) offer cautionary insights, illustrating how certain compost inputs can unintentionally hinder nutrient availability, underscoring the need for science-informed regulation. In developing country contexts, policies integrating economic incentives with sustainable technologies have shown promise. Khonje et al. (2022) demonstrate that input subsidies coupled with Integrated Soil Fertility Management (ISFM) significantly improve smallholder income and nutritional outcomes in Malawi. Han et al. (2023) add a new dimension by valuing microbial biodiversity in economic terms, advocating its inclusion in soil health policy frameworks. The findings indicate that multidimensional, adaptive policies based on ecological science and stakeholder participation are most effective for achieving sustained improvements in soil health.

### 3.1.3 Soil health and nutrient management

The nexus between soil health and nutrient management remains a cornerstone of sustainable agricultural development. Early conceptual models, such as Krautkraemer's (1994) renewable resource framework, emphasized the need for long-term, balanced strategies to maintain soil fertility. Subsequent research has explored biological indicators (Doran and Zeiss, 2000), accessible assessment tools (e.g., SMAF by Andrews et al., 2004), and composite indices like the Soil Quality Index (SQI) and

**TABLE 1** Literature survey on global initiatives and strategies for promoting soil health and sustainable agriculture.

| Author(s) and year | Key findings | Identified gaps | Suggested future research |
|---|---|---|---|
| **Farmers' perception and knowledge of soil quality** | | | |
| Bennett and Cattle (2013), Wen and Ma (2024), Mathanda et al. (2025), Bagnall et al. (2020), Asthana & Kumar (2008), Abera et al. (2021) | Farmer adoption of soil practices rises with evident benefits and high trust, but expansion is constrained by costs, access, and weak extension. Equity and effective communication are crucial | Current research lacks long-term, cross-regional analysis and overlooks key institutional, economic, and socio-cultural drivers—including gender, age, and traditional knowledge—of soil health practice adoption | Future research must prioritise long-term, region-specific studies that investigate social capital, policies, and communication in rural contexts, while incorporating cultural, gender, and traditional knowledge to facilitate sustainable adoption |
| **Policy and institutional implications** | | | |
| Gopikrishna (2012), Salvati (2014), Berdesheva et al. (2014), Koch et al. (2013), Bowman and Lynch, (2019), Keenor et al. (2021), Arrouays et al. (2021), Maroušek et al. (2022), Khonje et al. (2022), Han et al. (2023) | Despite the presence of incentives, educational initiatives, and modern tools, existing policy gaps, inadequate infrastructure, elevated costs, and bureaucratic obstacles hinder the scalability of soil health practices | Limited long-term data, inadequately examined socio-cultural and gender barriers, along with region-specific tools, hinder the sustainable and inclusive adoption of soil health practices | Emphasise the importance of biological indicators and long-term studies, tackle socio-economic and cultural obstacles, and develop standardised tools that are accessible and user-friendly for farmers to promote broader adoption |
| **Soil health and nutrient management** | | | |
| Krautkraemer (1994), Doran and Zeiss (2000), Andrews et al. (2004), Qi et al. (2009), Armenise et al. (2013), de Paul Obade and Lal (2016), Reddy (2011), Liu et al. (2016), Li et al. (2021), Agnihotri et al. (2021), Congreves et al. (2015), Nunes et al. (2018), Jian et al. (2020), Joshi et al. (2019), Mehra and Singh (2018), Biswas et al. (2017), Bünemann et al. (2018), Bai et al., (2018), Eze et al. (2022), Middleton et al. (2021), Gurmessa (2021), Huang and Hartemink (2020) | Sustainable practices enhance soil health and increase yields, supported by incentives and educational initiatives. Advanced tools employing physical, chemical, and biological indicators evaluate soil quality with an accuracy of 80%–90%. Adoption is constrained by financial barriers, accessibility challenges, and insufficient utilisation of biological indicators | Research lacks long-term data, standardized biological indicators, and cross-regional validation, with limited focus on socio-economic barriers and practical scalability | In order to validate methods for scalable, policy-integrated adoption, future research should incorporate biological indicators, conduct long-term and regional studies, and address socio-economic constraints |
| **Climate resilience** | | | |
| Colombi et al. (2025), Kumar et al. (2025), Asefa et al. (2025), Bhatnagar et al. (2024), Tiwari et al. (2011) | Regenerative and climate-smart techniques increase soil health, but costs, infrastructure, and technical gaps hinder uptake despite governmental and community support | Policies are less relevant and scalable without long-term data, standardised measures, and a focus on biological, socio-economic, and gender variables | Addressing socio-economic, gender, and cultural barriers, utilising biological indicators, and performing long-term, cross-regional studies are essential for the scalable and effective policy adoption |
| **Technology adoption for sustainability** | | | |
| Carlisle (2016), Kannan and Ramappa (2017), Osabohien (2024) | Soil technologies improve yields and reduce losses, driven by incentives and education, but hindered by high costs and limited access | Research lacks long-term data, regional and biological insights, with limited focus on socio-cultural, gender, economic factors, and policy incentives | Future research should address socio-cultural, gender, and regional factors, include biological indicators, and assess long-term impacts and policy incentives for adoption |
| **Precision farming and management** | | | |
| Van Den Berg (2002), Verma and Sharma (2007), Turinawe et al. (2015), Wu et al. (2019), Zhao and Wu (2021), Wade et al. (2020), Wilhelm et al. (2022), Zhou et al. (2022) | Precision farming boosts soil health and yields through training, incentives, and data tools, yet persistent issues like salinity and high costs expose its limited scalability | The absence of long-term data, biological indicators, and socio-economic analysis undermines research relevance, scalability, and real-world applicability | Future research should include biological indicators, long-term and regional studies, and address socio-economic and adoption barriers for scalable precision farming |

Source: Literature survey.

Integrated Quality Index (IQI), which enable multidimensional evaluations of soil function (Qi et al., 2009; Armenise et al., 2013; de Paul Obade and Lal, 2016). These methodologies have been applied globally and nationally to evaluate the impacts of management practices on soil quality. In India, Reddy (2011) highlighted imbalances arising from chemical fertilizer overuse and organic manure shortages, calling for integrated approaches that combine organic and inorganic nutrient sources. More recently, advanced techniques such as SVM-based classification (Liu et al., 2016), remote sensing-derived soil health indices (Li et al., 2021), and GIS-based erosion models (Agnihotri et al., 2021) have enabled precision diagnostics for soil health monitoring. Empirical studies have validated the benefits of sustainable practices such as conservation tillage, crop rotation, and cover cropping (Congreves et al., 2015; Nunes et al., 2018; Jian et al., 2020), while site-specific interventions, such as the Bhoochetana Mission in Karnataka (Joshi et al., 2019) demonstrate the effectiveness of targeted nutrient management tools like SHCs in improving yields. Tailored zonal strategies (Mehra and Singh, 2018) and rice system-focused research (Biswas et al., 2017) further underscore the value of context-sensitive approaches.

Recent literature has also broadened to include interdisciplinary evaluations of sustainable land management. Reviews by Bünemann et al. (2018) and Bai et al. (2018) advocate for using multi-indicator frameworks and site-specific baselines. Other studies highlight the importance of integrating farmer knowledge (Eze et al., 2022), utilizing innovative soil evaluation techniques (Middleton et al., 2021), and addressing context-specific challenges such as soil acidity and low organic matter (Gurmessa, 2021; Huang and Hartemink, 2020). A growing concern is the influence of land use change particularly practices like shifting cultivation on soil degradation. These findings point to the urgent need for integrating land use considerations into nutrient and soil management policies, particularly in erosion-prone agro-ecological zones.

### 3.1.4 Climate resilience

The relationship between climate resilience and soil health is increasingly recognized as a critical factor in sustainable agriculture and environmental management. In this context, the nexus between climate resilience and soil health has become a focal point of research aimed at mitigating the adverse effects of climate variability and promoting sustainable land management practices. Among the most prominent interventions are regenerative agriculture (RA), climate-smart agriculture (CSA), and precision agriculture, each offering pathways to strengthen soil health while mitigating climate vulnerabilities. Recent evidence underscores the efficacy of RA in improving both soil quality and the delivery of multiple ecosystem services. Colombi et al. (2025), through a systematic review, demonstrated that RA practices significantly enhance soil structure, organic matter content, and biological functioning. Complementing this, Kumar et al. (2025) identified key regenerative strategies, such as conservation agriculture, crop rotation, cover cropping, organic amendments, biochar application, and agroforestry that contribute to carbon sequestration, improved biogeochemical cycling, and increased resilience to climatic variability. Similarly, the adoption of CSA practices has shown promising outcomes in enhancing both productivity and resilience. Studies by Asefa et al. (2025) and Bhatnagar et al. (2024) report that CSA implementation leads to notable improvements in crop yields, farm incomes, resource use efficiency, and reductions in greenhouse gas emissions, while simultaneously strengthening the adaptive capacity of smallholder systems.

An illustrative case from India is presented by Tiwari et al. (2011), who evaluated the environmental impact of Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) activities in the drought-prone Chitradurga district of Karnataka. Their study employed indicators such as water availability and soil quality to assess the program's role in reducing climate vulnerability. Findings revealed that MGNREGA interventions, such as groundwater recharge structures, soil conservation works, and afforestation with Pongamia contributed to enhanced irrigation capacity, improved soil fertility, and increased carbon sequestration potential. These landscape-level interventions highlight the importance of integrating soil health into broader climate resilience and rural development strategies.

### 3.1.5 Technology adoption for sustainability

The intersection between soil health and technology adoption for sustainability remains an underexplored yet critically important area of study. Research efforts have begun to illuminate the factors influencing the adoption of sustainable agricultural technologies, though significant gaps persist. Carlisle (2016) provides a comprehensive examination of the adoption gap for soil health practices in United States. The study identifies a range of barriers, including equipment limitations, ongoing costs, policy constraints, and entrenched community perceptions. Notably, it highlights the influence of farm size, economic returns, and intrinsic motivations on adoption decisions, challenging the adequacy of traditional rational actor models. Further expanding the discourse on technology adoption, Kannan and Ramappa (2017) investigated the factors driving the adoption of soil nutrient management technologies among paddy farmers in Karnataka, India. Their analysis, employing a bivariate probit model, reveals that training in fertilizer application and education significantly enhance adoption rates. The study also underscores the importance of accessibility to soil testing facilities, which, along with the availability of family labor, plays a pivotal role in farmers' decisions to adopt sustainable practices. Complementing these findings, Osabohien (2024) examines the relationship between soil technology adoption and post-harvest losses in Nigeria. Utilizing data from the LSMS-ISA, the study reveals that the adoption of certified crops markedly reduces post-harvest losses, while the impacts of pesticides, herbicides, and fertilizers are less pronounced. Key factors influencing adoption include cooperative membership, age, and education levels.

### 3.1.6 Precision farming and management

The integration of precision farming with soil health management has emerged as a key strategy in advancing agricultural sustainability. Early research in India's semi-arid regions (Van Den Berg, 2002) and the northwest Himalayas (Verma and Sharma, 2007) emphasized the importance of combining organic amendments with fertilizers to sustain soil productivity. The introduction of the Carbon Management Index (CMI) in these studies reinforced the value of monitoring soil carbon as a core metric for long-term sustainability an approach closely aligned with precision agriculture's emphasis on data-driven input management.

Globally, the adoption of precision practices has expanded, with studies identifying critical biophysical and socio-economic variables shaping outcomes. Turinawe et al. (2015), for instance, demonstrated that education, land tenure, and labor availability significantly influence the adoption of soil and water conservation technologies in Uganda. Similarly, Wu et al. (2019) and Zhao and Wu (2021) emphasized localized soil conditions such as salinity, pH, and nutrient imbalances as central to site-specific soil health strategies, highlighting the need for tailored interventions. Technological advancements are further redefining precision soil management. Wade et al. (2020) showed that biologically active soils reduce the need for nitrogen fertilizers while improving yield performance. Machine learning applications, such as those proposed by Wilhelm et al. (2022), now enable predictive diagnostics of soil health using microbiome data, offering scalable, cost-effective tools for real-time decision-making. In

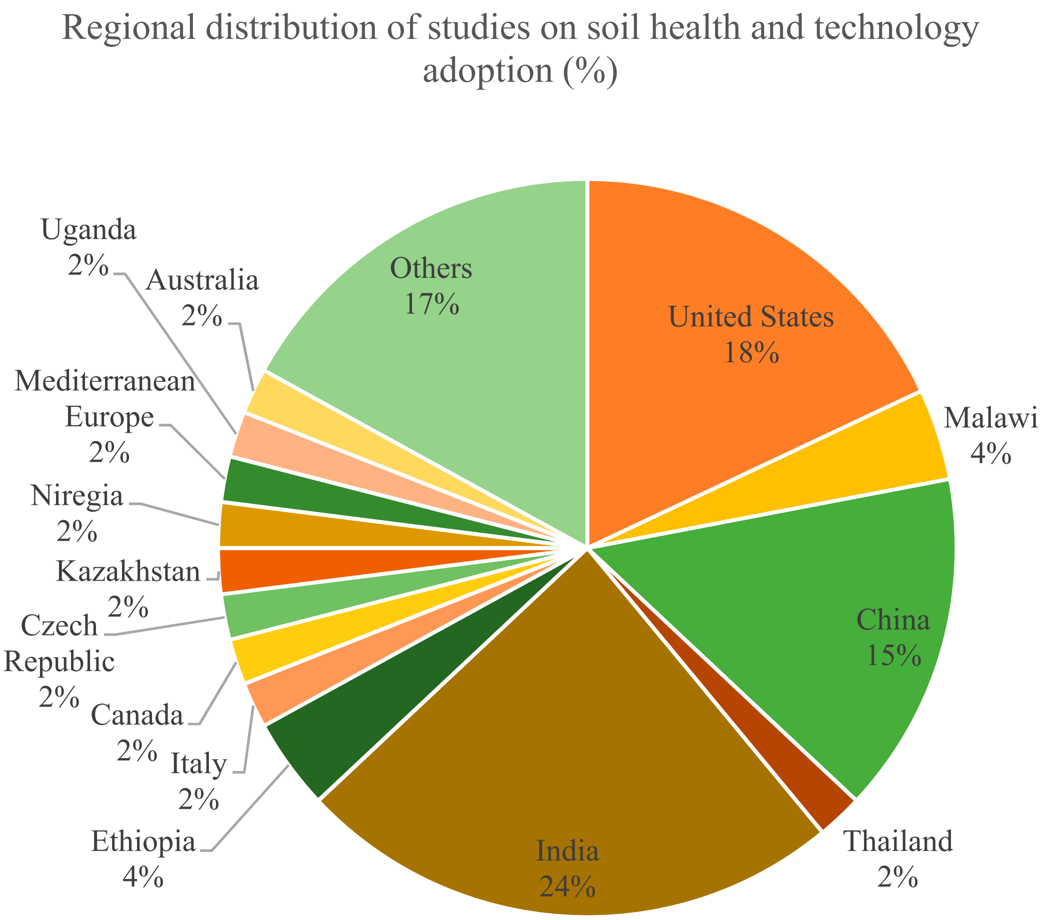


FIGURE 5
Regional distribution of studies on soil health and technology adoption (%). Note: 'Others' denotes studies without a specified country context or with general/global focus. Source: Authors' compilation based on reviewed studies.

China, Zhou et al. (2022) developed a Soil Quality Index (SQI) for barley-producing zones, demonstrating the efficacy of targeted practices like lime application and nutrient supplementation in improving crop outcomes. Collectively, these studies affirm that precision farming when combined with organic inputs, conservation practices, and advanced diagnostic tools can significantly enhance soil health.

Figure 5 illustrates that India (23%) is at the forefront of soil health research, followed by global contributions (17%), the U.S. (17%), and China (15%), while other nations contribute smaller percentages (2%–4%) to address regional challenges.

## 3.2 Overview of India's agricultural landscape and soil health challenge

As of 2021, India holds the largest cropland area globally, with 168 million hectares under cultivation (FAO, 2023). Nearly half of Indian households rely on agriculture, contributing approximately 14.5% to national GDP (Gulati and Juneja, 2022). However, soil degradation poses a major threat, with 32% of land classified as degraded and 25% affected by desertification (FAO, 2024). In response, the Government of India launched the SHC scheme in 2015 to promote balanced fertilizer use and improve crop productivity. The program provides farmers with crop and soil-specific recommendations based on laboratory testing. By 2023, over 23.5 crore SHCs had been distributed, supported by a robust network of over 8,000 soil testing laboratories, including static, mobile, mini, and village-level units (Press Information Bureau Government of India, 2023). Each card includes detailed physical and chemical soil characteristics, such as pH, electrical conductivity, organic carbon, and macro- and micronutrient profiles, alongside geolocation, irrigation source, and farm size (Purakayastha et al., 2019; Reddy, 2019). This decentralized infrastructure underpins India's efforts toward sustainable soil management and long-term agricultural resilience.

India's investment in soil health reflects a strategic and sustained policy commitment, particularly through the SHC scheme. Over 6 years, government funding has steadily increased, underscoring efforts to scale and institutionalize the program (Figure 6). The initiative began in 2014–15 with a foundational allocation of \$2.765 million, primarily to establish infrastructure for soil testing and card distribution. This was followed by a sharp rise to \$11.173 million in 2015–16 a 304% increase marking a deliberate scale-up in sample collection and laboratory capacity. Funding continued to grow in subsequent years, reaching \$15.483 million in

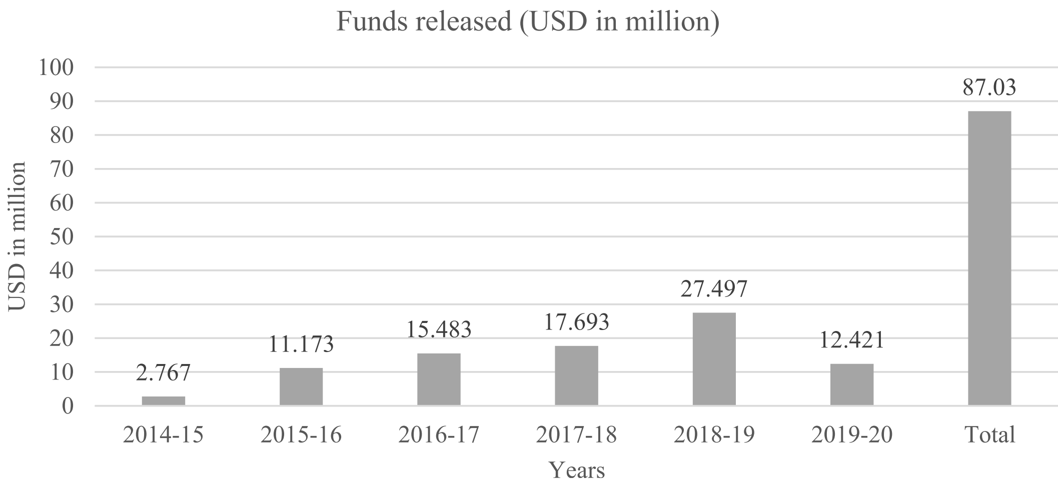


FIGURE 6
Financial progress of soil health card scheme 2015–2020. Source: Government of India, 2023–24.

2016–17 and $17.693 million in 2017–18, representing annual increases of 39% and 14%, respectively. These consistent investments reflect a phased and performance-oriented expansion of the SHC scheme, aimed at strengthening its operational reach and long-term sustainability. Funding for the SHC scheme peaked in 2018–19 at $27.497 million—a 55% increase from the previous year indicating intensified efforts to broaden the scheme's coverage and operational capacity. However, in 2019–20, allocations declined sharply to $12.42 million, reflecting a 55% reduction. This apparent downturn in SHC activity may reflect an emerging shift from aggressive expansion toward consolidation prioritizing delivery quality, data reliability, and improved farmer engagement to address long-standing operational inefficiencies (Patel et al., 2023). Over the 6-year period, total funding reached $87.03 million, underscoring the Indian government's sustained commitment to soil health as a pillar of sustainable agriculture, food security, and long-term rural economic resilience.

The SHC scheme has contributed significantly to improving agricultural outcomes in India by enhancing soil fertility management. Empirical evidence indicates a 5%–6% increase in crop yields and an 8%–10% reduction in chemical fertilizer use, translating into cost savings and environmental benefits (Ministry of Agriculture and Farmers' Welfare, 2020; Ministry of Agriculture and Farmers' Welfare, 2021). These outcomes align with India's goal of doubling farmers' income while promoting more sustainable agricultural practices. Moreover, improved soil health supports greater water retention, reducing irrigation dependency and increasing resilience to climatic shocks such as droughts and floods. Ankhila et al. (2023) observed that the SHC scheme has enhanced nutrient use efficiency and reduced agriculture's carbon footprint, contributing to both farm profitability and national climate goals.

While the SHC scheme shows promise in supporting the SDGs, the literature presents a more nuanced picture. Most studies highlight benefits including increased farmer awareness, improved productivity, and reduced fertilizer dependence (Ankhila et al., 2023; Rabha and Barman, 2021; Kumar et al., 2019). However, challenges persist, such as inconsistent SHC utilization, limited access to testing facilities in remote areas, and inadequate follow-up support (Reddy, 2019; Patel et al., 2023). Delays in SHC issuance and varied farmer engagement with recommendations further constrain impact.

To assess these dynamics systematically, the literature can be organized into four thematic strands: (1) awareness and perception of SHCs, (2) utilization patterns, (3) impacts on agricultural outcomes, and (4) implementation challenges. This framework offers a holistic perspective, capturing both the achievements and operational limitations of the SHC scheme. By critically examining these dimensions, the paper identifies key leverage points for enhancing the scheme's effectiveness and scaling its contribution to sustainable agriculture.

### 3.2.1 Awareness or perception about soil health cards

The first strand of literature on farmers' awareness and perception of the SHC scheme reveals mixed findings, with studies indicating both limited and positive awareness. For instance, Patel et al. (2017) and Reddy (2019) reported that a significant majority of farmers exhibit moderate to high levels of awareness about SHCs, with the South, West, Central, and Eastern zones showing particularly high awareness due to proactive state initiatives. Whereas Rawat et al. (2019) and Chakrawarty et al. (2018) highlights that the adoption of SHC recommendations varies, with some farmers fully integrating the advice into their practices, while others exhibit only partial adoption. The reasons for partial adoption include limited access to resources and a lack of comprehensive understanding of SHC recommendations. However, where adoption is high, it is positively correlated with factors such as education, mass media exposure, and extension services. The effectiveness of SHCs in enhancing soil health is further supported by studies like those of Shehrawat et al. (2018) and Khan (2019), who found that a substantial number of farmers are aware of the benefits of SHCs, including the reduction of input costs and improved soil nutrient management. The studies also reveal that a considerable percentage of farmers are knowledgeable about soil sampling and the use of the SHC portal, which are essential components of the SHC program.

Despite the overall positive impact of SHCs, challenges remain, particularly in terms of the operational aspects of the SHC program. Kaur et al. (2019) and Madhu et al. (2020) identified several barriers to the effective utilization of SHCs, including difficulties in navigating the SHC portal and the need for more mobile soil testing laboratories. Additionally, there is a disparity in the level of knowledge among farmers, with a significant portion still possessing only a moderate or low understanding of the SHC scheme. These challenges suggest that while SHCs have been instrumental in promoting soil health awareness, further efforts are needed to enhance farmer education and improve the accessibility of SHC-related resources.

### 3.2.2 Utilization patterns of soil health cards

The second strand of literature in India's initiative context outlines the utilization patterns of SHC. The literature on the utilization patterns of SHCs presents a comprehensive overview of how farmers engage with this tool, revealing significant variations in adoption and effectiveness across different regions and practices. Specifically, studies have consistently shown that SHCs influence farmers' fertilizer management decisions, leading to more judicious use of inputs. For instance, Chouhan et al. (2017) reported significant yield increases in paddy, soybean, and maize following the application of recommended fertilizer doses, with paddy yields increasing by 19.42%, soybean by 13.79%, and maize by 9.3%. Makadia et al. (2017) further demonstrated that farmers with SHCs were less likely to overuse nitrogenous fertilizers for crops like sugarcane and kharif paddy, indicating a shift towards more balanced fertilizer use. This aligns with Parewa et al. (2016), who highlighted the SHC scheme's objective of promoting integrated nutrient management, emphasizing the balanced use of inorganic fertilizers, organic manures, and biofertilizers to enhance soil health and productivity.

The ability of SHCs to provide crop-specific recommendations and a comprehensive overview of soil health has been a crucial factor in their utilization. Patel et al. (2017) found that 52% of respondents had a high level of knowledge regarding soil testing and SHC usage, which they leveraged to manage fertilizer dosages effectively and maintain soil health. Similarly, Chowdary et al. (2018) noted that SHCs offer detailed soil health indicators and nutrient recommendations, empowering farmers to enhance productivity through informed input application. However, challenges remain, as highlighted by Rabha and Barman (2021), who found that a significant proportion of farmers in Assam were unable to read or understand SHC recommendations, leading to poor adherence to the guidelines. Despite these challenges, the SHC has proven to be a valuable tool in improving farmers' knowledge and practices related to soil health. Khan (2019) noted that the majority of respondents demonstrated positive knowledge of various aspects of soil health, including soil sampling and nutrient status, although gaps in knowledge about the cost of sampling and fertilizer dosage calculation persisted. Purakayastha et al. (2019) added that the soil health index (SHI), influenced by factors such as soil texture and tillage practices, is a crucial component of SHCs, offering a more nuanced understanding of soil health compared to routine soil testing. The SHC's ability to provide tailored recommendations based on these indicators further enhances its utility.

### 3.2.3 The impact of soil health cards

The impact of SHC scheme on agricultural productivity and economic outcomes is a focal point of recent studies, highlighting their critical role in optimizing nutrient management and enhancing crop yields. Chouhan et al. (2017) demonstrated that the implementation of SHC recommendations led to significant increases in crop yields, with maize showing a 9.6% rise, paddy a 19.42% increase, and soybean a 13.79% improvement. These yield enhancements were accompanied by notable increases in net income, particularly for maize, where profits surged from USD 39.10 to USD 93.75, underscoring the economic benefits of SHCs in guiding fertilizer application and other agronomic practices. Further, supporting these findings, Padmaja and Angadi (2018) investigated the long-term effects of SHC-driven micronutrient management on sugarcane yields. Their study revealed that the average yield increased from 403.14 quintals to 412.52 quintals per acre, reflecting the positive impact of sustained adherence to SHC recommendations. This highlights the SHC's role in not only immediate productivity gains but also in fostering sustainable agricultural practices through improved nutrient management over time. Singh et al. (2019) expanded on this by examining the SHC's impact on the cost-efficiency and productivity of rabi crops in Madhya Pradesh. Their analysis showed substantial increases in yields for chickpea (36.55%), wheat (23.13%), and mustard (20.01%), coupled with corresponding rises in net returns 8.18% for mustard, 25.22% for wheat, and 20.80% for chickpea. These results emphasize the SHC's effectiveness in enhancing both agricultural productivity and farmers' incomes, particularly in the context of rabi cropping systems. In a comparative study conducted by Abhishek et al. (2020), the differential impact of SHCs on beneficiaries versus non-beneficiaries in Karnataka was assessed. Beneficiaries of the SHC scheme reported a higher yield of 75.34 quintals per hectare for paddy, compared to 71.05 quintals for non-beneficiaries, despite slightly higher cultivation costs. This study reinforces the SHC's potential to significantly boost agricultural productivity and suggests that the benefits of the SHC scheme outweigh the additional costs incurred, making a strong case for its widespread adoption.

### 3.2.4 Constraints faced by farmers regarding soil health cards

The last strand of literature discusses studies that emphasize the constraints faced by farmers regarding soil health cards. As expected, several studies highlight the various challenges experienced by the farmers. For example, Chowdary and Theodore (2016) provided an insightful analysis, highlighting that despite a significant proportion of farmers (67%) expressing satisfaction with SHC recommendations, the lack of adequate follow-up by extension agencies remains a critical barrier. Dwivedi (2016) further amplifies this concern by pointing to the urgent need for a robust soil health monitoring system and increased farmer awareness to bridge this gap and ensure that SHCs translate into tangible benefits for soil health and agricultural productivity. Expanding on these challenges, Naruka et al. (2018) reveals that while farmers generally possess a moderate level of knowledge about SHCs, critical barriers such as limited awareness of the importance of micronutrients, high fertilizer costs, and the unavailability of organic manure significantly hinder their effective use. These

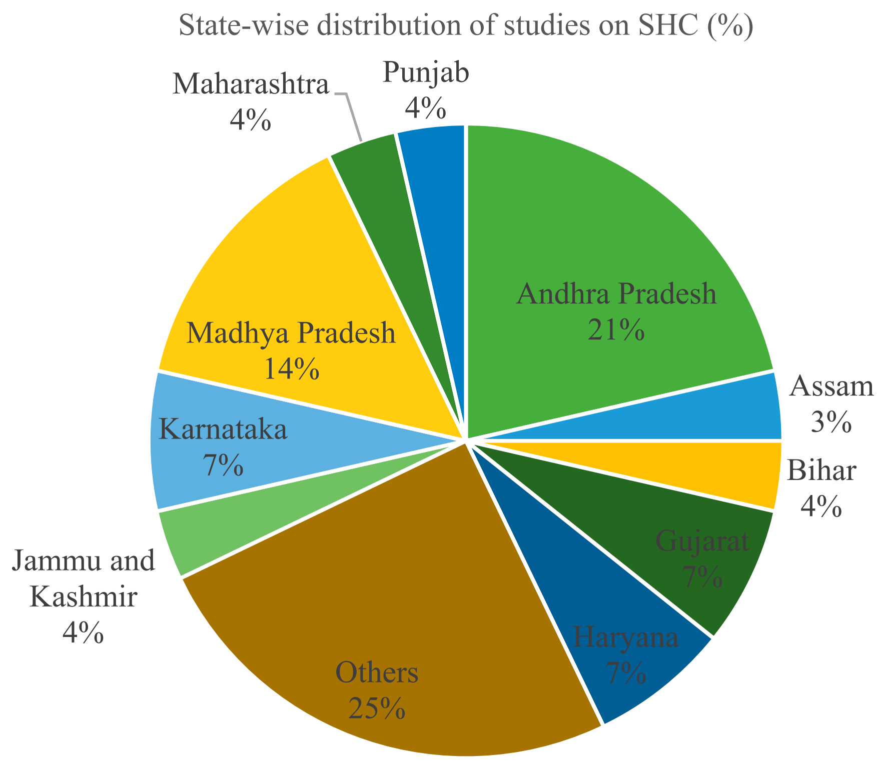


FIGURE 7
State-wise Distribution of reviewed studies on the SHC Scheme in India. Note: 'Others' denotes studies without a specified state context or with a general focus. Source: Authors' compilation based on reviewed studies.

findings indicate that the potential of SHCs to enhance soil health management is curtailed by economic and informational barriers, which must be addressed through targeted interventions. Babu et al. (2019) adds a layer of complexity to this discussion by revealing that 85.84% of farmers struggle with calculating fertilizer doses based on soil nutrient status, compounded by issues such as the late issuance of SHCs after crop harvest (82.51%), delays between soil sample collection and card issuance (79.17%), and the absence of farmers during soil sample collection (72.92%). These operational challenges suggest the need for a more streamlined, farmer-inclusive process to ensure the timely and accurate dissemination of SHCs. Furthering this discourse, Chakrawarty et al. (2019) and Kumar et al. (2019) emphasize the pivotal role of SHCs in promoting sustainable agricultural practices through balanced nutrient management. However, Kumar et al. (2019) also highlights significant constraints, including the prolonged time gap between soil sample collection and card issuance, difficulties in understanding SHC information, and challenges in calculating fertilizer doses. These findings suggest that while SHCs are recognized for their potential to foster sustainable agricultural practices, their effectiveness is compromised by procedural inefficiencies and a lack of adequate farmer training.

Figure 7; Tables 2, 3 highlight the thematic patterns and key findings emerging from the SHC-related studies. The findings reveal a disproportionate concentration of studies in Andhra Pradesh (21%), and Madhya Pradesh (14%), while several regions—such as Odisha, Himachal Pradesh, and the broader Northeastern belt—remain significantly underrepresented (Figure 7). This suggests a need for research in less-studied regions, particularly those with unique agro-climatic challenges such as hilly terrains or high rainfall. Further, the reviewed studies predominantly focus on major crops (e.g., wheat, rice), with minimal attention to minor crops like millets, pulses, or horticultural crops, which are critical for nutritional security and climate resilience (Table 2). This gap limits the applicability of SHC recommendations for diverse cropping systems. In the case of socio-demographic/geographic characteristics, SHC adoption tends to be more effective among farmers with higher education levels, cooperative membership, access to irrigation, and medium-to-large landholdings predominantly in wealthier regions compared to rainfed, smallholder-dominated areas where adoption remains limited (Table 3). Challenges in the latter include low awareness, limited access to soil testing facilities, and resource constraints among marginal farmers.

## 4 Policy implications and recommendations

This section outlines strategic policy recommendations to strengthen soil health governance and enhance the effectiveness of India's SHC scheme, in alignment with the SDGs. While global research affirms the foundational role of soil health in sustainable agriculture, the Indian experience with the SHC initiative highlights both its transformative potential and persistent implementation challenges. To address these, the following policy directions are proposed across three key areas.

TABLE 2 Categorization of Studies by crop category.

| Crop category | Crop(s) covered | Authors |
|---|---|---|
| Paddy/Rice (including Sali Rice) | Paddy, Sali rice | Rabha and Barman (2021), Makadia et al. (2017), Padmaja and Angadi (2018), Abhishek et al. (2020), Reddy (2011), Ankhila et al. (2023) |
| Wheat and Pulses/Oilseeds | Wheat, black gram, mustard, chickpea | Padmaja and Angadi (2018), Rawat et al. (2019), Singh et al. (2019) |
| Groundnut | Groundnut | Reddy (2011) |
| Cotton | Cotton | Padmaja and Angadi (2018) |
| Maize/Millets | Maize | Padmaja and Angadi (2018), Rawat et al. (2019) |
| Soybean | Soybean | Rawat et al. (2019), Chakrawarty et al. (2019) |
| Sericulture/Mulberry | Mulberry | Khan (2019) |
| Sugarcane | Sugarcane | Padmaja and Angadi (2018) |

Source: Literature survey.

TABLE 3 Categorization of studies by socio-demographic focus.

| Category | Socio-demographic focus description | Authors |
|---|---|---|
| Education/Literacy | Education level, literacy, awareness | Chakrawarty et al. (2019), Rawat et al. (2019), Chowdary et al. (2018), Patel et al. (2017), Purakayastha et al. (2019), Kaur et al. (2019), Madhu et al. (2020), Reddy (2019) |
| Irrigation/Infrastructure | Irrigated area, lab access, physical infrastructure | Chakrawarty et al. (2019), Reddy (2019), Parewa et al. (2016) |
| Farm Size/Landholding | Size of land owned or operated | Chakrawarty et al. (2019), Purakayastha et al. (2019), Kaur et al. (2019), Rabha and Barman (2021), Rawat et al. (2019), Chowdary et al. (2018) |
| Extension Services/Training | Access to extension agents, technical advice, training participation | Madhu et al. (2020), Ankhila et al. (2023), Rabha and Barman (2021), Reddy (2019), Khan (2019) |
| Membership/Farmer Organizations | Belonging to cooperatives, SHG-type bodies, or FPOs | Ankhila et al. (2023), Singh et al. (2019) |
| Income/Economic Constraints | Income levels, high fertilizer costs, affordability of inputs | Babu et al. (2019), Rabha and Barman (2021), Naruka et al. (2018), Rawat et al. (2019) |
| Age and Experience | Age, farming experience | Chakrawarty et al. (2019), Kaur et al. (2019), Rabha and Barman (2021), Chowdary et al. (2018) |
| Motivation/Attitudes/Orientation | Scientific orientation, achievement/risk orientation, management attitude | Madhu et al. (2020) |
| Information Access/Media Exposure | Cosmopoliteness, information awareness, mass media exposure | Chowdary et al. (2018), Reddy (2019), Madhu et al. (2020) |

Source: Literature survey.

## 4.1 Role of policy and regulations in promoting soil health-focused practices

Robust policies and regulations are vital for promoting soil health-focused practices. The SHC scheme in India is a commendable step in this direction, providing farmers with detailed information about soil nutrient status and recommendations for corrective measures, thereby encouraging sustainable soil management. However, studies have highlighted challenges and slow progress in different states, largely due to inadequate regulatory frameworks. To address these shortcomings, it is crucial to implement stronger oversight mechanisms and increase investments in infrastructure, ensuring that all regions fully benefit from the SHC scheme. This includes revising and updating regulations to incorporate the latest scientific knowledge and best practices in soil management. Establishing clear guidelines and standards for soil health management, coupled with strict enforcement, can significantly enhance policy effectiveness. Comprehensive soil health policies should integrate various aspects of soil management, including erosion control, nutrient management, and organic farming, and be developed in consultation with stakeholders such as farmers, researchers, and industry experts. Expanding incentive structures for sustainable soil management practices, such as increased subsidies for organic farming inputs and financial support for adopting conservation agriculture practices, will also encourage wider adoption. Furthermore, investing in advanced monitoring and evaluation systems, leveraging technologies like remote sensing and Geographic Information Systems (GIS), can improve the accuracy and efficiency of soil health assessments.

Additionally, to enhance the effectiveness of soil health intervention, Government and development agencies should strategically integrate the SCH scheme with existing key national agricultural programs, MGNREGA, National Mission for Sustainable Agriculture (NMSA), Pradhan Matri Krishi Sinchayee Yojana (PMKSY), and Rastriya Krishi Vikas Yojana (RKVY). For instance, embedding resource augmentation activities, such as vermicomposting, water harvesting, and afforestation—within MGNREGA can enhance both environmental outcomes and rural livelihoods through labor-intensive approaches. NMSA with its emphasis on climate-smart and regenerative agricultural practices, aligns naturally with the SHC's objectives. SHC data on soil nutrient status can inform NMSA's soil health management and nutrient-based subsidy programs, ensuring tailored fertilizer use that enhances sustainability. Similarly, PMKSY, which promotes efficient water use through micro-irrigation, can leverage SHC recommendations to optimize both water and nutrient management in vulnerable regions Finally, RKVY's decentralized, state-driven approach can facilitate SHC implementation by supporting localized soil testing infrastructure, farmer training, and context-specific interventions.

### 4.2 Capacity building and awareness programs for sustainable soil management

Capacity building and awareness programs are essential for promoting sustainable soil management, particularly in India, where average education levels among farmers are low, and awareness is limited. Educating farmers about the importance of soil health and best practices for maintaining it can lead to significant improvements in agricultural sustainability. The success of the SHC scheme underscores the need for comprehensive educational initiatives that reach a broad audience. Policymakers should focus on developing tailored training programs that address the specific needs and contexts of different farming communities, incorporating both theoretical and practical components. Enhancing the capacity and reach of agricultural extension services is crucial, necessitating investments in training for extension workers, increasing the number of extension agents, and utilizing digital technologies to extend their reach. Community-based approaches, such as farmer cooperative groups, should be encouraged to lead and practice sustainable soil management initiatives. Additionally, the government should support the establishment of farmer field schools, participatory training programs, and other community engagement initiatives that promote collective action and knowledge sharing. The role of technology in capacity building cannot be overstated online training modules, mobile apps, and social media platforms can provide farmers with access to valuable information and resources on sustainable soil management practices, though proper training for accessing these tools is necessary.

### 4.3 Collaborative efforts for addressing transboundary soil health challenges

Soil health challenges often transcend national boundaries, requiring collaborative efforts at the international level. International cooperation, facilitated by organizations such as the United Nations, FAO, and regional bodies, is essential for sharing knowledge, resources, and best practices. Policymakers should actively participate in international cooperation efforts to address transboundary soil health challenges, including engaging in global forums, contributing to international research initiatives, and supporting the development of international guidelines and standards for soil health management. Regional collaboration is particularly effective in addressing soil health challenges specific to certain geographical areas. As demonstrated by initiatives like the world bank's poverty eradication schemes in least developed areas, regional efforts can significantly enhance outcomes. Policymakers should therefore promote the establishment of regional soil health networks, facilitate cross-border knowledge exchange, and support the development of region-specific action plans. Investing in collaborative research and development efforts is crucial for driving innovation in soil health management. Policymakers should support joint research projects, facilitate partnerships between research institutions, and promote the exchange of knowledge and technology across borders. Multi-stakeholder partnerships, involving governments, research institutions, non-governmental organizations, and the private sector, are instrumental in enhancing the effectiveness of collaborative efforts. Supporting these partnerships through funding, capacity building, and policy support will be essential in achieving sustainable soil health management on a global scale.

## 5 Summary and future perspectives

Promoting sustainable soil health practices is essential for achieving agricultural sustainability, food security, and environmental resilience in India and beyond. This review underscores the pivotal role of India's Soil Health Card (SHC) scheme in advancing these goals. With over 23.58 crore cards distributed, the program has been associated with a 5%–6% increase in crop yields and an 8%–10% reduction in chemical fertilizer use. These outcomes are supported by the country's expansive soil testing infrastructure, reflecting a strong institutional commitment to soil health. Beyond documenting achievements, the review highlights the need for integrated policy frameworks, targeted capacity-building, and international cooperation to address soil degradation as a transboundary challenge. While existing studies have explored SHC-related awareness, adoption, and productivity impacts, they remain largely descriptive and based on cross-sectional data. To assess the long-term effectiveness of the scheme, future research should employ longitudinal data and rigorous methodologies including quasi-experimental designs and panel data analyses. Such approaches are critical to evaluating the SHC's sustained impact on input use efficiency, cost reduction, and productivity enhancement. Strengthening the evidence base through methodological rigor will enable more informed policy decisions and contribute meaningfully to global efforts in sustainable soil management.

## Author contributions

RT: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. SK: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. DR: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. PJ: Supervision, Writing – original draft, Writing – review and editing. TS: Supervision, Writing – original draft, Writing – review and editing.

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