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RESEARCH ARTICLE

Strategies to promote precision farming in India using the Analytic Hierarchy Process (AHP)

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Abstract

Precision agriculture (PA), a climate-smart approach, utilizes advanced technologies such as remote sensing, GIS, GPS and variable-rate applications to optimize resource use, reduce environmental impacts and enhance agricultural productivity. Despite its potential, the adoption of PA in India faces significant barriers, particularly for small and marginal farmers who represent 89.4 % of the farming community. This study aimed to identify and prioritize strategies to promote PA adoption in western and north western zones of Tamil Nadu (2023) using the Analytic Hierarchy Process (AHP), a robust decision-making tool suitable for addressing complex multi-criteria problems. Four strategic categories-socio-economic, farm-level, political and technological-were analyzed through expert evaluations. Results revealed that farm-level strategies hold the highest priority (scaling factor = 0.288), followed by technological strategies (0.246), socio-economic strategies (0.234) and political strategies (0.232). The high ranking of farm-level strategies underscores the importance of implementing measures such as laser land levelers, precision nutrient management and water-use efficiency tools. The calculated Consistency Ratio (CR = 0.0081) confirmed the reliability and validity of these results. These findings provide practical and research baked strategies for grassroots agricultural institutions such as Krishi Vigyan Kendras (KVKs), Agricultural Technology Management Agencies (ATMAs) and NGOs, emphasizing the need to redirect resources toward farm-level interventions to scale up PA practices and achieve sustainable agricultural development which could potentially raise the adoption among small and marginal farmers by about 20-25 % within the next five years.

Keywords: AHP method; agriculture sustainability; climate change solutions; farm-level strategies; policy interventions; precision farming; technological strategies

Abbreviations: AHP - Analytic Hierarchy Process ; PA - Precision agriculture ; KVKs - Krishi Vigyan Kendras ; ATMAs - Agricultural Technology Management Agencies; CSA - Climate Smart Agriculture ; IoT - Internet of Things; SAS - Situation Assessment Survey; LLL - Laser Land Levelers ; CLCC - Customized Leaf Color Charts ; PFDCs - Precision Farming Development Centres; PMKSY - Pradhan Mantri Krishi Sinchayee Yojana; NMSA - National Mission on Sustainable Agriculture; SMAM - Sub-Mission on Agricultural Mechanization ; NGOs - Non-Governmental Organizations; CI - Consistency Index ; CR - Consistency Ratio ; GIS - Geographic Information Systems ; GPS - Global Positioning Systems

Introduction

Making agriculture sustainable and climate-resilient requires adopting innovative approaches collectively termed Climate Smart Agriculture (CSA). CSA combines eco-friendly practices such as organic farming, integrated systems, conservation agriculture, regenerative farming, soil reclamation and PA. These methods optimize resources, reduce environmental impact and maximize yields by managing inputs like seeds, fertilizers, water and pesticides. PA, smart farming, digital farming and agriculture 4.0 provide social, economic and environmental benefits (1), while robotics and autonomous technologies address labour shortages (2) and enhance job appeal in agriculture (3). Remote sensing, data analytics and IoT tools enable predictive analytics, real-time monitoring and informed decision-making (4), with potential to boost profitability, sustainability and production (5). The actual outcomes depend on context such as location, crop type and farmer capacity.

Nevertheless, PA adoption remains slow (6) due to limited awareness, lack of investment funds and short technology lifespans (1). In India, 89.40 % of farmers are small and marginal (SAS, NSS 77th round) with an average monthly income of Rs. 10218, making PA tools financially inaccessible. The effective use of these modern tools is also limited by socio-educational barriers. India accounts for 37 % of the world's adult illiterate population, according to the UNESCO *Education for All Global Monitoring Report 2013-14*, which estimated 287 million illiterate adults (UNESCO, 2014) (7). The rural literacy rate is only 66.7 % (8). Together, these factors restrict the adoption of modern PA technologies and reduce their potential to improve agricultural productivity.

Implementing precision/digital agriculture technologies in production represents a criti-cal economic decision for agricultural producers, as achieving potential economic and envi-ronmental benefits often requires a considerable financial investment (9). The decision-making process is influenced by factors such as expected cost savings, antici-pated yield increases and the resulting expected profitability and return on investment, as well as the producer's risk tolerance, openness to new or environmentally friendly tech-nologies and the level of public support (10). However, components of precision farming popular in Indian conditions are enclosed in Table 1 supporting the 5Rs principle of precision farming (11).

According to a report by the Council on Energy, Environment and Water (CEEW) authored by previous researchers (12), drip irrigation and sprinkler systems are the most widely adopted precision farming (PF) techniques in India, covering approximately 9.2 million hectares and benefiting an estimated 3 million farmers. Beyond micro-irrigation, other technologies such as automated irrigation systems, Laser Land Levelers (LLL) and customized leaf color charts (CLCC) are increasingly gaining popularity due to their cost-effectiveness and adaptability (13).

The Government of India (GOI) has established 22 Precision Farming Development Centres (PFDCs) to further promote precision farming to test, validate and adapt new PF technologies for local conditions (14). Additionally, several government initiatives directly or indirectly support precision farming. Direct initiatives include the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) with motto of per drop more crop and the Namo Drone Didi scheme where women of SHG groups are trained to be drone pilots and provide Drone as service for pesticide spraying (15, 16). While indirect support is provided through the National Mission on Sustainable Agriculture (NMSA) to opt for climate-smart technologies and the Sub-Mission on Agricultural Mechanization (SMAM) (15, 17). These efforts aim to enhance the adoption of precision farming practices nationwide, improving productivity and resource use efficiency.

Despite significant efforts to promote PA, farmers continue to face numerous barriers to its adoption. According to previous studies, the adoption of precision agriculture technologies is influenced by personal factors such as age, education, farm size, innovativeness and socio-economic conditions (18). Additionally, systemic constraints persist (19) Fig. 1, including:

Infrastructure-related barriers

Limited access to credit (4), inadequate marketing facilities and insufficient availability of precision tools and machinery.

Economic challenges

High input costs, price instability and lack of affordable technologies.

Information constraints (20)

Limited technical expertise, inadequate training and insufficient contact with extension personnel.

Environmental and social constraints

Issues such as land fragmentation, cultural resistance and environmental variability.

The drivers and barriers of smart farming adoption can be classified into four categories: individual, organizational, technological and external factors, integrating multiple approaches to understanding adoption dynamics (21). Individual factors include age, education, gender, technology literacy (22). Organizational factors encompass farm size, farm location, income from farming, skilled labour (23). Technological are perceived benefits, compatibility, performance expectancy, perceived ease to use, perceived complexity (24). External factors involve information sources, social influence, government support, technical support. Given these challenges, it is imperative to identify priority areas and implement targeted actions to address these barriers effectively (25).

A focused approach is critical to enhancing the visibility of PA benefits, promoting its widespread adoption and ensuring long-term agricultural sustainability. While PA holds significant potential to revolutionize farming practices through its resource-efficient and high-impact technologies, its fragmented and inconsistent implementation has limited its overall effectiveness. This highlights the pressing need for a systematic and phased strategy to translate policy recommendations into tangible, ground-level outcomes. This study addresses these gaps by providing actionable insights and guidance for grassroots agricultural institutions such as Krishi Vigyan Kendras (KVKs), Agricultural Technology Management Agencies (ATMAs) and non-governmental organizations (NGOs). By emphasizing the adoption and effective deployment of precision farming strategies, the study aims to empower these institutions to foster sustainable agricultural practices, ultimately contributing to enhanced productivity, environmental conservation and socio-economic benefits for farming communities. Sector-specific and region-specific factors significantly influence the adoption of precision agriculture technologies, which should be considered when formulating policies and strategies (26, 27).

Methodology

With the review of the literature, a model was curated (problem modelling) about the strategies to promote precision farming under four subheadings socio-economic strategies, farm-level strategies, political strategies and technological strategies. Each of these components had certain suggestions to improve precision farming as presented in Fig. 2.

Through online forms, a questionnaire was sent to extension experts, scientists, extension officers and research scholars with the above model to get relevant responses. Respondents execute a pair-wise comparison of strategies on a nine-point continuum by employing the Saaty scale, based on its relative importance, where 1 denotes equal importance, 3

Table 1. Components of precision farming

5Rs of precision farming	Components of precision farming
Right time	Timely sowing/planting
Right source	Quality seed or planting material, Application of organics (FYM/ Bio compost/cake/green manuring/crop residue)
Right place	Drip/ sprinkler method of irrigation
Right amount	Fertigation, Herbigation and Plant protection measures
Right manner	Precise land preparation, Mulching

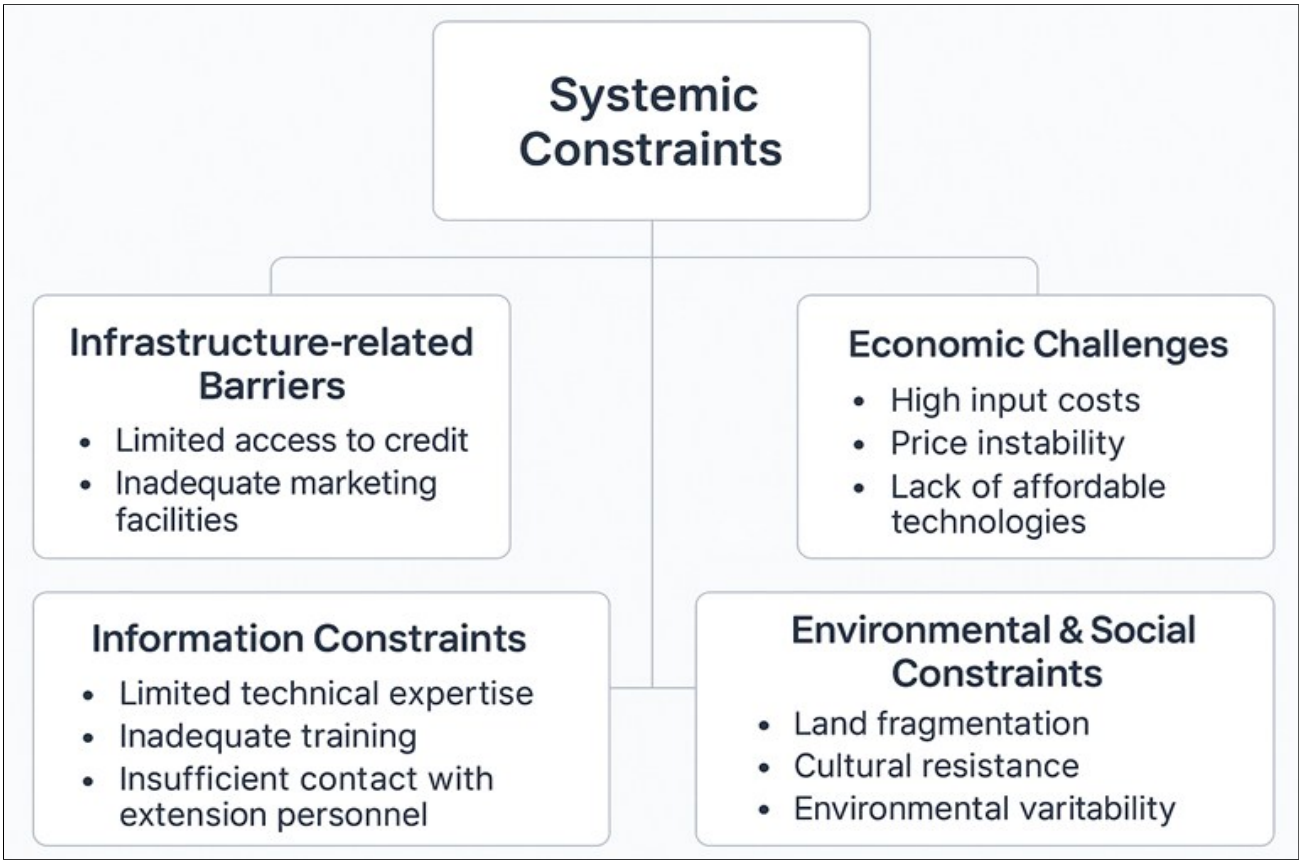

Fig. 1. Systemic constraints affecting the adoption of precision agriculture technologies.

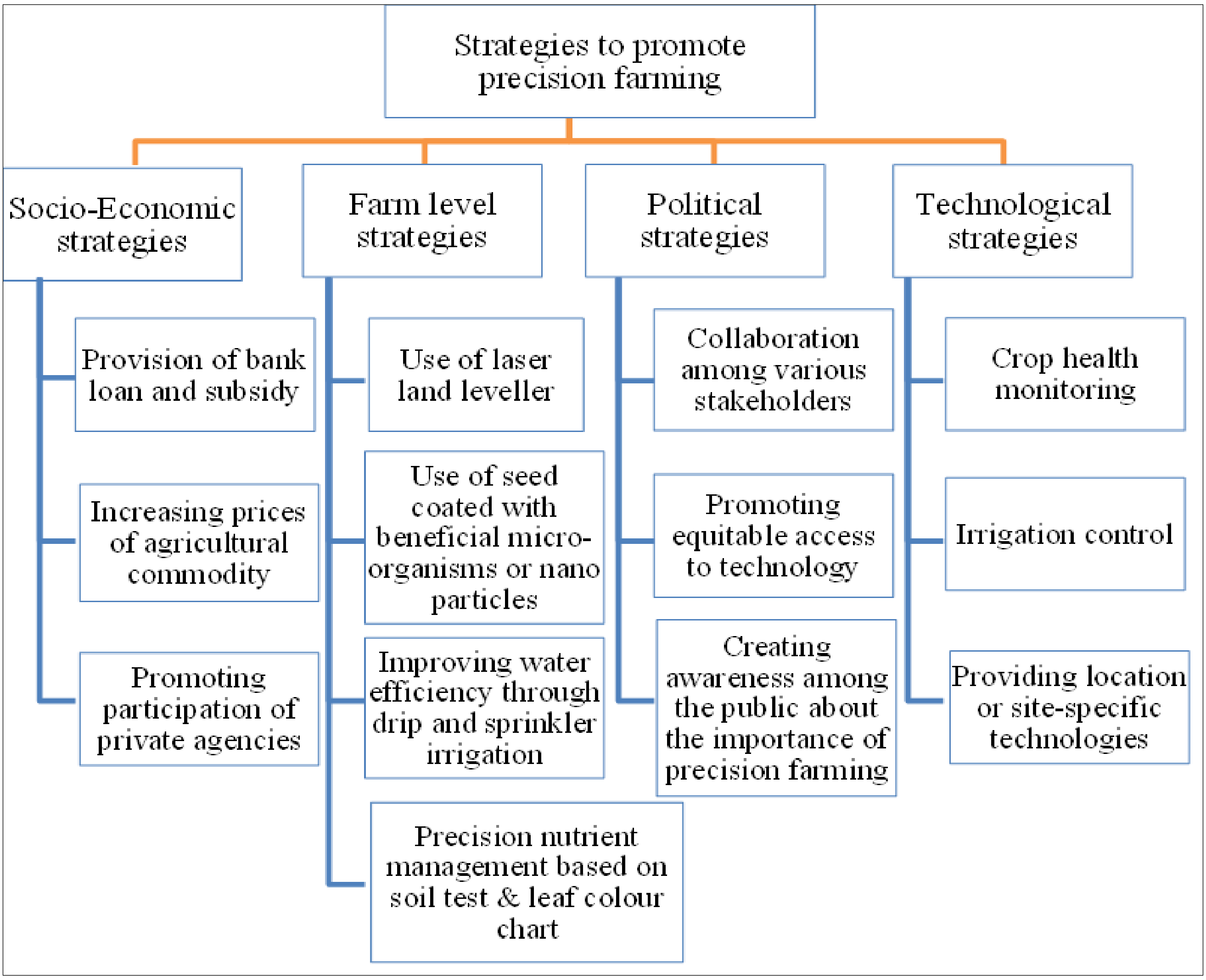

Fig. 2. Strategies to promote precision farming.

denotes moderate importance, 5 denotes strong importance, 7 denotes very strong importance and 9 denotes extreme importance of one strategy over another (28).

A total of 450 respondents were contacted, including 175 research scholars from TNAU (pursuing Ph.D. in Agronomy, Agricultural Extension, Soil Science, Agricultural Economics and Nanotechnology), 140 extension officers, 95 extension experts and 40 scientists. After a fortnight interval of waiting, the responses obtained from 205 extension experts as a response rate of 45.56 %. were subjected to analysis employing the Analytical Hierarchy Process (AHP) to prioritize the strategies. A comparison of early and late respondents across key variables revealed no significant differences ($p > 0.05$), indicating that non-response bias was likely minimal. The study was restricted with Tamil Nadu.

AHP is a structured decision-making approach that is particularly useful for handling complex issues with multiple criteria and alternatives. The analysis was carried out using Microsoft Excel for the spreadsheet operations to perform all these calculations.

A. The formula to calculate the number of pairs in AHP (29) is mentioned below:

$$\text{Number of paris in AHP} = \frac{n(n-1)}{2}$$

Where, n = number of compared elements

B. The formula to calculate the Consistency Index (CI), to determine the consistency of the matrix (30) is as follows:

$$\text{Consistency Index} = \frac{(\lambda max) - n}{n-1}$$

Where, n - number of criteria or components being compared

C. After calculating the Consistency Index, the Consistency Ratio (CR) was calculated by using the following formula:

$$CR = \text{Consistency Index} / \text{Random Index}$$

The random index (Table 2) is identified from the Random Consistency Index developed by previous researchers (31).

Results and Discussion

The Geometric Mean values were calculated from the responses obtained for each pair and presented in Table 3.

The pairwise comparison matrix was constructed using the geometric means calculated for each pair of strategies. For instance, the geometric mean for the comparison between socioeconomic and technological strategies was determined to be 0.8351. Accordingly, the reciprocal value, representing the comparison of technological strategies to socio-economic strategies, was calculated as 1/0.8351 = 1.197. This systematic approach was applied to all strategy pairs to form the complete pairwise comparison matrix, as presented in Table 4.

The column-wise summation of the pairwise comparison matrix was used to calculate the scaling factors. By dividing the score of pair-wise matrix values with the sum of each column and then the average of these values in a row computed to derive the scaling factors. These scaling factors represent the relative priority or weight of each category in the context of the decision-making framework.

The rankings of the scaling factors from Table 5 indicate that farm-level strategies (0.288) hold the highest priority, followed by technological strategies (0.246). Farm-level strategies ranked highest (0.288), reflecting measures like crop diversification, climate-smart varieties and soil–water conservation that directly reduce risk. Technological strategies followed (0.246), highlighting precision farming tools, mechanization and ICT use. Socio-economic strategies (0.234) such as credit access, training and collective action and political strategies (0.232) like subsidies, insurance and supportive policies ranked lower, yet remain essential enablers. Thus, while farm-level actions drive resilience most directly, technological, socio-economic and political strategies must align as complementary policy levers to sustain long-term impact. Technologies' complexity and perceived ease

Table 2. 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

Table 3. Calculation of geometric mean

S. No.	Pairs	Geometric Mean
1	Socio-Economic and Technological strategies	0.8351
2	Political and Farm level strategies	0.6819
3	Technological and Political strategies	0.9017
4	Political and Socio-economic strategies	1.0130
5	Technological and Farm level strategies	0.8813
6	Farm level and Socio-Economic strategies	0.9287

Table 4. Formation of the matrix, calculation of the sum

Category	Socio-economic strategies	Technological strategies	Political strategies	Farm level strategies
Socio-economic strategies	1.00	0.835	1.013	0.929
Technological strategies	1/0.8351= 1.197	1.00	0.902	0.881
Political strategies	1/1.013 = 0.987	1/0.902 = 1.109	1.00	0.682
Farm level strategies	1/0.929 = 1.077	1/0.881= 1.135	1/0.682 = 1.466	1.00
Sum	4.261	4.079	4.381	3.492

Table 5. Calculation of scaling factor and ranking of the strategies

Category	Socio-economic strategies	Technological strategies	Political strategies	Farm level strategies	Scaling factor	Rank
Socio-economic strategies	0.235	0.205	0.231	0.266	(0.235+0.205+0.231+0.266)/4 0.234	3
Technological strategies	0.281	0.245	0.206	0.252	0.246	2
Political strategies	0.232	0.272	0.228	0.195	0.232	4
Farm level strategies	0.253	0.278	0.335	0.286	0.288	1

of use were frequently cited as barriers, a result supported by previous findings (22). Though training, demonstrations and user-friendly mobile-based tools have reduced initial barriers, these measures help, sustained support and continuous learning are essential. These technological barriers highlight the need for user-friendly, cost-effective solutions to facilitate broader adoption. Similar results were observed, revealing that the main goal of farmers using precision farming is to increase income, which can be achieved through the more cost-effective use of agricultural inputs and selectively applied work processes such as sowing and harvesting (32, 33). At the same time, there is a large amount of technical literary sources which conclude that the most significant advantage of using PF is that it could potentially reduce in the greatest measure the environmental damage resulting from agriculture (34).

Socio-economic strategies (0.234) and political strategies (0.232) ranked third and fourth, respectively. These results are relatively in line with previous researchers performed a literature review to study drivers of Precision Agriculture Technologies adoption (35). In addition, based on the expected usefulness maximization approach, it was concluded that socioeconomic factors specifically age, adopter's experience and financial situation have a negligible effect on the adoption of precision agriculture technologies (36). Though age, income and risk perception often influence adoption respondents' profile differs, the impact of these factors may vary in this study. It is evident that economic factors do not solely drive the decision but are also influenced by social and political considerations that shape the agricultural producer's decision to adopt precision/digital agriculture technologies (37).

PA is predominantly practiced by medium to large-scale farmers. Though our study covered medium and large farmers, PA adoption among small farmers also often depends on subsidies and supportive policies. A higher likelihood of large-sized farms to adopt precision agriculture technologies (PAT) was found. However, to expand the adoption of PA tools and increase the area under PA, respondents emphasized the need for grassroots-level implementation that includes small and marginal farmers (38). This inclusive approach highlights the importance of targeting strategies such as use of land levelers, seed coated with beneficial organisms and water use efficiency, which contributed to farm-level strategies being ranked as the top priority. Therefore, ground-level extension institutes like KVKs, ATMA and NGOs need to divert their resources to the implementation of farm-level strategies in promoting the PA.

The relatively low ranking of political strategies can be attributed to the government's significant investments in various schemes to promote precision farming. Given this existing momentum, the emphasis on political strategies may be less critical compared to direct farm-level, technical and socio-economic interventions for achieving measurable results.

To ensure the validity of the AHP results, the Consistency Index (CI) and Consistency Ratio (CR) were calculated. The process involved the following steps displayed in Table 5:

Weighted sum calculation

Each scaling factor was multiplied by the corresponding column-wise cell values in Table 4 and the results were summed row-wise and presented in Table 6.

λ_{max} Calculation

The weighted sum values for each row were divided by the corresponding scaling factors. The average of these values provided the Lambda max, which was found to be 4.022 as found in Table 6.

With n = 4, the Consistency Index (CI) was calculated using the formula:

$$CI = (4.022 - 4) / (4-1) = 0.0073$$

Using a Random Index (RI) value of 0.900 (as mentioned in Table 2), the Consistency Ratio (CR) was calculated as:

$$CR = CI/RI = 0.059 / 0.900 = 0.0081$$

Since the CR value (0.0081) is less than the threshold of 0.1, the AHP results are deemed consistent and reliable, confirming the robustness of the derived priorities and scaling factors.

Conclusion

Precision agriculture, as a vital pillar of climate-smart agriculture, harnesses modern tools such as remote sensing, information GIS, GPS and variable seed rate applications to enhance both efficiency and sustainability in farming. While the findings offer valuable insights for promoting PA, it is important to note that the evidence base is derived from Tamil Nadu and caution should be exercised before generalizing to the national level. Despite its potential, the tangible outcomes of PA have been limited due to staggered implementation and uneven adoption. The success of precision farming relies not only on the readiness and willingness of farmers but also on the timely availability of accurate and practical information. While the findings offer valuable insights for promoting PA, it is important to note that the evidence base is derived from Tamil Nadu and caution should be exercised before generalizing to the national level.

The adoption of PA technologies tends to follow a pattern where initial uptake is seen among innovative and well-informed farmers, followed by gradual diffusion to the wider farming community. However, many farmers-especially small and marginal holders-remain hesitant, often waiting for widespread validation before embracing new technologies. These patterns highlight the need for inclusive strategies that cater to different categories of adopters and address the structural limitations hindering widespread uptake.

To amplify the impact of PA, this study identified four

Table 6. Calculation of lambda max (λ_{max})

Category	Socio-economic strategies	Technological strategies	Political strategies	Farm level strategies	Row Sum	Row sum/ Scaling factor
Socio-economic strategies	0.234	0.205	0.235	0.268	0.942	4.023
Technological strategies	0.280	0.246	0.209	0.254	0.989	4.020
Political strategies	0.231	0.273	0.232	0.196	0.932	4.022
Farm level strategies	0.252	0.279	0.340	0.288	1.159	4.025
		Average Value (λ_{max})				4.022

overarching strategic dimensions: socio-economic, farm-level, political and technological. Using the AHP, a structured multi-criteria decision-making tool, the study prioritized these strategies as perceived by agricultural extension personnel. The results clearly indicated that farm-level strategies hold the highest importance, followed by technological, socio-economic and political strategies. To improve reliability and generalizability, subsequent research should validate the AHP framework with farmers from varied regions and apply fuzzy-AHP to address uncertainty in expert assessments.

The calculated Consistency Ratio (CR) values validated the robustness and reliability of these prioritizations. Based on these findings, grassroots agricultural support systems-such as KVKs, ATMAs and non-governmental organizations should focus their efforts and resources on implementing key farm-level strategies. These include the adoption of laser land levelers, seed treatments with beneficial organisms, precision nutrient management techniques, use of leaf colour charts and efficient water management practices.

The original research question-prioritizing strategies for PA adoption-was fully addressed through the AHP, which identified farm-level strategies as the highest priority, followed by technological, socio-economic and political strategies.

Despite the well-documented social, economic and environmental benefits of PA, its adoption remains limited among farmers. It is therefore essential to explore and understand the key drivers and barriers influencing its uptake. Such insights are critical from both microeconomic and policy-making standpoints, enabling the design of more effective, inclusive and targeted interventions that can accelerate the diffusion and adoption of precision farming technologies across diverse agricultural landscapes.

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Authors' contributions

PSR conceptualized the study, designed the research framework and supervised the overall research process. AV carried out the data collection, executed the Analytic Hierarchy Process (AHP) and contributed to drafting the methodology and results sections. SMG conducted the literature review, analyzed the strategic components and assisted in preparing visual representations. AM was responsible for writing and refining the introduction and conclusion, formatting references in Vancouver style and managing the final editing and proofreading of the manuscript. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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