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RESEARCH ARTICLE

Determinants of the adoption of biological control agents in Andhra Pradesh

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Abstract

This study, conducted in the Kurnool district of Andhra Pradesh, India, in 2024, explored the factors influencing farmers' adoption of biological control agents (BCAs). Kurnool, an agriculturally significant region, was divided into four clusters: Kallur, Pathikonda, Kodumur and Panyam. A total of 120 farmers were selected using a convenience sampling method, chosen due to logistical constraints and the exploratory nature of the research. Data were gathered through semi-structured household interviews and supplemented by key informant discussions to provide additional context. The study examined adoption of BCAs as the dependent variable, with independent variables including age, gender, education, primary occupation, farming experience, farm income, farm size, training and membership in agricultural organizations. Analysis using a forward stepwise logistic regression model identified farm size, annual income and training as significant positive factors influencing awareness and adoption of BCAs. Results showed that 25 % of the sampled farmers were using BCAs. Key barriers to adoption included a lack of knowledge, reliance on chemical fertilizers due to entrenched agricultural practices, high costs and limited access to credit. To address these challenges, the study recommends implementing targeted education programs, enhancing access to affordable credit and fostering cooperative networks and public-private partnerships to strengthen collaboration between farmers and agricultural organizations. The findings emphasize the need for comprehensive policy measures to support sustainable agricultural practices through the promotion of BCAs.

Keywords

adoption factors; Andhra Pradesh; biological control agents; sustainable agriculture; training and education

Introduction

Pollination plays a critical role in crop production, facilitating plant reproduction, directly boosting yields and improving the quality of fruits, vegetables and seeds. Approximately 75 % of food crops depend on pollinators like bees, underscoring their importance for global food security. Simultaneously BCAs contribute to sustainable farming by reducing the need for chemical pesticides, thereby protecting pollinators and promoting ecosystem balance. Integrating pollination services with BCAs enhances sustainable agriculture, ensuring productivity, biodiversity and resilience (1). Despite their vital role, ecosystem services such as biological control have been under-researched in the context of agroecosystems (2). BCAs uses natural organisms to manage pests, offering a cost-effective, sustainable alternative to chemical methods and reducing crop losses (3). Four main types of BCAs have been identified:

natural, conservation, classical and augmentative (4). At the farm level, BCAs reduces pest outbreaks and offers economic benefits by lowering management costs (5). Additionally, it promotes positive social-ecological outcomes, such as reducing health risks associated with pesticide exposure (6). However, despite its promotion over the past decade, the adoption of biological control remains limited due to various challenges (7). Global declines in biological control adoption are linked to land-use changes and reduced habitat for beneficial organisms (8). While ecological research on organisms supporting biological control is extensive, social research on adoption remains sparse (9). Farmers' perceptions play a crucial role in adoption decisions, as they reflect motivations to embrace or avoid practices promoting natural predators (10). Several barriers hinder the widespread adoption of BCAs. Limited extension services, inadequate technical training and insufficient access to technological information constrain knowledge transfer (11). While socio-economic factors do not directly influence access to technology, their interplay with a farmer's socio-economic status determines the extent of its use (12). Furthermore, competition from the inorganic fertilizer industry hampers the adoption of biological control measures, as studies indicate that inorganic fertilizer use can negatively affect the adoption of sustainable practices like biological control (13). Male-headed households and older farmers are more likely to adopt inorganic methods due to labor constraints and the perceived competitiveness of chemical inputs. Larger farms and greater farming experience also increase the likelihood of relying on inorganic practices. Conversely, households primarily engaged in agriculture lean towards organic approaches, although group farming initiatives do not always guarantee widespread adoption (14). Using BCAs instead of chemical fertilizers offers significant potential to enhance productivity and profitability for smallholder farmers while strengthening Andhra Pradesh agricultural economy. Studies indicate that adopting biological controls can increase crop yields by 15-25 %, while reducing pest management costs by 30-40 %, saving ₹5000-₹7000 per hectare. This shift not only lowers input costs but also boosts profits, with cotton farmers reporting an additional ₹8000-₹10000 per hectare in earnings. Furthermore, reduced reliance on chemicals improves soil health, supporting long-term agricultural sustainability. Collectively, these benefits could drive a 5-7 % growth in Andhra Pradesh agricultural GDP over the next five years (15). Despite these benefits, the adoption of BCAs remains low. This research aims to identify the socio-economic, institutional and technical factors influencing the adoption of biological control practices and to propose actionable strategies for overcoming barriers to sustainable agricultural development.

Materials and Methods

Study area

Geographically, Andhra Pradesh shares borders with Tamil Nadu, Karnataka and Telangana. Kurnool district, located in the western part of Andhra Pradesh, is a key region for commercial farming and was selected as the study area for this research. The district was divided into four clusters Kallur, Pathikonda, Kodumur and Panyam by treating each municipality as a distinct cluster. A total of 120 farmers were randomly selected, with at least 30 participants from each cluster. The survey was conducted between May and July 2024, utilizing semi-structured interviews to gather insights directly from farmers. The clustering approach ensured that the sample was representative of the district's diverse population. Additionally, convenience sampling was employed to target farmers with substantial experience and agriculture as their primary livelihood, aiming to gather informed perspectives on the adoption of biological control agents. This targeted sampling approach, while effective in focusing on experienced farmers, may introduce exclusion bias by overlooking less experienced or resource-constrained farmers. To address this limitation, marginalized groups were included in the research framework. Moreover, response bias, which can arise from reliance on a single group, was mitigated by triangulating data through surveys and interviews to capture a range of perspectives and ensure balanced analysis. By emphasizing experienced farmers, this study effectively identified the core challenges in adopting biological control agents, providing a nuanced understanding of the factors influencing their adoption in Kurnool's agricultural context.

Percentage analysis- This research employed percentage analysis to evaluate farmers' inclinations toward adopting biological control agents. Key variables such as age, gender, education level, occupation, farming experience, size of landholdings, membership in agricultural groups and training participation were analyzed. The analysis was conducted by calculating the percentage of participants who demonstrated a preference or inclination toward these factors using the formula:

$$\text{Percentage analysis} = \frac{\text{Number of respondents}}{\text{Total Number of samples}} \times 100$$

This approach provided a clear understanding of the demographic and socio-economic trends influencing the adoption of biological control agents.

Logistic regression- This study utilized logistic regression to assess the extent of bio control agent adoption among small and marginal farmers (16). Logistic regression is a statistical method that models the relationship between a binary dependent variable such as adoption (yes/no) and one or more independent variables, allowing for the identification of significant predictors influencing adoption behavior.

$$\log\left(\frac{p}{1-p}\right) = \beta_o + \beta_1X_1 + \beta_2X_2 + \ldots\ldots\ldots\ldots + \beta_kX_k$$

Where:

P is the probability of the event (adoption of BCA).

β_o is the intercept.

$\beta_1, \beta_2 \ldots \beta_{(k)}$ are the coefficients of the independent variables.

$X_1, X_2, \ldots X_k$ are the independent variables (demographic factors).

Exploratory factor analysis- The study employed Exploratory Factor Analysis (EFA) to identify the underlying group factors influencing farmers' adoption of biological control agents (BCAs). A structured questionnaire incorporating a 5-point Likert scale was used to measure variables such as dealer influence, product quality, peer group impact, affordability (low price), yield potential (high yield), pricing/discounts, advertisements and the role of agricultural officers. The 5-point Likert scale, provided a standardized method for capturing and analyzing farmers' perceptions, enabling the identification of key factors that significantly impact adoption decisions.

The scale is as follows: 1=strongly Disagree/Not important, 2=Disagree/slightly important, 3=Neutral/Moderately Important, 4=Agree/Important, 5=Strongly Agree/Very Important. Data analysis categorized key factors shaping adoption decisions.

Garret ranking- The Garrett ranking method was employed to identify and prioritize the challenges faced by farmers in the study region while adopting BCAs. Farmers were instructed on ranking specific pre-identified criteria based on their perceived level of difficulty.

The ranks assigned by the respondents were converted into scores using the following formula:

$$\text{Percent Position} = \frac{(\text{Rank} - 0.5) \times 100}{\text{Total Number of respondents}}$$

The calculated percent positions were then matched with Garrett's Table to derive the corresponding scores. These scores provided a quantitative representation of the challenges, enabling the study to effectively highlight the most critical barriers to the adoption of BCAs.

Results

Demographic and Socioeconomic Insights

The adoption of BCAs is influenced by various demographic and socio-economic factors. While attributes like age, gender, education, occupation, farming experience and training have limited direct impact, factors such as farm income, landholding size and group membership are critical determinants (17, 18). Farmers with smaller incomes and limited landholdings show a higher tendency to adopt BCAs due to their cost-effectiveness and environmental benefits. These findings align with research indicating that smallholders prioritize economically viable solutions (19, 20). BCAs are often seen as a long-term cost-saving alternative because they reduce reliance on expensive and environmentally harmful chemical pesticides. Improving education and resources is vital for smaller farmers to adopt BCAs. Education through training, awareness and peer learning boosts understanding, while resources like subsidies, reliable BCA access, infrastructure and technical support enable effective adoption. Combined with supportive policies, these efforts drive sustainable agriculture. Membership in agricultural groups or cooperatives further boosts adoption by enabling knowledge exchange, collective bargaining and access to resources (21). Initiatives such as peer-learning workshops, demonstration plots and community-driven training programs significantly enhance farmers' confidence and proficiency in using BCAs. For instance, in Andhra Pradesh, participatory sessions organized by agricultural groups have effectively demonstrated BCA benefits, leading to higher adoption rates (22, 23). For example, in certain regions of Andhra Pradesh, agricultural groups have successfully organized participatory sessions where farmers can directly observe the benefits of BCAs, thereby increasing their adoption rates.

Explanatory Socioeconomic factors influencing the adoption of biological control

Table 1 explains the Understanding farmers' demographics is vital for designing targeted interventions. In this study, 42.5 % of respondents fall within the middle-age group, reflecting a demographic open to innovation while relying on established practices. Middle-aged farmers leverage experience to evaluate BCAs but remain adaptable to new techniques. Women head only 4 % of households, highlighting a gender imbalance driven by patriarchal norms that limit their decision-making in agriculture (24). Educational attainment significantly influences BCAs adoption, with 64 % of respondents having basic education, which enhances their ability to understand and apply sustainable practices (25). For example, educated farmers are more likely to attend training and adapt BCAs to specific farming needs. Agriculture is the primary occupation for 67 % of respondents, underlining its centrality to livelihoods (26). Respondents average 35 years of farming experience, enabling them to recognize BCAs' long-term benefits, though entrenched practices may resist change. Farm sizes range from 1 to 10 hectares, averaging 1-2 hectares, with annual incomes averaging ₹48 lakh. Smallholders often prefer BCAs as cost-effective alternatives, while wealthier farmers may rely on traditional methods due to familiarity. Cooperative membership has 80 % and training participation has 70 % are critical enablers of adoption, promoting community-driven education and sustainable practices.

Evaluation and Overview about predicted impact of explanatory variables on the adoption of BCAs

Table 2 presents the adoption of BCAs is influenced by various demographic and socioeconomic factors, but some relationships remain ambiguous. Age (mean = 1.88, SD = 0.752) has a mixed impact, likely varying with gender roles and decision -making structures, as highlighted in studies on gendered agricultural dynamics (27). Gender (mean = 1.041, SD = 0.200) shows a negative association, with males being more likely to adopt, reflecting the traditional dominance of men in agricultural decision-making (28). Education (mean = 3.233, SD = 0.761) exhibits a minimal negative influence, potentially due to the disconnect between formal education and practical training, particularly for women farmers (29).Occupation (mean = 1.583, SD = 0.784) and farming experience (mean = 3.566, SD = 1.128) display uncertain effects, with variability stemming from differences in exposure to innovation and resources across demographics.Similarly, farm income (mean = ₹147,895, SD = 73.92) and landholding size (mean = 2.333 hectares, SD = 1.033) demonstrate ambiguous relationships due to heterogeneity in farming priorities and uneven access to inputs, which can obscure patterns in BCAs adoption (30). Group membership (mean = 1.233, SD = 0.374) is a weak predictor and negatively associated with adoption (coefficient = -0.311, P = 0.002), due to coordination challenges and occasional resistance among group members (31). Training (mean = 1.808, SD = 0.374; coefficient = 0.041, P = 0.637) and education (coefficient = 0.03, P = 0.575) similarly demonstrate limited impacts, emphasizing gaps in program quality, accessibility and contextual relevance (32). These insights highlight the complexity of adoption patterns and underscore the need for targeted interventions tailored to address socioeconomic and demographic barriers while fostering collaboration and innovation in BCAs implementation.

Table 1. Explanatory Socioeconomic factors influencing the adoption of BCAs

Variables	Adoption of biological control agents (BCAs)		Total	P - value
	Apply	Don't apply		
Age				
Young age (<25 years)	9(7.5)	26 (21.7)	34(29.2)	
Middle age (26-49years)	13(10.8)	51 (42.5)	64(53.3)	0.210
Old age (> 50 years)	8(6.7)	13 (10.8)	21(17.5)	
Total	30 (25)	90(75)	120(100)	
Gender				
Male	29 (24.1)	86 (71.8)	115 (95.8)	
Female	1 (0.8)	4 (3.2)	5 (4)	0.539
Total	30 (25)	90(75)	120(100)	
Education level				
Illiterate	0(0)	4 (3.3)	4(3.3)	
Primary	4 (3.2)	6 (5)	10 (3.2)	
Secondary	14 (11.7)	47 (39.2)	61 (11.7)	0.575
Intermediate	11 (9.2)	33 (27.5)	44 (9.2)	
Graduate	1(0.8)	0 (0)	1 (0.8)	
Total	30 (25)	90(75)	120(100)	
Occupation				
Agriculture	13(10.8)	54(45)	67(55.8)	
Non-Agriculture	11(9.2)	30(25)	41(34.2)	
Agriculture plus Business	2(1.7)	5(4.2)	7(5.9)	0.571
Agriculture plus Employment	4(3.3)	1(0.8)	5(4.1)	
Total	30 (25)	90(75)	120(100)	
Farming Experience				
10 years	1 (0.8)	5 (4.2)	6 (5)	
20 years	3 (2.5)	13 (10.8)	16 (13.3)	
30 years	11(9.2)	18 (15)	29 (24.2)	0.716
40 years	9 (7.5)	33 (27.5)	42 (35)	
50 years	6 (5)	21 (17.5)	27 (22.5)	
Total	30 (25)	90(75)	120(100)	
Farm Income				
<5 Lakhs	13(10.8)	45(37.5)	58(48.3)	
5-10 Lakhs	9(7.5)	27(22.5)	36(30)	
10-15 lakhs	5(4.2)	13(10.8)	18(15)	0.001***
>15 lakhs	3(2.5)	5(4.2)	8(6.7)	
Total	30 (25)	90(75)	120(100)	
Size of landholdings				
Marginal (< 1hec)	11(9.2)	24(20)	35 (29.2)	
Small (1-2 hec)	7 (5.8)	32(26.7)	39 (32.5)	
Medium (4-8hec)	8(6.7)	9(7.5)	17(14.2)	0.006***
Large (>10 hec)	4(3.3)	25(20.8)	29 (24.1)	
Total	30 (25)	90(75)	120(100)	
Membership in groups				
Yes	11 (15.8)	12(10)	23(19.2)	
No	19 (15.8)	78 (65)	97 (80.8)	0.002***
Total	30 (25)	90(75)	120(100)	
Training				
Yes	9 (7.5)	28 (23.3)	37 (30.8)	
No	21 (17.5)	62 (51.7)	83 (69.5)	0.567
Total	30 (25)	90(75)	120(100)	

<0.01 is significant

Table 2. Evaluation and overview of the explanatory variables and their predicted impact on the adoption of BCAs

Explanatory variables	Definition and measurement	Mean ± Standard Deviation	Expected sign
Age	Respondent age; years (discrete)	1.883 ± 0.752	+/-
Gender	Respondent gender;1=Male, 2=Female	1.041 ± 0.200	-
Education	Respondent education; years (discrete)	3.233 ± 0.761	-
Main occupation	Main occupation of Respondent; 1= Agriculture, 2= Non-Agriculture, 3=Agriculture plus Business, 4=Agriculture plus Employment (nominal)	1.583 ± 0.784	+/-
Experience in farming	Respondent farming experience; Years (discrete)	3.566 ±1.128	-
Farm income	Respondent farm income; Rupees (INRs) (continuous)	147895.00 ±73.92	+/-
Size of landholdings	farm size; Hectare (ha) (continuous)	2.333 ±1.033	+/-
Group membership	Membership participated in any Organization; 1=Yes, 2=No	1.233 ±0.374	+/-
Training	Biological control agents-related training received; 1=Yes,2=No	1.808 ± 0.374	-
Adoption	Adoption of biocontrol agent; 1=Yes, 2=No	1.691 ± 0.452	+/-

Logistic regression analysis using the forward LR method

Table 3 explains the binary logistic model reveals key factors influencing BCAs adoption, highlighting the complexity of agricultural adoption dynamics. Farm income, farm size and membership in organizations emerged as significant predictors. Larger farms showed a positive correlation with adoption, benefiting from economies of scale and better resource access, making BCAs more feasible (33). In contrast, membership in organizations exhibited a significant negative association at the 1 % level, reflecting inefficiencies such as poor coordination, conflicting interests and a reliance on traditional methods. These challenges limit innovation and knowledge sharing, underscoring the need for improved governance and better group coordination to foster a supportive environment for BCAs adoption (34). Economic barriers, such as high costs and limited credit, were critical adoption constraints. Interestingly, farmers with smaller incomes and landholdings were more inclined to adopt BCAs for their cost-effectiveness, contrasting with wealthier farmers who preferred chemical fertilizers for perceived profitability (35). Education and farm size had positive but statistically insignificant effects, indicating that while formal education may not directly impact adoption, it indirectly influences decisions toward chemical inputs. Unexpectedly, farming experience and training negatively impacted adoption, suggesting gaps in current training programs and their local applicability. Many initiatives fail to address farmers' specific challenges, reducing their effectiveness, aligning with critiques of poorly contextualized agricultural extension programs (36). At the 1 % significance level, farm income had a critical positive effect, emphasizing the financial capacity needed to adopt BCAs, while membership in related organizations showed a positive and significant influence on adoption (37). Despite a positive relationship, education and training showed insignificant impacts, highlighting the need for tailored interventions that integrate practical, localized knowledge about BCAs. Addressing these challenges requires financial support like subsidies and credit schemes, improved group governance to enhance collaboration and context-specific training programs to make BCA adoption more accessible and impactful. Overall, these findings underscore the interplay of economic, organizational and experiential factors. A multi-pronged approach, addressing financial accessibility, group dynamics and effective training, is essential to mitigate barriers and promote sustainable agricultural practices through broader adoption of BCAs (38).

Table 3. Logistic regression analysis using the forward LR method

Variables	Adoption of biological control agents	
	Coefficient	P-value
Age	-0.072	0.21
Gender	-0.119	0.539
Education	0.03	0.575
Main occupation	-0.029	0.571
Experience in farming	0.013	0.716
Farm income	0.156	0.001***
Size of landholdings	0.095	0.006***
Group membership	-0.311	0.002***
Training	0.041	0.637
Constant	1.434	0

Kaiser-Meyer-Olkin (KMO) and Bartlett's test results

Table 4 highlights a strong, overarching reason for the low KMO (0.619) in this research is that the survey items capture multiple distinct dimensions of farmers' decision-making-financial incentives (e.g., prices, discounts), social influences (e.g., peers, dealers), institutional trust (e.g., Department of Agriculture, extension services) and product attributes (e.g., quality, high yield). Because these dimensions do not share enough common variance (they each measure fundamentally different aspects of adoption), the resulting inter-item correlations are relatively low, which in turn drives down the overall KMO. Additionally, Bartlett's test showed a significant chi-square value of approximately 282.499 with 45 degrees of freedom, indicating significance at the 0.01 level.

Table 4. Kmo and Bartlett test

Kaiser-Meyer-Olkin measure of sampling adequacy		0.619
Bartlett's Test of Sphericity	Approx. Chi-Square	282.449
	Df	45
	Sig.	.000

Rotated component matrix

Table 5 highlights the factor loadings following varimax rotation can be found in Table 6. The analysis identifies four components influencing decision-making, with significant loadings (≥ 0.5). Component 1 (Sales and Institutional Influence) emphasized professional advice and institutional credibility, driven by strong loadings for Agriculture Sales representatives (0.901), the Department of Agriculture (0.844) and financial incentives like prices and discounts (0.718), consistent with studies on renewable energy adoption that underline institutional trust and financial motivation as pivotal influences (39). Component 2

Table 5. Rotated component matrix

Variables	Component			
	1	2	3	4
Dealers influence	0.376	-0.438	0.345	**0.536**
Quality	0.176	**0.655**	0.189	0.449
Peers group	-0.376	0.257	**0.665**	-0.027
Low price	0.083	**0.653**	-0.077	0.027
High yield	-0.063	**0.78**	0.166	-0.031
Prices, discounts	**0.718**	0.404	-0.029	-0.001
Advertisements	-0.174	0.151	-0.151	**0.863**
Sales rep/ Agriculture	**0.901**	-0.016	-0.055	-0.053
Dept of Agriculture	**0.844**	-0.055	0.155	0.005
Peers group	0.26	-0.031	**0.812**	-0.03

(Quality and Yield) highlighted intrinsic product attributes such as high yield (0.78), quality (0.655) and affordability (0.653), emphasizing performance metrics that directly impact productivity, aligning with findings from technology adoption research (40). Component 3 (Social Influence) underscored the role of interpersonal dynamics, with peer group influence (0.812) illustrating the importance of social proof and trusted networks in shaping behaviors, as supported by research on mobile technology adoption (41). Component 4 (Advertising Influence) captured the persuasive power of marketing efforts and dealer strategies, with advertisements (0.863) and dealer influence (0.536) playing key roles, consistent with consumer behavior studies highlighting marketing's impact on decision-making (42). Collectively, these findings underscore the multifaceted nature of farmers' decision-making processes, influenced by institutional trust, product attributes, social dynamics and advertising. The moderate KMO value indicates the need for refining survey dimensions to increase shared variance and strengthen future analyses. By building institutional trust, emphasizing product performance, leveraging social networks and enhancing marketing strategies, policymakers and stakeholders can better address adoption barriers, aligning support mechanisms with the diverse factors shaping farmers' decisions to promote sustainable agricultural practices.

Components and Factor Components

Table 6 presents the factor analysis identified four key components influencing farmers' adoption of BCAs, supported by relevant studies. Sales-Related Factors (25.204 % variance) include sales representatives, field officers, agriculture departments and discounts, aligning with the importance of institutional support and communication in agricultural innovation adoption (43). Economic Factors (19.742 %) focus on high yield, quality and low price, reflecting cost-effectiveness priorities (44). Social Influencing Factors (12.878 %) involve peer groups and brand loyalty, resonating with the role of social networks in driving innovation adoption. Purchase Decision Factors (11.731 %) highlight advertisements and dealer influence, corresponding to how external perceptions and subjective norms shape decisions (45). Together, these components provide critical insights into the drivers of BCA adoption and inform strategies to enhance their uptake.

Table 6. Components and factor components

Components	Variance percent	Factors
Sales related factors	25.204	Sales rep/ Field officer Dep of Agriculture Prizes, Discounts
Economic factors	19.742	High yield Quality Low price
Social influencing factors	12.878	Peer group Brand loyalty
Purchase decision factors	11.731	Advertisements Dealers influence

Constraints faced by farmers in acquiring biological control agents

Table 7 explains the key barriers to BCA adoption, with the lack of knowledge about usage (Mean Score = 71.62, Rank I) emerging as the most significant obstacle, reflecting a knowledge gap that can be addressed through targeted education and training, including demonstration plots and interactive workshops (46). Financial constraints rank second and third, with no credit facility (Mean Score = 61.88, Rank II) and high costs (Mean Score = 57.60, Rank III) as critical issues, necessitating financial support mechanisms such as subsidies, improved credit access and cost-sharing initiatives (47). Perceptions of no significant difference between BCAs and other products (Mean Score = 51.18, Rank IV) hinder adoption, highlighting the need for comparative trials and success stories to demonstrate BCAs' unique benefits (48). Logistical barriers, including the lack of local availability (Mean Score = 40.11, Rank V) and untimely access (Mean Score = 27.96, Rank VII), underline systemic inefficiencies requiring investments in distribution networks and partnerships with local dealers. Additionally, a lack of interest among farmers (Mean Score = 39.64, Rank VI) underscores the importance of awareness campaigns to build trust and enthusiasm for sustainable farming practices. Addressing these challenges through education, financial incentives, logistical improvements and targeted awareness can significantly enhance BCAs adoption.

Table 7. Constraints faced by farmers in acquiring the BCAs

S. NO	Particulars	Mean score	Rank
1	Lack of knowledge of the usage of BCAs	71.62	I
2	No credit facility	61.88	II
3	High cost	57.60	III
4	No difference in product with other brands	51.18	IV
5	Not available all requirements locally	40.11	V
6	Lack of interest among farmers in the usage of BCAs	39.64	VI
7	Not available in time	27.96	VII

Conclusion

The adoption of BCAs is influenced by demographic, socioeconomic and systemic factors. While attributes like age, gender and education have limited impact, farm income, landholding size and group membership are critical determinants. Smallholder farmers favor BCAs for cost-effectiveness, with cooperatives providing essential platforms for knowledge exchange and resource access. Middle-aged and experienced farmers show openness to BCAs, but systemic gender imbalances and educational disparities hinder broader adoption. Targeted educational initiatives and inclusive policies are essential for addressing these inequities. Factor analysis highlights four adoption drivers: sales and institutional influence, product quality and yield, social dynamics and marketing strategies. Integrated approaches that combine education, financial support, infrastructure development and strategic marketing are necessary. In conclusion, addressing barriers with context-specific interventions can enhance BCA adoption, promoting environmental sustainability, economic resilience and food security in farming communities. Robust policies and stakeholder engagement are key to fostering sustainable agricultural practices. Key barriers include knowledge gaps, financial constraints and logistical challenges. Educational outreach through demonstration plots, workshops and success stories can bridge these gaps, while financial mechanisms like subsidies and credit facilities can alleviate economic burdens. Investments in supply chain infrastructure and partnerships with local distributors are vital for ensuring access to BCAs.

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Authors' contributions

VV carried out experimentation and drafted the manuscript and DK planned, supervised and edited the manuscript. All authors were involved in planning and analysis and provided critical feedback on the manuscript. All authors read and approved the final manuscript.

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During the preparation of this work, the authors used Chat GPT to improve language and readability, to reduce grammatical errors and to frame opt words and sentences ensuring that the manuscript has specific terminologies for the beneficiaries. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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