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Teaching effectiveness in agricultural higher education: insights from PCA-based indexing and AHP constraint prioritization

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Introduction: Teaching effectiveness is a critical determinant of learning quality, skill development, and academic performance in agricultural higher education. However, empirically grounded assessments remain limited in Indian agricultural universities, where challenges related to pedagogy, student engagement, and institutional support persist. This study develops a multidimensional, statistically derived Teaching Effectiveness Index (TEI) to evaluate student-perceived teaching effectiveness across three premier agricultural institutions.

Methods: Data were collected from 180 postgraduate students using a structured questionnaire comprising 75 sub-indicators across three dimensions: Pedagogical Proficiency, Learning Engagement, and Educational Environment Dynamics. Principal Component Analysis (PCA) was used to derive empirical weights for constructing the TEI, and institutional differences were assessed through non-parametric tests. The Analytic Hierarchy Process (AHP) was applied in parallel to identify and prioritize student-perceived constraints affecting teaching effectiveness.

Results: The Indian Agricultural Research Institute (IARI) achieved the highest TEI score (0.74), followed by GBPUAT and BHU (0.71 each). PCA indicated that innovative teaching strategies, technology integration, meaningful internships, and resource adequacy contributed most strongly to teaching effectiveness. AHP analysis ranked research-related constraints as the most critical barriers (priority weight = 0.267), followed by knowledge-development (0.229) and course-related constraints (0.206).

Discussion: Prominent challenges included the non-provision of research funds, inadequate laboratory facilities, limited software-related guidance, and insufficient practical exposure. This study demonstrates the value of integrating PCA-based empirical weighting with AHP-based prioritization to produce a comprehensive, scalable framework for evaluating teaching effectiveness. The findings underscore the need for targeted reforms to enhance pedagogical innovation, strengthen research and digital infrastructure, and expand experiential learning opportunities in agricultural universities.

KEYWORDS
agricultural higher education, analytic hierarchy process (AHP), principal component analysis (PCA), student-perceived constraints, teaching effectiveness

1 Introduction

High-quality teaching in agricultural higher education is essential for preparing a skilled workforce capable of addressing emerging challenges in food systems, climate resilience, and technological transformation. Global frameworks such as Sustainable Development Goal 4 emphasize inclusive, equitable, and quality education as a foundation for social and economic development (UNESCO, 2023). As agriculture increasingly integrates digital technologies, advanced research methods, and climate-smart innovations, expectations from agricultural universities and educators have intensified (Burman, 2023). However, the transformation of teaching practices in many developing countries, including India, has not kept pace with evolving learner needs. India's agricultural universities comprising 74 institutions nationwide play a central role in human-resource development and contribute significantly to national food and livelihood security. Despite their importance, several studies have reported persistent challenges related to teaching quality, pedagogical innovation, and student engagement within these institutions (Tapiwa, 2021). Traditional lecture-centric approaches, limited practical exposure, inadequate digital infrastructure, and restricted opportunities for experiential learning continue to constrain students' academic and professional development. These systemic issues limit the ability of agricultural graduates to apply theoretical knowledge to real-world contexts.

Teaching effectiveness is a multidimensional construct shaped by pedagogical proficiency, learning engagement, and the broader institutional environment. Pedagogical proficiency encompasses instructional clarity, learner-centered strategies, and the effective integration of technology into teaching (Roberts and Dyer, 2004; Moore and Kuol, 2005). Learning engagement reflects students' cognitive, behavioral, and emotional involvement, strengthened through active learning, timely feedback, and collaborative activities (Mulongo, 2013). The institutional environment including infrastructure, administrative support, research facilities, and digital resources provides the structural foundation for effective teaching and learning (Perryman, 2013; Muchiri and Kiriungi, 2015). Moreover, innovations such as knowledge-management systems, online internships, and blended learning approaches have been shown to enhance interdisciplinary learning and improve educational outcomes (Bhusry and Ranjan, 2012; Chand and Deshmukh, 2019).

The field of agricultural education plays a pivotal role in shaping the future of rural communities by providing essential knowledge and skills to students pursuing careers in agriculture. However, the effectiveness of teaching in this domain is influenced by a myriad of factors related to both teachers and students. Despite the critical importance of agricultural education, there exists a significant gap in understanding the intricate dynamics of teaching effectiveness and the attributes that contribute to or hinder it. Over the years, the agricultural education landscape has witnessed changes in curriculum, teaching methodologies, and the socio-economic context within which education is delivered. It is imperative to recognize the impact of these changes on the teaching-learning process and the overall effectiveness of agricultural education. While efforts have been made to enhance the quality of teaching through teacher training programs and professional development opportunities, studies focusing on comprehensive examination of the effectiveness and constraints that affect overall teaching-learning environment in the agricultural education context are limited. Despite the recognized importance of teaching effectiveness, systematic and statistically grounded evaluations remain limited in the context of Indian agricultural universities. Existing studies tend to examine isolated aspects of teaching or rely on descriptive assessments, often assigning equal weight to indicators and overlooking the interconnected nature of teaching quality. As a result, institutional comparisons and evidence-based policy decisions remain limited. To address these gaps, the present study develops a comprehensive Teaching Effectiveness Index (TEI) using PCA-derived empirical weightages across 75 sub-indicators covering three core dimensions: Pedagogical Proficiency, Learning Engagement, and Educational Environment Dynamics. In parallel, the study employs AHP to systematically evaluate and prioritize student-perceived constraints related to teaching methods, research support, knowledge development, infrastructure, and communication. This combined PCA-AHP framework offers a scalable approach to assessing teaching effectiveness and identifying critical institutional bottlenecks. Despite the growing body of literature on teaching effectiveness in higher education, most existing studies focus on isolated dimensions of teaching quality or rely on descriptive indices that assign equal weights to indicators. Empirically derived, multidimensional indices that capture the relative contribution of pedagogical, engagement-related, and institutional factors remain limited, particularly in the context of Indian agricultural universities. Moreover, previous studies seldom integrate systematic constraint analysis with teaching effectiveness measurement, restricting the translation of evaluation outcomes into actionable policy and institutional reforms. Addressing these gaps, the present study develops a statistically weighted Teaching Effectiveness Index (TEI) using Principal Component Analysis and complements it with Analytic Hierarchy Process-based prioritization of student-perceived constraints, thereby offering a context-specific and methodologically integrated framework for evaluating teaching effectiveness in agricultural higher education. The objectives of the study are to:

1. Develop a multidimensional Teaching Effectiveness Index for agricultural universities using PCA-derived weightages; and
2. Identify and prioritize the major constraints affecting teaching effectiveness using the Analytic Hierarchy Process.

2 Conceptual framework

Teaching effectiveness in higher education is grounded in established educational theories that explain how learning occurs and how instructional environments influence student outcomes. Constructivist Learning Theory, advanced by Piaget (1973) and Vygotsky (1978) emphasizes that learners actively construct knowledge through interaction, reflection, and guided instruction, providing a theoretical foundation for pedagogical proficiency. Student Engagement Theory, particularly Astin (2014) Theory of Student Involvement, 2014 and Kuh (2009) engagement framework, 2009 highlights the role of cognitive, behavioral, and emotional participation in shaping meaningful learning experiences, supporting the learning engagement dimension. Experiential Learning Theory, proposed by Kolb, 2014 underscores the importance of learning through concrete experience, reflection, and application, aligning closely with institutional factors such as laboratory work, internships, and research exposure that characterize educational environment dynamics. While these theories are conceptually distinct, they are complementary in explaining teaching effectiveness in higher education, alongside other related perspectives in educational psychology. Teaching effectiveness in higher education is widely recognized as a multidimensional construct shaped by pedagogical practices, student engagement, and the broader institutional environment. Drawing from established educational quality models (Roberts and Dyer, 2004; Moore and Kuol, 2005), this study conceptualizes student-perceived teaching effectiveness as an integrative outcome influenced by three core dimensions: Pedagogical Proficiency, Learning Engagement, and Educational Environment Dynamics. Pedagogical proficiency encompasses instructional clarity, teacher preparedness, fairness, and the use of student-centered strategies. Learning engagement reflects students' cognitive, emotional, and behavioral involvement in the learning process, shaped by interactive pedagogies, feedback systems, and motivational factors. Educational environment dynamics capture the institutional structures-resources, digital access, administrative responsiveness, and opportunities for experiential learning-that enable or constrain effective teaching-learning interactions (Figure 1).

To complement this dimensional understanding, the study also recognizes that student-perceived constraints play a critical role in shaping teaching effectiveness. These constraints operate across five domains: Courses and Teaching Methods, Research-Related Limitations, Knowledge and Professional Development, Infrastructure, and Communication. Prior literature highlights how insufficient practical exposure, weak research support, inadequate training opportunities, infrastructural gaps, and limited interaction can collectively undermine the teaching–learning ecosystem in agricultural universities (Singh et al., 2021; Makwana, 2013; Kujur et al., 2019). In this framework, constraints are not treated merely as external barriers but as systemic conditions that directly influence students' perceptions of teaching quality and indirectly shape how pedagogical and engagement processes unfold.

The conceptual framework guiding this study therefore integrates two interconnected components:

1 The multidimensional structure of teaching effectiveness, and.
2 The hierarchically organized constraint environment that affects educational experiences.

The three teaching effectiveness dimensions are hypothesized to contribute collectively to the formation of an overall Teaching Effectiveness Index (TEI), while the five constraint categories constitute perceived obstacles that negatively influence the same outcome. Although the study does not employ causal hypothesis testing, the framework positions teaching effectiveness as the central dependent construct, emerging from the combined influence of pedagogical, engagement-related, and environmental factors, alongside the structural constraints perceived by students. By integrating these conceptual elements, the framework provides a coherent foundation for the study's analytical strategy. PCA is used to empirically derive the internal structure and weightages of the teaching effectiveness dimensions, while AHP facilitates the systematic ranking of constraint categories based on student judgment. Together, these approaches offer a holistic understanding of how instructional quality and institutional barriers intersect to shape teaching effectiveness in agricultural higher education, and they support a comprehensive evaluation of the factors that require attention for meaningful pedagogical improvement.

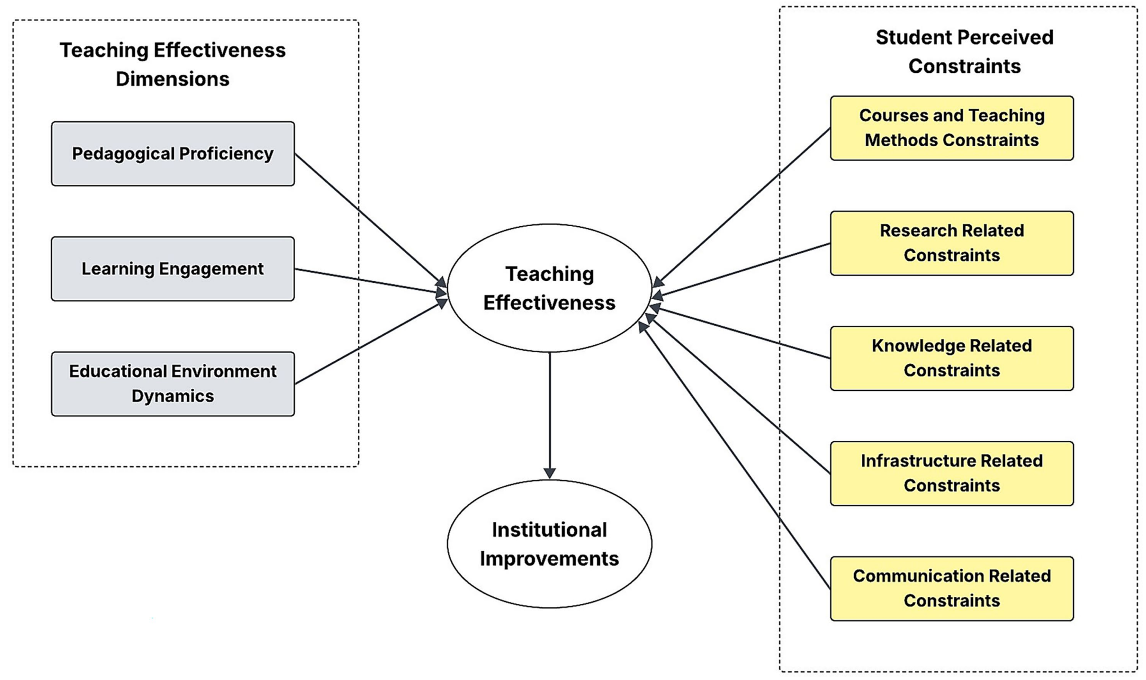

FIGURE 1
Conceptual framework of teaching effectiveness and student-perceived constraints.

3 Materials and methods

3.1 Locale of study

In India, there are 63 State Agricultural Universities, four Deemed-to-be Universities, three Central Agricultural Universities (CAUs), and four Central Universities (CUs) with faculties specializing in agriculture. This makes a total of 74 universities where agriculture is taught. Table 1 shows the distribution of these universities across India (ICAR, 2025).

Three agricultural universities out of the 74 in India was purposefully selected for data collection, which include one Deemed University (DU), one state agricultural university (SAU), and one central university with agriculture as a faculty. The three selected universities were the Indian Agricultural Research Institute, New Delhi, G. B. Pant University of Agriculture and Technology, Pantnagar, and Banaras Hindu University, Varanasi.

3.2 Sampling and data collection

The sample size was justified using Cochran's sample size formula:

$$n = \left(Z^2 \times p \times (1 - p)\right) / E^2$$

Where, Z represents the standard normal variate at 95% confidence level (1.96), p is the estimated proportion (0.5, used conservatively for maximum variability), and E is the margin of error (0.08–0.10). Accordingly, the final sample provides a margin of error of ±8–10%. With 60 participants per institution, the design achieved approximately 80% statistical power ($\alpha = 0.05$) to detect medium effect sizes (Cohen's $d \approx 0.5$) in inter-institutional comparisons, thereby ensuring statistical robustness. The respondents for this study selected such that the students were included if they were enrolled in postgraduate coursework, had attended at least one complete semester of instruction, and provided informed consent of IARI, New Delhi, GBPUAT, Pantnagar, Uttarakhand and BHU, Varanasi, Uttar Pradesh. Institutions were purposively selected based on the National Institutional Ranking Framework (NIRF), India Rankings 2023 in Agriculture and Allied Sectors, the Indian Agricultural Research Institute ranked first among all the agricultural universities in India. Among the state Agricultural universities, G. B. Pant University of Agriculture and Technology, Pantnagar came in the top three and Banaras Hindu University, Varanasi ranked first among the central university with agriculture as a faculty.

TABLE 1 Distribution of universities in India having agriculture as a subject.

Sr. no	Universities	Number
1	State Agricultural Universities	63
2	Deemed to be Universities	4
3	Central Agricultural Universities (CAU)	3
4	Central Universities (CUs) with Agriculture Faculty	4
Total		74

A structured questionnaire was developed based on an extensive literature review, expert input, and modifying existing teaching-effectiveness frameworks (Roberts and Dyer, 2004; Moore and Kuol, 2005). The questionnaire was designed to capture students' perceptions of teaching effectiveness across pedagogical, engagement-related, and institutional dimensions. Responses from students were recorded on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). Cronbach's alpha values for all three TEI dimensions exceeded 0.80, indicating strong internal consistency. The data were collected from different departments under the six schools viz., Crop improvement, Plant protection, Basic sciences, Social science, Natural resource management, and Horticultural science. Among these six, 10 students each were selected randomly in-order to collect 60 responses from a single university and a total of 180 responses from the three universities (Figure 2).

3.3 Methodology

To systematically measure teaching effectiveness, a composite index was developed, informed by a review of established models and consultations with subject-matter experts. Three core dimensions were finalized: Pedagogical Proficiency, representing teacher-related attributes; Learning Engagement, reflecting student-related factors; and Educational Environment Dynamics, encompassing institution-related variables. Each dimension comprised five indicators, with five sub-indicators under each, yielding a total of 75 sub-indicators. To assign statistical weightages to the sub-indicators, Principal Component Analysis (PCA) was employed. Sub-index scores were subsequently computed through normalization, followed by aggregation into the final Teaching Effectiveness Index, on the basis of which institutions were categorized into low, medium, and high effectiveness groups. To complement the index, the study also identified and ranked constraints affecting teaching effectiveness. These were organized into five dimensions: Courses and Teaching Methods, Research-Related Constraints, Knowledge/Development Constraints, Infrastructure Constraints, and Communication Constraints. AHP was employed to prioritize these constraints through a structured decision-making process. The procedure involved problem modeling, pairwise comparisons of indicators using Saaty's nine-point scale, aggregation of judgments through the geometric mean method, and consistency testing using the Consistency Index (CI) and Consistency Ratio (CR) to ensure reliability. Final priority weights were then calculated to determine the relative importance of each constraint, enabling both qualitative and quantitative decision factors to be ranked within a rigorous hierarchical framework.

Prior to full-scale data collection, the instrument was pre-tested with 5% of the total respondents drawn from across the three institutions. The pre-test served to identify linguistic ambiguities, assess clarity, and evaluate the overall reliability of the tool. Feedback suggested only minor linguistic modifications, while items that generated null responses were removed from the final version. Respondents included in the pre-test were excluded from the main survey to maintain the validity and integrity of the final sample.

3.3.1 Development of teaching effectiveness index

Various models available on teaching effectiveness was thoroughly studied and utilized with further modifications for the development of a composite index of teaching effectiveness. Suitable

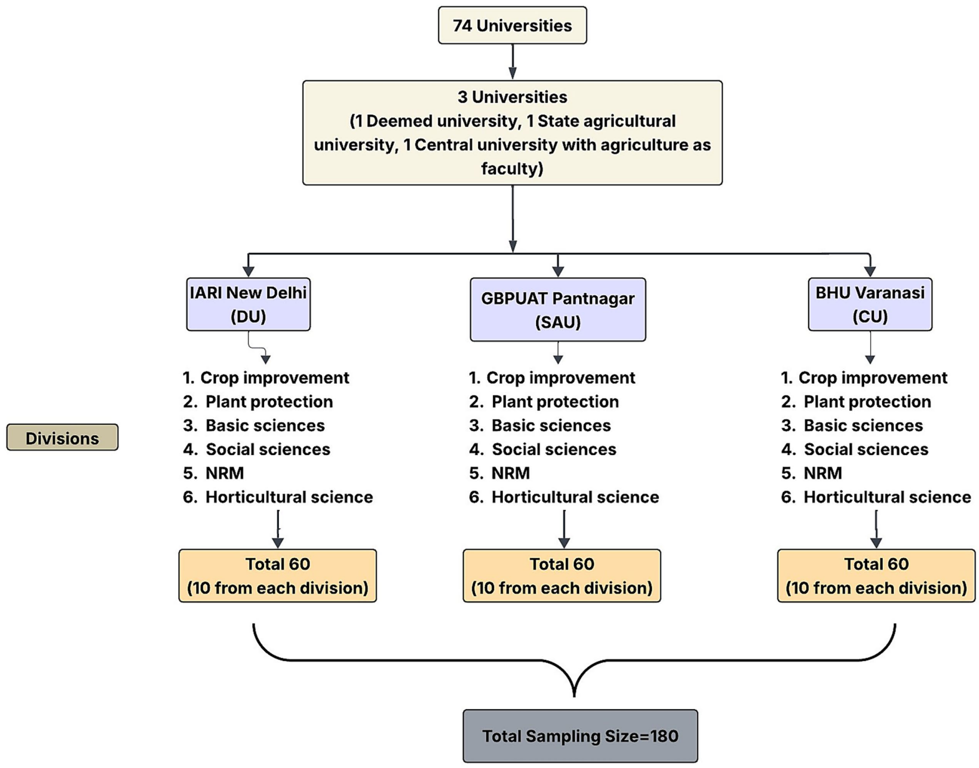

FIGURE 2
Sampling framework for the study.

dimensions and it's indicators to measure its dimensions was developed for the index formation.

3.3.1.1 Step 1: compilation and finalization of indicators and sub-indicators

A comprehensive list of dimensions, indicators, and sub-indicators for teaching effectiveness was compiled and finalized after an extensive literature review and discussions with experts, teachers, and students. The indicators selected for the teaching effectiveness index include Pedagogical Proficiency (a teacher-related variable), Learning Engagement (a student-related variable), and Educational Environment Dynamics (an institutional-related variable). A total of 15 indicators were identified, with each indicator having five sub-indicators, resulting in a total of 75 sub-indicators to measure teaching effectiveness. Table 2 presents the three dimensions and fifteen indicators chosen for the development of the teaching effectiveness index.

3.3.1.2 Step II: developing sub-teaching effectiveness index

A sub-index for each variable was developed by normalizing the data using the following formula:

$$\text{Sub Teaching Effectiveness Index}\left(\text{STEI}\right) = \textit{Actual value} - \textit{Minimum value} \div \textit{Maximum value} - \textit{Minimum value}$$

Higher index values indicate greater teaching effectiveness, while lower index values indicate lesser teaching effectiveness.

3.3.1.3 Step III: assigning weights through PCA analysis

In previous research, some indices were developed by assigning equal weight to all factors/variables/indicators, which could lead to inaccuracies due to the varying contributions of each factor. This study aimed to address these issues by determining weights through PCA based on actual data variation from respondents. After standardizing the data, PCA was used to assign weights to the indicators using the statistical software SPSS. PCA also helped consolidate the variables into a few principal components.

3.3.1.4 Step IV: computation of final teaching effectiveness index

To calculate the final teaching effectiveness index, the assigned weights were multiplied by each variable to compute each principal component score through linear summation. The PCA scores of those principal components explaining more than 95% of the total variation were used for the final index.

The composite index (I) was calculated using the following formula:

$$\text{I} = \left[\Sigma\left(\text{Xi} \times \Sigma\left(\text{Lij} \times \text{Ej}\right)\right)\right] / \left[\Sigma\left(\Sigma\left(\text{Lij} \times \text{Ej}\right)\right)\right]$$

Where:
I = composite index
Xi = normalized value of the i-th indicator
Lij = factor loading of indicator i on factor j
Ej = eigenvalue of factor j

3.3.1.5 Step V: classification of institutes according to teaching effectiveness index score

After calculating the final teaching effectiveness index, the teaching effectiveness for all three agricultural universities was also determined. Teaching effectiveness was categorized into three levels- high, medium, and low- based on individual scores. The classification of the three universities into these categories was done normalizing the individual index scores of each university and classified into three equal parts from zero to one.

3.3.2 Ranking of constraints by analytic hierarchy process (AHP)

This method is based on pair-wise comparison but associated with hierarchic formulation of multi-criteria. This method has significant advantage of providing 'objective decision', based on subjective and personal preference of an individual or group of individuals. This method has the ability to make quantitative and qualitative decision attributes commensurable and has flexibility with regard to the setting objectives (Kangas, 1992) (Figure 3).

3.3.2.1 Steps for AHP Construction

3.3.2.1.1 Step I: problem modeling

The goal should be well-defined, along with the various factors influencing it. After identifying these factors, it is essential to derive

TABLE 2 Dimensions and indicators for development of teaching effectiveness index.

Sr. no	Dimensions	Indicators
1	Pedagogical Proficiency	I. Clarity in Instruction II. Adaptability to Learning Styles III. Innovative Teaching Strategies IV. Student-centred Approach V. Effective Use of Technology
2	Learning Engagement	I. Active Participation II. Application of Knowledge III. Attitudes Toward Learning IV. Completion of Learning Objectives V. Feedback Utilization
3	Educational Environment Dynamics	I. Quality of Learning Resources II. Student Involvement in Decision-Making III. Internship and Placement Opportunities IV. Technology Integration and accessibility V. Administrative support

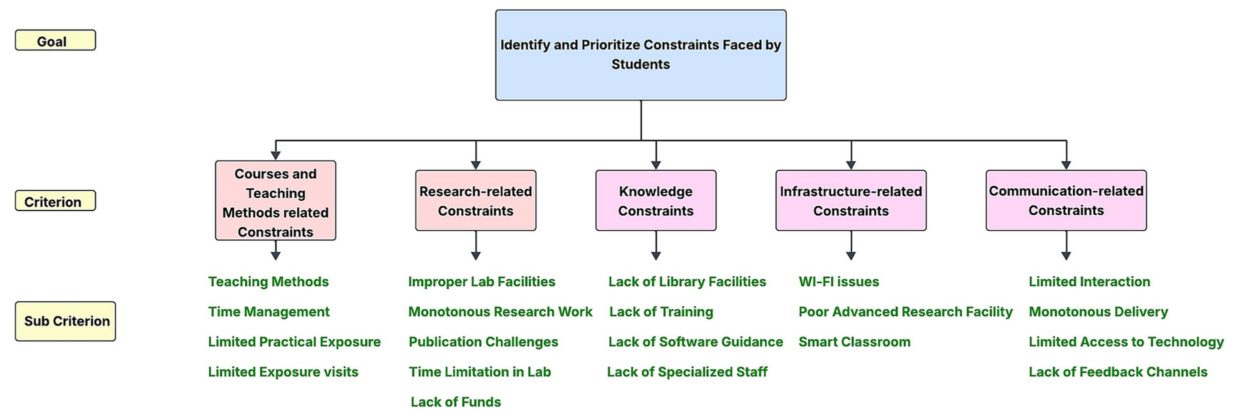

FIGURE 3
AHP framework used in the study.

FIGURE 4
Kruskal-Wallis test.

TABLE 3 Table of random indices.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Adopted from Saaty and Forman (1992), actual calculation made by Saaty (1977).

specific criteria. The problem structure should aim to include a limited number of criteria while still covering a broad range of aspects.

3.3.2.1.2 Step II: pair-wise comparison

In the next level, indicators are also compared, pair-wise as explained in Figure 4 among themselves. Expert judgments were organized into a pairwise comparison matrix $A = \left[a_{ij} \right]$, where each element represents the relative importance of indicator $i$over indicator j using Saaty's 1–9 scale (Table 3).

3.3.2.1.3 Step III: judgemental scale

Saaty (1977) proposed one nine-point scale to have a pair-wise comparison of different dimensions and indicators as given below in Table 3.

3.3.2.1.4 Step IV: aggregation of judgement

Aggregating individual priorities can be done with geometric mean. Chang et al. (2009) compared different aggregation methods and categorically stated that methods of aggregation did not influence the final results.

3.3.2.1.5 Step V: determination of consistency ratio

As priorities only would be usable and valid, if derived from matrices that are consistent; so a consistency check must be applied. Saaty (1977) has proposed a Consistency Index (CI), which is related to the eigen value method. 'Consistency Index' can be calculated by the following formula.

$$CI = \frac{(\lambda max - n)}{(n - 1)}$$

Where n = Dimension of the matrix λ_{max} = Eigen value

- The consistency ratio, the ratio of CI and RI, is given by: CR = CI/RI

Where RI is the random index

3.3.2.1.6 Step VI: calculation of priorities

Identification of scaling factor is of utmost importance, as the scaling factor or priority would show how much importance a particular factor has, in terms of overall goal. Local priority of criteria tells about the cardinal importance of each factor.

4 Results

4.1 Development of teaching effectiveness index

Various models available on teaching effectiveness was thoroughly studied and utilized with further modifications for the development of a composite index of teaching effectiveness. Suitable dimensions and it's indicators to measure its dimensions was developed for the index formation. The Quality Teaching Model (NSW Department of Education and Training (NSWDET), 2003) has three dimensions of pedagogy: Intellectual Quality, Quality Learning Environment, and Significance. Each dimension comprises six elements. Student evaluation of teaching (SET) is one of the most criticized (Ellis et al., 2003) and yet the most prevalent (Richardson, 2005; Shevlin et al., 2000) practices in higher education. The instrument uses 18 behavioral performance examples along three performance dimensions on a six-point rating scale. It captures 10 key areas of faculty performance that students can observe: course design, instruction skills, depth of knowledge, facilitation skills, student-faculty interaction, ability to motivate, quality of assignments, organization of assessment, perceived fairness, and quality of feedback. The dynamic model of educational effectiveness (Kyriakides and Creemers, 2008) is based on the assumption that each factor can be measured by taking into account the following five dimensions: frequency, focus, stage, quality, and differentiation. Frequency is a quantitative way to measure the functioning of each factor whereas the other four dimensions examine the qualitative characteristics of the functioning of the factor. Marzano (2007) while framing the model of effective teaching included eight indicators of teaching effectiveness: establishing learning goals, student interaction with new knowledge, student practice to deepen understanding, engaging students, effective teaching methodologies, effective classroom management, effective student-teacher relationships, and effective assessment. Mahra et al. (2020) identified three major indicators of teaching effectiveness: teacher-related, student-related and institutional-related indicators with several sub-indicators under respective indicators.

In the present study, Principal Component Analysis (PCA) was employed to determine the weightage of the 75 sub-indicators associated with teaching effectiveness. Following Kaiser (1958) criterion, only components with eigenvalues greater than one were retained, resulting in the extraction of 15 principal components. These components together accounted for 75.41% of the total variance, indicating

TABLE 4 Eigenvalues extracted using principal component analysis.

Rotation sums of squared loadings				
Component	Total	% of variance	Cumulative %	Variance/cumulative sum relative contribution (Variance ÷ 75.41%)
1	14.978	19.97	19.97	0.26
2	4.63	6.173	26.144	0.08
3	4.522	6.029	32.173	0.08
4	4.428	5.904	38.077	0.08
5	3.435	4.58	42.656	0.06
6	3.391	4.521	47.178	0.06
7	3.37	4.494	51.672	0.06
8	2.918	3.89	55.562	0.05
9	2.799	3.733	59.295	0.05
10	2.528	3.371	62.665	0.04
11	2.464	3.286	65.951	0.04
12	2.235	2.98	68.931	0.04
13	1.808	2.411	71.342	0.03
14	1.7	2.266	73.609	0.03
15	1.354	1.805	75.413	0.02

that the multidimensional nature of teaching effectiveness was well captured. The average communality value across the sub-indicators was 0.7541, which exceeds the recommended threshold of 0.70, confirming the adequacy of the dataset for factor analysis.

The Rotation Sums of Squared Loadings presented in Table 4 illustrate the proportion of variance explained by each retained component. The first component contributed 19.97% of the variance, while subsequent components contributed progressively smaller shares, with the fifteenth component still accounting for 1.81%. Collectively, these components provided a comprehensive representation of the variance structure of the data. To facilitate interpretation, the initial PCA solution-containing both positive and negative loadings were normalized. Specifically, negative values were squared, the column totals were computed, and each cell was divided by its respective column sum, producing a normalized component matrix. This transformation yielded relative weights that were easier to interpret and apply.

Finally, the relative contribution of each component was calculated by dividing the percentage of variance explained (Table 4) by the overall cumulative variance (75.41%). These proportions were then combined with the normalized matrix through a sum-product calculation, producing the final weightage values for each of the 75 sub-indicators. This procedure ensured that each sub-indicator's weightage was derived not arbitrarily but in proportion to its statistical contribution, thereby enhancing the validity and robustness of the Teaching Effectiveness Index.

Table 5 outlines the indicators and sub-indicators representing the dimension of Pedagogical Proficiency, along with their communality values and assigned weightages. This dimension reflects teacher-related attributes, including clarity, adaptability, innovation, student-centeredness, and technology use. Sub-indicators under Clarity in Instruction (e.g., clear explanations, straightforward assignments, effective communication) show moderate to high communalities (0.653–0.745), confirming their essential role in effective pedagogy. Adaptability to Learning Styles also contributed meaningfully, with values ranging from 0.675 to 0.762, underscoring the importance of flexible approaches that address diverse learner needs.

The highest communalities were observed for Innovative Teaching Strategies such as the use of creative methods (0.836) and fostering a dynamic environment (0.839), suggesting that innovation strongly enhances student engagement. Similarly, Effective Use of Technology demonstrated consistently high values (0.752–0.813), with technology for research and collaboration emerging as particularly influential (0.813). Student-centered Approaches also played a significant role, especially in promoting participation (0.785) and supportive classroom environments (0.795), though student-led discussions showed relatively lower influence (0.602). It can be interpreted that, while clarity and adaptability remain important, the findings indicate that innovation, technology integration, and student-centered practices are the most impactful components of pedagogical proficiency in agricultural higher education.

Table 6 presents the dimension of Learning Engagement, comprising five clusters: active participation, application of knowledge, attitudes toward learning, completion of objectives, and feedback utilization. Active Participation indicators (e.g., class discussions, meaningful project contributions, enthusiasm) showed moderate to high communalities (0.670–0.777), confirming their value in promoting interactive learning environments. Application of Knowledge reflected particularly strong results, with the highest communality for reflection on learning experiences (0.801; weightage 0.0141), highlighting the importance of applying theory to practice and fostering innovation. The cluster of Attitudes Toward Learning demonstrated consistent values (0.667–0.761), emphasizing curiosity, resilience, and a positive learning outlook as key

TABLE 5 Components of pedagogical proficiency and their relative contributions.

Sr. no	Indicators	Sub indicators	Communality values	Weightage
1	Clarity in Instruction	The instructor's explanations are clear.	0.653	0.0115
2		Course material is communicated effectively.	0.698	0.0123
3		Assignment instructions are straightforward.	0.745	0.0132
4		Examples enhance understanding of concepts.	0.675	0.0119
5		Questions and clarifications are encouraged.	0.738	0.0130
6	Adaptability to Learning Styles	Teaching methods suit learning styles.	0.762	0.0135
7		Techniques accommodate diverse preferences.	0.675	0.0119
8		Learning approaches cater to individual needs.	0.742	0.0131
9		The pace adjusted based on feedback.	0.722	0.0128
10		Additional support is provided.	0.736	0.0130
11	Innovative Teaching Strategies	Innovative teaching methods are used.	0.836	0.0148
12		Technology engages students creatively.	0.666	0.0118
13		Real-world examples are integrated.	0.733	0.0130
14		Creativity and critical thinking encouraged.	0.74	0.0131
15		A dynamic learning environment fostered.	0.839	0.0148
16	Student-centered Approach	Active participation is promoted.	0.785	0.0139
17		Student input shapes course content.	0.675	0.0119
18		Student-led discussions done.	0.602	0.0107
19		Personalized support is offered.	0.699	0.0123
20		A supportive classroom atmosphere is created.	0.795	0.0140
21	Effective Use of Technology	Technology is integrated into lectures.	0.783	0.0138
22		Online platforms are used effectively.	0.771	0.0136
23		Multimedia resources supplement teaching.	0.752	0.0133
24		Technology for research and collaboration.	0.813	0.0144
25		Relevant emerging technologies are included.	0.794	0.0140

TABLE 6 Components of learning engagement and their relative contributions.

S. no	Indicators	Sub indicators	Communality values	Weightage
1	Active Participation	Students engage in class discussions.	0.741	0.0131
2		Contributions to projects are meaningful.	0.67	0.0118
3		Enthusiasm for learning is evident.	0.725	0.0128
4		Extra learning opportunities are sought out.	0.72	0.0127
5		Ownership of the learning journey is shown.	0.777	0.0137
6	Application of Knowledge	Theoretical concepts applied to real scenarios.	0.788	0.0139
7		Practical skills are proficiently used.	0.74	0.0131
8		Knowledge is integrated across courses.	0.682	0.0121
9		Innovation in addressing challenges.	0.771	0.0136
10		Learning experiences are reflected upon.	0.801	0.0141
11	Attitudes Toward Learning	A positive attitude toward learning is shown.	0.667	0.0118
12		Curiosity about new ideas is expressed.	0.677	0.0120
13		Resilience in overcoming challenges.	0.761	0.0135
14		Feedback is actively sought for improvement.	0.746	0.0132
15		Additional learning opportunities are pursued.	0.76	0.0134
16	Completion of Learning Objectives	Course objectives are mastered.	0.804	0.0142
17		Course requirements are met or exceeded.	0.753	0.0133
18		Knowledge and skills are applied proficiently.	0.77	0.0136
19		Progress in learning objectives is consistent.	0.795	0.0141
20		Reflection on learning outcomes is evident.	0.73	0.0129
21	Feedback Utilization	Feedback is sought to improve performance.	0.741	0.0131
22		Constructive criticism is welcomed.	0.797	0.0141
23		Feedback is used to enhance learning.	0.732	0.0129
24		Areas for improvement are identified through self-assessment.	0.787	0.0139
25		Feedback is proactively incorporated into growth.	0.775	0.0137

drivers of engagement. Similarly, Completion of Learning Objectives showed some of the strongest communalities in this dimension, with mastery of course objectives (0.804; 0.0142) and consistent progress (0.795; 0.0141) ranking highly, suggesting that achieving outcomes is central to student engagement. Finally, Feedback Utilization emerged as a significant factor, with constructive criticism (0.797; 0.0141) and proactive incorporation of feedback (0.775; 0.0137) reinforcing the role of reflective practices in improving learning. Thus, the results indicate that application of knowledge, mastery of objectives, and effective feedback utilization are the strongest contributors to learning engagement, while active participation and positive attitudes provide supportive foundations for sustained student involvement.

Table 7 summarizes the dimension of Educational Environment Dynamics, which incorporates five clusters: quality of learning resources, student involvement in decision-making, internship and placement opportunities, technology integration and accessibility, and administrative support. The cluster on Quality of Learning Resources demonstrated strong communalities (0.738–0.823), with the highest contribution from access to diverse resources (0.823; 0.0146), confirming the importance of resource adequacy and variety in fostering effective learning. Student Involvement in Decision-Making also showed high influence, particularly through student participation in academic decisions (0.808; 0.0143) and empowerment to voice opinions (0.794; 0.0141), reflecting the value of participatory governance in higher education. Internship and Placement Opportunities emerged as one of the strongest clusters, with the highest communality recorded for meaningful internships (0.847; 0.0150) and strong institutional support for securing placements (0.837; 0.0148). These findings underscore the centrality of experiential learning and industry linkages in preparing students for professional careers. The dimension of Technology Integration and Accessibility revealed moderate-to-high communalities, with relevant technological advancements (0.814; 0.0144) and inclusive technology resources (0.797; 0.0141) standing out as key contributors. Lower values were noted for access to tech-enabled classrooms (0.623; 0.0110) and digital literacy training (0.646; 0.0114), suggesting areas requiring institutional strengthening.

Finally, Administrative Support exhibited consistently strong results, particularly in services supporting student wellbeing (0.809; 0.0143) and a sense of being supported by administration (0.821; 0.0145). This highlights the broader institutional environment as an essential enabler of teaching effectiveness and student satisfaction. Thus, the results indicate that internship opportunities, access to diverse resources, and robust administrative support are the most influential components of educational environment dynamics, while technology accessibility presents an area for further improvement.

4.2 Distribution of teaching effectiveness index scores across institutions

The distribution of Pedagogical Proficiency Index scores (Table 8) revealed substantial inter-institutional variation. At BHU, a relatively high proportion of students (43.3%) fell into the 'Low' category (<0.05), while 18.3% were in the 'Medium' range (0.05–0.8), and 38.3% in the 'High' category (>0.8). In contrast, both IARI and GBPUAT reported stronger pedagogical proficiency, with half of their respondents (50.0%) in the 'High' category. IARI also recorded 23.3% 'Low' and 26.7% 'Medium', while GBPUAT reported 31.7% 'Low' and 18.3% 'Medium'. These results suggest that IARI and GBPUAT demonstrate comparatively stronger pedagogical proficiency relative to BHU. The Learning Engagement Index (Table 9) further highlighted institutional differences. At BHU, 36.7% of students were in both the 'Low' (<0.65) and 'High' (>0.78) categories, with 26.7% in 'Medium'. IARI exhibited stronger engagement, with only 20.0% in the 'Low' category, 38.3% in 'Medium', and the highest proportion (41.7%) in 'High'. GBPUAT showed a more balanced distribution with 30.0% 'Low', 31.7% 'Medium', and 38.3% 'High'. Overall, these results indicate that IARI achieved the most favorable outcomes in terms of learner engagement.

Analysis of Educational Environment Dynamics (Table 10) also showed distinct patterns. BHU had the largest proportion of students in the 'Low' category (<0.63) at 41.7%, alongside 25.0% 'Medium' (0.63–0.78) and 33.3% 'High' (>0.78). IARI reported comparatively stronger perceptions of the educational environment, with only 25.0% in 'Low', 33.3% in 'Medium', and the highest proportion (41.7%) in 'High'. GBPUAT fell between the two, with 33.3% 'Low', 30.0% 'Medium', and 36.7% 'High' (Table 11).

Overall, the findings indicate that IARI consistently outperformed BHU and GBPUAT across the three dimensions, particularly in learner engagement and educational environment. However, the average teaching effectiveness index scores - 0.74 for IARI and 0.71 for both GBPUAT and BHU, suggest that while teaching practices are generally robust, there remains scope for improvement. Targeted interventions, especially in pedagogical innovation and strengthening the institutional environment, could further enhance outcomes. The findings underscore the importance of continuous evaluation and refinement of teaching strategies to ensure that agricultural higher education remains responsive to evolving academic and professional demands.

The Kruskal-Wallis test was used to compare the teaching effectiveness index across IARI, GBPUAT, and BHU. While the results indicated no statistically significant differences among the three institutions ($H = 1.999$, $p = 0.368$), IARI recorded the highest mean rank, reflecting relatively stronger teaching effectiveness. GBPUAT and BHU showed comparable outcomes, suggesting that although IARI demonstrates a leadership position, overall teaching effectiveness across the institutions remains broadly similar.

4.3 Ranking of constraints faced by students in agricultural education affecting teaching effectiveness

AHP analysis revealed that the highest priority was assigned to Research-Related Constraints, with a weight of 0.267 (Table 12). Students consider barriers within the research domain to be the most significant impediments to their academic success. Specific concerns included improper laboratory facilities, monotonous research activities, difficulties in publishing articles, time limitations in laboratories, and above all, non-provision of funds (Figure 5).

Among these, inadequate financial support and resource availability were regarded as the most critical issues, reflecting the central role of research in postgraduate education and the need for sustained institutional investment. The second most pressing category was Knowledge and Development-Related Constraints, with a priority weight of 0.229. Respondents emphasized gaps such as *the lack of structured training opportunities, insufficient workshops, limited guidance in software use, and shortage of specialized staff*. In particular, the absence of software-related training and mentoring was identified as a high-priority challenge, suggesting to integrate modern digital competencies and skill-building modules into the postgraduate curriculum. These findings highlight the necessity of knowledge-based capacity development to complement formal coursework.

Courses and Teaching Methods, with a weight of 0.206, ranked third in overall importance. While lower than research and development challenges, this dimension still revealed concerns related to *time management, limited exposure visits, insufficient practical learning opportunities, and ineffective teaching strategies*. The emphasis placed on practical exposure and dynamic teaching methods suggests that students are not only attentive to content delivery but also to the experiential and interactive aspects of learning, which play a vital role in shaping competencies.

Communication-Related Constraints, weighted at 0.153, emerged as the fourth-ranked priority. Key issues included *limited interaction between students and faculty, monotonous delivery styles, restricted access to technology, and the absence of robust feedback channels*. These findings point to challenges in two-way communication within the

TABLE 7 Components of educational environment dynamics and their relative contributions.

S. no	Indicators	Sub indicators	Communality values	Weightage
1	Quality of Learning Resources	Learning resources meet student needs.	0.738	0.0130
2		Availability of resources sufficient.	0.784	0.0139
3		Lab facilities support hands-on learning.	0.768	0.0136
4		Up-to-date resources are maintained.	0.744	0.0132
5		Access to diverse learning resources.	0.823	0.0146
6	Student Involvement in Decision-Making	Students involved in academic decisions.	0.808	0.0143
7		Student in curriculum development.	0.761	0.0135
8		Feedback opportunities are provided.	0.777	0.0137
9		Students and faculty collaboration.	0.773	0.0137
10		Students empowered to voice opinions.	0.794	0.0141
11	Internship and Placement Opportunities	Meaningful internship opportunities.	0.847	0.0150
12		Diverse internship options.	0.791	0.0140
13		Industry connections for internships.	0.827	0.0146
14		Support for securing internships.	0.837	0.0148
15		Internships for professional development.	0.802	0.0142
16	Technology Integration and Accessibility	Technology integrated into learning.	0.745	0.0132
17		Access to tech-enabled classrooms.	0.623	0.0110
18		Digital literacy training is offered.	0.646	0.0114
19		Technology resources are inclusive.	0.797	0.0141
20		Relevant technology advancements.	0.814	0.0144
21	Administrative support	Adequate administrative support.	0.765	0.0135
22		Timely information on academic policies	0.765	0.0136
23		Staff are responsive to inquiries.	0.76	0.0134
24		Services support student wellbeing.	0.809	0.0143
25		Feeling supported by administration enhances satisfaction.	0.821	0.0145

TABLE 8 Distribution of pedagogical proficiency index scores across institutions.

Mean index score	BHU		IARI		GBPUAT	
	Frequency	Percent	Frequency	Percent	Frequency	Percent
Low (Less than 0.05)	26	43.33	14	23.33	19	31.67
Medium (0.05–0.8)	11	18.33	16	26.67	11	18.33
High (Above 0.8)	23	38.33	30	50.00	30	50.00

TABLE 9 Distribution of learning engagement index scores across institutions.

Mean index score	BHU		IARI		GBPUAT	
	Frequency	Percent	Frequency	Percent	Frequency	Percent
Low (Less than 0.65)	22	36.67	12	20.00	18	30.00
Medium (0.65–0.78)	16	26.67	23	38.33	19	31.67
High (Above 0.78)	22	36.67	25	41.67	23	38.33

TABLE 10 Distribution of educational environment dynamics index scores across institutions.

Mean index score	BHU		IARI		GBPUAT	
	Frequency	Percent	Frequency	Percent	Frequency	Percent
Low (Less than 0.63)	25	41.67	15	25.00	20	33.33
Medium (0.63–0.78)	15	25.00	20	33.33	18	30.00
High (Above 0.78)	20	33.33	25	41.67	22	36.67

TABLE 11 Comparison of the teaching effectiveness of the selected universities.

Category (score range)	IARI (n = 60)	GBPUAT (n = 60)	BHU (n = 60)
Low (0–0.33)	3 (5.0%)	12 (20.0%)	10 (16.7%)
Medium (0.33–0.66)	28 (46.7%)	20 (33.3%)	28 (46.7%)
High (0.66–1.00)	29 (48.3%)	28 (46.7%)	22 (36.6%)

Kruskal–Wallis Test Results: H = 1.999, df = 2, Asymp. Sig. = 0.368.

classroom and institution, thereby highlighting the need for improved pedagogical dialogue, student feedback mechanisms, and more engaging instructional delivery.

Finally, Infrastructure-Related Constraints were given the lowest overall priority (0.146). Although concerns such as *poor Wi-Fi connectivity, inadequate facilities for advanced research, and limited availability of smart classrooms* were acknowledged, students regarded them as relatively less critical compared to the academic, pedagogical, and communicational barriers. Nevertheless, the importance of infrastructure should not be underestimated, as these elements constitute the foundation upon which effective teaching and research environments are built. These results suggest that while infrastructural provisions remain important, students perceive research-related and knowledge-development constraints as the most pressing challenges that directly influence teaching effectiveness and learning outcomes in agricultural higher education.

In this AHP analysis represented in Table 13, the local weight represents the priority of each major constraint category relative to the other categories. For example, "Research-related constraints" have the highest local weight (0.2667), meaning they are considered the most influential constraint group overall, followed by knowledge-related (0.2287) and course-related constraints (0.2060). The global weight, on the other hand, reflects the overall contribution of each individual indicator (IND 1, IND 2, etc.) to the entire hierarchy, combining both the local weight of the constraint category and the indicator's own relative weight within that category. For instance, within research-related constraints, IND 5 has a higher global weight (0.0827) because it has both a high local influence within the category and the category itself is highly weighted. The CI and CR values included in the table confirm the internal consistency

TABLE 12 Ranking of constraints using analytic hierarchy process (AHP).

Dimensions	Priority weights	Lambda max	CI	CR	Rank
Courses and teaching methods	**0.206**				
Teaching methods	0.211	4.104	0.035	0.039	**4**
Time management	0.251				**3**
Limited practical exposure	0.279				**1**
Limited exposure visits	0.259				**2**
Research related constraints	**0.267**				
Improper lab facilities	0.167	5.086	0.021	0.019	**3**
Monotonous research work	0.147				**5**
Publication of articles	0.213				**2**
Time limitation in lab	0.163				**4**
Non provision of funds	0.310				**1**
Knowledge related constraints	**0.229**				
Lack of facility in library	0.213	4.046	0.015	0.017	**3**
Lack of training and workshops	0.286				**2**
Lack of guidance using software	0.299				**1**
Lack of specialized staff	0.203				**4**
Infrastructure related constraints	**0.146**				
Wi-fi facility	0.367	3.003	0.002	0.003	**1**
Poor facility for advanced research	0.324				**2**
Smart classroom	0.309				**3**
Communication-related constraints	**0.153**				
Limited interaction	0.299	4.124	0.041	0.046	**2**
Monotonous delivery	0.199				**3**
Limited access to technology	0.317				**1**
Lack of feedback channels	0.185				**4**

Bold values represents Ci (Consistency Index), Cr (Consistency Ratio), and Lamda Factor (Maximum Eigenvalue) which are critical factors used to validate the reliability of pairwise comparisons.

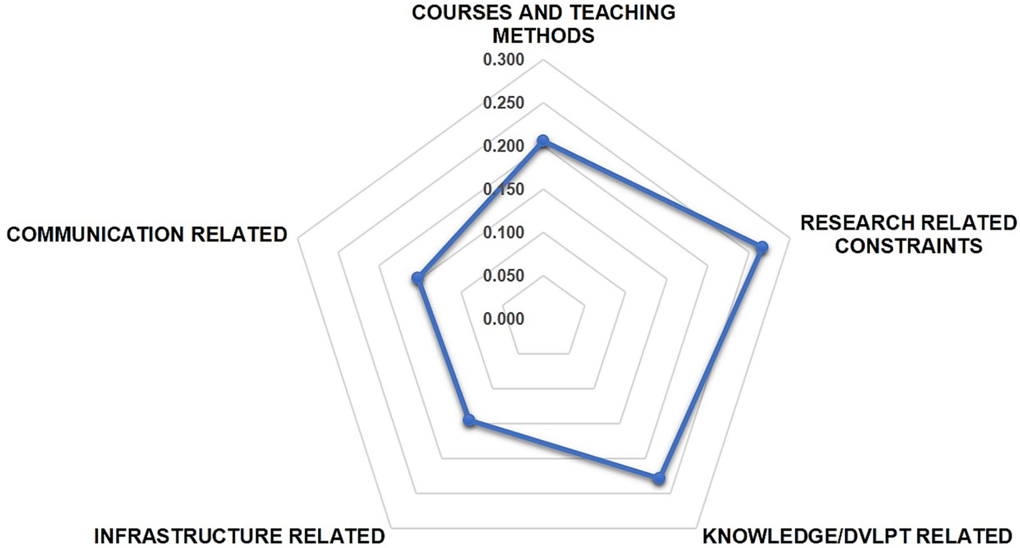

FIGURE 5
Priority weights of the constraints of teaching effectiveness.

of expert judgments (CR < 0.1), ensuring that the weighting results are statistically reliable. Overall, the combination of local and global weights helps identify not only which domains are most critical, but also which specific indicators within those domains require the most attention.

5 Discussion

The results of this study reveal substantial institutional differences in teaching effectiveness across BHU, IARI, and GBPUAT, reinforcing the idea that teaching quality in agricultural higher education is strongly shaped by both instructional proficiency and the surrounding institutional ecosystem. The findings should be interpreted as reflecting student-perceived teaching effectiveness rather than objectively observed teaching quality. The higher pedagogical proficiency observed at IARI and GBPUAT, where 50% of students reported high proficiency compared to 43.33% at BHU, aligns with earlier evidence that instructional clarity, teacher preparedness, and fairness significantly contribute to effective teaching (Roberts and Dyer, 2004; Hines et al., 1985; Eck et al., 2019). These findings echo the broader emphasis on pedagogical proficiency as a central determinant of student learning in agricultural disciplines, where clarity of explanation, adaptability to learner needs, and structured feedback are critical. Although Brown et al. (2009) questioned the usefulness of learning-style frameworks, the present results reaffirm that overall instructional quality, rather than stylized pedagogical matching, plays a more decisive role in shaping student learning outcomes. BHU's comparatively lower scores in this dimension suggest limitations in feedback mechanisms (Moore and Kuol, 2005) and slower integration of innovative, technology-enabled teaching practices (Byrom and Bingham, 2001).

Learning engagement also varied significantly across institutions, with IARI again demonstrating the strongest performance (41.67% in the high category), followed by GBPUAT (38.33%) and BHU (36.67%). These findings correspond with earlier research showing that interactive and experiential teaching methods foster deeper cognitive and behavioral engagement among students (Nierenberg, 1998; Mulongo, 2013). The stronger engagement at IARI may reflect the availability of digital tools, collaborative learning spaces, and effective use of knowledge-management systems, factors that have been shown to enhance interdisciplinary understanding and student motivation (Bhusry and Ranjan, 2012). By contrast, lower engagement at BHU and GBPUAT may be linked to challenges in feedback utilization (Banerjee, 2014) and limited alignment between instructional strategies and students' intrinsic motivations (Aithal and Kumar, 2016). These variations underscore the importance of structured feedback loops, learner-centered pedagogy, and technology integration in promoting sustained learning engagement.

Differences were also evident in educational environment dynamics, where IARI once again outperformed the other institutions, with 41.67% of students reporting a high-quality academic environment. This is consistent with findings that resource-rich environments characterized by accessible learning materials, administrative responsiveness, and structured internship opportunities enhance teaching effectiveness and student satisfaction (Muchiri and Kiriungi, 2015; Chand and Deshmukh, 2019). Furthermore, effective technology integration and strong institutional support systems, including clear communication channels and timely administrative processes, are known

TABLE 13 AHP-derived local and global priority weights of the constraint dimensions and their indicators.

Constraints	Priority weights	Indicator	Local	Global	Ci	Cr	Lambda factor
Course related	0.206	IND 1	0.211	0.043	**0.034**	**0.039**	**4.104**
	0.206	IND 2	0.250	0.051			
	0.206	IND 3	0.279	0.057			
	0.206	IND 4	0.259	0.053			
Research related	0.266	IND 1	0.167	0.044	**0.021**	**0.019**	**5.085**
	0.266	IND 2	0.147	0.039			
	0.266	IND 3	0.213	0.057			
	0.266	IND 4	0.163	0.043			
	0.266	IND 5	0.310	0.083			
Knowledge related	0.228	IND 1	0.212	0.049	**0.015**	**0.017**	**4.046**
	0.228	IND 2	0.285	0.065			
	0.228	IND 3	0.298	0.068			
	0.228	IND 4	0.202	0.046			
Infrastructure related	0.145	IND 1	0.366	0.053	**0.002**	**0.003**	**3.003**
	0.145	IND 2	0.324	0.047			
	0.145	IND 3	0.309	0.045			
Communication related	0.153	IND 1	0.298	0.046	**0.041**	**0.046**	**4.124**
	0.153	IND 2	0.199	0.030			
	0.153	IND 3	0.317	0.048			
	0.153	IND 4	0.184	0.028			

Bold values represents Ci (Consistency Index), Cr (Consistency Ratio), and Lamda Factor (Maximum Eigenvalue) which are critical factors used to validate the reliability of pairwise comparisons.

to significantly improve the teaching-learning environment (Edannur and Marie, 2017; Perryman, 2013). BHU's relatively lower performance suggests gaps in digital infrastructure, administrative coordination, and access to modern teaching resources.

The prioritized constraints identified through AHP further clarify the systemic barriers influencing teaching effectiveness. Research-related constraints emerged as the most critical (priority weight 0.310), consistent with national and institutional reports that highlight chronic shortages of research funds, inadequate laboratory facilities, and delays in procuring scientific materials (Singh et al., 2021; Makwana, 2013). Limited practical exposure and reliance on outdated teaching methods also mirror earlier observations about the insufficient emphasis on experiential learning in Indian agricultural education (Al-Seghayer, 2014; Kujur et al., 2019). Knowledge-development challenges, such as inadequate software training and lack of specialized staff, continue to hinder students' ability to develop essential digital and analytical competencies issues frequently noted in postgraduate agricultural programs across India (Singh et al., 2021). Communication-related constraints, including restricted access to ICT tools and limited student–teacher interaction, align with recent studies emphasizing the need to strengthen digital awareness and interactive learning environments (Das et al., 2023).

A notable strength of this study lies in its alignment with national trends observed across India's State Agricultural Universities (SAUs). Several national assessments, including ICAR's Education Quality Review Reports and NAHEP-led diagnostic studies, have highlighted systemic weaknesses in pedagogical innovation, digital infrastructure, practical exposure opportunities, and research support across many agricultural universities (Burman, 2023). The relatively stronger TEI performance of IARI in this study is consistent with NAHEP's findings that centrally funded institutions tend to demonstrate higher adoption of modern pedagogical tools, stronger administrative systems, and greater investment in digital and research infrastructure. Conversely, the constraints identified at BHU and GBPUAT mirror well-documented challenges across SAUs, including insufficient laboratory resources, unstable internet connectivity, slow modernization of learning facilities, and gaps in technical training support. The convergence of these results with national-level diagnostics reinforces the systemic nature of the challenges documented here and highlights the need for institution-wide and system-wide reforms.

A critical insight of this study is the integration of TEI outcomes with AHP-based constraint prioritization. Institutions with higher TEI scores, such as, IARI tended to report lower intensities of structural and pedagogical constraints, suggesting a clear connection between institutional investment and educational quality. Conversely, BHU's lower TEI score aligns with higher constraint severity, indicating that deficits in infrastructure, research support, and pedagogical resources have a measurable impact on overall teaching effectiveness. This integrated interpretation underscores that teaching effectiveness cannot be isolated from the institutional context in which it occurs; rather, it reflects a complex interplay among pedagogy, engagement, and environmental factors. Overall, the findings carry several important implications for policy and practice. It is important to note that the findings of this study are based on student perceptions of teaching effectiveness. While student evaluations provide valuable insights into the teaching-learning experience, the results should be interpreted as indicative of perceived teaching effectiveness rather than objectively observed instructional quality. Furthermore, although the alignment between TEI scores and prioritized constraints suggests meaningful associations, the study does not establish causal relationships between constraints and teaching effectiveness outcomes. Strengthening research infrastructure, improving digital access, and upgrading laboratory facilities should be prioritized to support high-quality postgraduate education. Furthermore, expanding software training programs, developing faculty competencies in innovative teaching methods, enhancing administrative responsiveness, and increasing opportunities for internships and field-based learning can significantly enhance teaching effectiveness. These interventions align closely with ongoing national reforms under ICAR and NAHEP, which emphasize digital transformation, experiential learning, and improved academic governance within agricultural universities.

The study has certain limitations that should be acknowledged. First, the analysis is based exclusively on perceptions of postgraduate students from three agricultural universities. While students are key stakeholders in evaluating teaching effectiveness, the exclusion of faculty members, administrators, and policymakers limits the breadth of perspectives and generalizability of the findings. Second, the reliance on perception-based and cross-sectional data means that the Teaching Effectiveness Index reflects perceived rather than objectively observed teaching quality. Finally, although constraints were systematically prioritized using the Analytic Hierarchy Process, causal relationships between identified constraints and teaching effectiveness outcomes were not formally tested.

6 Conclusion and implications

This study provides a comprehensive and empirically grounded assessment of teaching effectiveness across three leading agricultural universities in India. The present study constructs a statistically derived Teaching Effectiveness Index (TEI) by applying Principal Component Analysis (PCA) to generate objective weights for multiple indicators. This index is further strengthened through the use of the Analytic Hierarchy Process (AHP) to systematically prioritize constraints as perceived by students. Together, these approaches yield a context-sensitive and methodologically robust framework for assessing teaching effectiveness in agricultural higher education. The TEI, developed is novel in five aspects; *Methodological integration*-as it combines PCA (a data-driven, statistical weighting technique) with AHP (a structured decision-making tool based on stakeholder perceptions). Such integration of objective and subjective methods is novel in teaching effectiveness studies, *statistically grounded weighting*-unlike conventional indices that rely on arbitrary or equal weights, this TEI uses PCA to derive weights empirically from the data, improving rigor and validity, *student-centered prioritization*-by incorporating AHP-based ranking of student-perceived constraints, the index directly embeds learner perspectives into the evaluation framework, *context specificity*-the framework is tailored to agricultural higher education, a domain where teaching effectiveness is often assessed using generic tools not suited to its practical and extension-oriented nature and *comprehensive evaluation*-it moves beyond single-metric or perception-only measures by linking performance indicators with constraint analysis, enabling more actionable insights.

Using a multidimensional Teaching Effectiveness Index (TEI) derived through Principal Component Analysis, the findings revealed clear institutional variations. IARI recorded the highest overall TEI score (0.74), followed by GBPUAT and BHU (0.71 each). IARI consistently outperformed the other institutions across all three dimensions - Pedagogical Proficiency, Learning Engagement, and Educational Environment Dynamics - indicating comparatively stronger instructional practices, higher student involvement, and a more supportive academic environment. In contrast, BHU exhibited notable weaknesses, particularly in student engagement and the robustness of its educational environment, underscoring the uneven quality of teaching practices across institutions. The AHP further identified research-related constraints as the most prominent barriers limiting effective teaching and learning. Inadequate research funding, limited laboratory support, and challenges related to publication emerged as critical bottlenecks requiring institutional attention. Knowledge-development constraints, such as insufficient training opportunities and lack of guidance in software applications, were also ranked highly by students. Their prioritization of software learning within the curriculum highlights the growing importance of digital competencies in post-graduate agricultural education. While communication-related and infrastructural challenges, such as restricted access to technology, interaction gaps, weak Wi-Fi connectivity, and limited advanced research facilities were comparatively less severe, they nonetheless represent structural issues that warrant systematic improvement.

Taken together, the findings highlight an urgent need to enhance teaching quality across agricultural universities through coherent, evidence-based, and standardized approaches. Faculty development programs tailored to institution-specific needs can strengthen pedagogical proficiency, while structured feedback mechanisms can improve classroom communication and foster more participatory learning environments. Addressing research-related barriers through improved funding, mentoring support for publication, and better integration of experiential learning can substantially enhance student engagement and academic outcomes. Expanding access to software training, digital tools, and industry collaborations can further prepare students for contemporary agricultural challenges. Overall, this study offers actionable and data-driven insights for policymakers, administrators, and educators seeking to elevate teaching effectiveness within agricultural higher education. By combining a statistically robust TEI with prioritized constraint analysis, it provides a scalable framework capable of guiding institutional reforms and promoting more equitable and effective learning environments across India's agricultural universities. Based on the findings, the following Policy Implications can be drawn

- *Strengthen research support systems across universities:* given that research-related constraints emerged as the top priority (0.310), universities and state agencies should allocate dedicated funds for postgraduate research, improve laboratory facilities, and streamline procurement processes. Establishing research-support cells in each institution can assist students with publication guidance, data analysis, and scientific writing support.
- *Integrate digital and software training into academic curricula:* students identified lack of software-related guidance as a major limitation. Policy frameworks should mandate the inclusion of data analysis, statistical software, and digital literacy modules within postgraduate programs. State Agricultural Universities (SAUs) under ICAR-NAHEP may standardize minimum digital competency requirements for students and faculty.
- *Enhance faculty pedagogical competence through targeted training:* variation across institutions, especially BHU's lower TEI performance, indicates a need for structured, continuous faculty development. Training programs on innovative pedagogy, outcome-based education, technology-enhanced teaching, and student-centered learning can improve instructional clarity and engagement.
- *Expand practical and experiential learning opportunities:* limited practical exposure and outdated teaching methods were major constraints identified by students. Universities should institutionalize field-based learning, laboratory immersion, internships, and industry collaborations. National programs under ICAR may develop guidelines to ensure minimum experiential-learning hours per semester.
- *Improve ICT and digital infrastructure across agricultural universities:* although infrastructure constraints were not the most severe, inadequate Wi-Fi and digital facilities continue to affect the teaching-learning environment. Investments in campus-wide high-speed connectivity, smart classrooms, and e-learning platforms are essential for modern agricultural education and digital pedagogy.
- *Strengthen feedback and communication mechanisms:* communication-related challenges such as limited student- teacher interaction and restricted use of ICT tools, highlight the need for institutional reforms. Establishing structured feedback systems, regular mentoring meetings, and online communication channels can improve responsiveness and enhance academic support.
- *Develop a standardized nationwide framework for teaching quality:* the uneven performance across institutions underscores the need for a unified national framework to evaluate and benchmark teaching effectiveness. ICAR may develop a standardized Teaching Quality Assurance Framework (TQAF) that includes clear indicators, performance metrics, and periodic assessments across all SAUs and agricultural universities.
- *Encourage evidence-based decision making through TEI and AHP tools:* the combined use of PCA-derived TEI and AHP prioritization offers a replicable method for continuous quality monitoring. Policymakers can adopt this empirical approach to guide resource allocation, identify weak institutional areas, and systematically target interventions.

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 approval for this study was obtained from the Research Advisory Committee of ICARIARI. Participation was voluntary and informed consent was obtained from all respondents. All responses were anonymized to ensure confidentiality.

Author contributions

SA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. GM: Conceptualization, Writing – original draft, Writing – review & editing. RP: Methodology, Writing – review & editing. SB:

Formal analysis, Methodology, Software, Writing – review & editing. MR: Formal analysis, Methodology, Software, Writing – review & editing. Satyapriya: Supervision, Visualization, Writing – review & editing. SS: Formal analysis, Investigation, Writing – review & editing. PJ: Data curation, Validation, Writing – review & editing. MM: Validation, Writing – original draft. BY: Formal analysis, Software, Writing – review & editing. RB: Supervision, Visualization, Writing – review & editing.

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