



RESEARCH ARTICLE

Determinants of bio-inoculant adoption behaviour among farmers in Tamil Nadu: An application of smart partial least squares structural equation modelling

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Abstract

The transition towards sustainable agriculture necessitates the adoption of eco-friendly alternatives to chemical fertilisers and pesticides. Bio inoculants, comprising beneficial microorganisms, offer significant potential to enhance soil health and crop productivity. However, despite their proven benefits, their adoption among farmers in India remains limited. Existing studies have largely focused on awareness and general adoption patterns, with limited empirical evidence on the combined influence of innovation attributes using advanced modelling approaches such as partial least squares structural equation modelling (PLS-SEM), particularly across diverse agro-climatic regions. This study addresses this gap by examining the determinants of bio-inoculant adoption behaviour among farmers in Tamil Nadu using PLS-SEM based on the innovation diffusion theory (IDT). A total of 240 farmers were selected from eight agro-climatic zones through purposive and snowball sampling techniques. The results indicate that 42.91 % of farmers have adopted bio-inoculants. Relative advantage, compatibility, complexity (low complexity) and observability significantly influence adoption behaviour, whereas trialability has no significant effect. Among these, complexity emerged as the most influential factor, highlighting the importance of ease of use in technology adoption. Despite these positive determinants, key constraints such as lack of awareness, inconsistent product quality and limited availability continue to hinder widespread adoption. The study recommends strengthening extension services, improving quality assurance mechanisms and enhancing farmer awareness through targeted interventions. These findings provide valuable insights for policymakers and extension agencies to promote sustainable agricultural practices through increased adoption of bio-inoculants.

Keywords: adoption behaviour; bio-inoculants; farmers' perception; innovation diffusion theory; partial least squares structural equation modelling; sustainable agriculture

Introduction

The rapid growth of the global population, currently estimated at 7.8 billion, has significantly increased the demand for agricultural production, posing serious challenges to global food security. The Food and Agriculture Organization projects that agricultural demand will rise by nearly 60 % by 2030 (1, 2). To meet this demand, modern agriculture has become heavily dependent on chemical fertilisers and pesticides. However, the excessive use of these inputs has led to several environmental and ecological issues, including soil degradation, nutrient imbalance, groundwater contamination and the decline of beneficial soil microorganisms (3, 4). These adverse effects threaten the long-term sustainability of agricultural systems.

In this context, sustainable agriculture has emerged as a crucial approach to ensure food security while preserving

environmental quality (5, 6). It focuses on maintaining soil health, improving productivity and ensuring ecological balance (7, 8). Among the various sustainable alternatives, bio-inoculants have gained considerable attention. Bio-inoculants consist of beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilising microbes and plant growth-promoting rhizobacteria, which enhance soil fertility and crop productivity (3, 4). Their application reduces dependence on chemical inputs and contributes to environmentally sustainable farming practices (9, 10).

Globally, the use of bio-based agricultural inputs has been increasing. For instance, the production of biopesticides has reached approximately 3000 tons annually, with significant market presence in countries such as the United States, Canada and Brazil (11, 12). Research has also demonstrated that inoculation with microorganisms

such as *Pseudomonas* spp. and *Azospirillum brasilense* can improve crop yields by 4–9 %. Despite these advantages, adoption rates vary widely across regions, particularly in developing countries where awareness and access remain limited (13, 14).

In India, although bio-inoculants are promoted as eco-friendly agricultural inputs, their adoption among farmers remains relatively low. Previous studies have identified several factors influencing adoption, including lack of awareness, inconsistent product quality, limited availability and inadequate extension support (15, 16). While these studies provide useful insights, most of them are descriptive in nature and focus on isolated factors affecting adoption behaviour.

However, there remains a significant research gap in terms of theory-driven empirical analysis of bio-inoculant adoption. Existing studies have rarely examined the combined influence of innovation attributes using advanced analytical techniques such as partial least squares structural equation modelling (PLS-SEM). Furthermore, there is limited empirical evidence integrating innovation diffusion theory (IDT) with adoption behaviour across diverse agro-climatic regions, particularly in Tamil Nadu.

The IDT provides a comprehensive framework to understand how farmers adopt new agricultural technologies. According to this theory, adoption is influenced by key attributes such as relative advantage, compatibility, complexity, observability and trialability. Analysing these attributes collectively can provide deeper insights into farmers' decision-making processes.

In view of the above research gap, the present study aims to examine the adoption behaviour of farmers towards bio-inoculants in Tamil Nadu using PLS-SEM within the framework of IDT. The study focuses on understanding the socio-economic profile of farmers adopting bio-inoculants and assessing the extent of adoption across different agro-climatic zones of the state. It also investigates how key innovation attributes, namely relative advantage, compatibility, complexity, observability and trialability, influence farmers' adoption behaviour. In addition, the study identifies the major constraints that limit the adoption of bio-inoculants among farmers.

Materials and Methods

Theoretical background

Innovation diffusion theory

Recently, the acceptance and adoption of bio-inputs such as bio-fertilisers and bio-pesticides have been subject to some research. Individual perceptions of innovative qualities influence adoption rates. The theory of diffusion of innovation (DOI) identifies five innovation traits: relative advantage, complexity, compatibility, observability and trialability. These factors explain 49–87 % of the variance in adoption rates (12). The concept of relative advantage relates to how a new technology outperforms current ones in terms of economic rewards, satisfaction, appropriateness, social factors and prestige (12). Early adopters who see a major advantage over existing practices are more likely to accept new technologies. "Complexity" refers to an idea or technology that is difficult to understand and use, leading to lower adoption rates. Adopting an invention requires new skills and a comprehensive grasp of technology. Younger and beginning farmers' ability to execute new practices influences their acceptance rate (13, 14). Complexity and adoption rate have a negative correlation, which contradicts other

features. This research defines complexity as a low complexity (LC) level, which is associated with a positive attitude. Compatibility refers to the alignment of an invention with an individual's current values, behaviours, beliefs and experiences. The term "observability" relates to how apparent an invention is to others, while "trialability" refers to how much a new technology may be employed or tried out by individuals (12).

Measurement instruments

The study's measurement items were directly adopted from IDT to match the study's requirements. The items for RA, COM, COX, TR and OBS were adopted from previous reports (12). A thorough evaluation of academic and practical publications was conducted to ensure content validity. A pilot study was undertaken to validate the research instrument of the proposed model. The objective of the pilot study was to identify and eliminate potential problems in the questionnaire e.g., grammatical and phrasing issues and validate the model predictability. The sample was collected from the Thanjavur district of Tamil Nadu since it is the largest producer and manufacturer of bio-inputs in India as per the data from the Centre for Science and Environment. The pilot study sample of 30 respondents was collected. The instrument was based on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

Sample design and data collection

The present study was conducted in eight districts representing different agro-climatic zones of Tamil Nadu, namely Erode, Thanjavur, Villupuram, Thiruvannamalai, Theni, Tuticorin, Dindigul (Kodaikanal region) and Pudukottai. These districts were selected to capture diversity in cropping systems and farming conditions.

The present study employed a combination of purposive sampling and snowball sampling techniques to select respondents. The use of non-probability sampling was considered appropriate due to the absence of a comprehensive sampling frame of farmers specifically using bio-inoculants in Tamil Nadu. Since bio-inoculant adoption is not uniformly documented across regions, it was not feasible to identify respondents through probability-based methods.

In the first stage, purposive sampling was used to select districts representing different agro-climatic zones of Tamil Nadu to ensure diversity in cropping patterns and farming conditions. Within each selected district, initial respondents (seed respondents) were identified with the assistance of agricultural extension officers, input dealers and local farmer groups who had prior knowledge of farmers using bio-inoculants.

Subsequently, snowball sampling was employed, wherein the identified respondents were requested to refer other farmers who had experience with bio-inoculants. To minimise referral bias and over-representation of closely connected farmer groups, multiple independent entry points were established in each district. Respondents were selected from different villages and networks to ensure variability. Additionally, cross-verification was performed to avoid duplication of respondents and to ensure that referred individuals met the study criteria. A total of 240 respondents were selected, with 30 farmers from each district, ensuring balanced representation across the study area.

Questionnaire development

The questionnaire for this study was developed based on the constructs of IDT, including relative advantage (RA), compatibility

(COM), complexity (COX), trialability (TR) and observability (OBS). The measurement items for these constructs were adapted from established literature on innovation adoption to ensure content validity (12).

Initially, five items were developed for each construct based on theoretical relevance and prior studies. The questionnaire was prepared in English and subsequently reviewed by subject matter experts, including agricultural extension professionals and researchers, to ensure clarity and contextual suitability.

The instrument was then translated into Tamil, the local language of the study area and a back-translation procedure was followed to maintain consistency between the original and translated versions. A pilot study was conducted with 30 farmers to assess the clarity, reliability and applicability of the instrument.

Based on pilot testing, item analysis and expert feedback, certain items were found to be redundant or exhibited low clarity and weak item-total correlation. These items were removed to improve the overall reliability and consistency of the instrument.

Following this refinement, relative advantage and observability were measured using five items each, compatibility and complexity using four items each and trialability using three items. Adoption behaviour was measured using four items, resulting in a total of 25 items.

The variation in the number of items across constructs is consistent with prior studies based on IDT, where constructs are operationalised using a minimum of three indicators to ensure adequate representation. Trialability was measured using three items as they sufficiently captured the construct without redundancy, while constructs such as relative advantage and observability required more items due to their broader conceptual dimensions.

This refinement ensured parsimony while maintaining content validity and measurement reliability. All retained items satisfied acceptable reliability and validity criteria, with Cronbach's alpha values exceeding the recommended threshold.

Data analysis

The suggested research model was tested using the PLS-SEM technique. Structural equation modelling (SEM) is a multivariate statistical approach used to examine complex relationships among latent and observed variables through a confirmatory and hypothesis-testing framework. The SEM can be performed using two major approaches, namely covariance-based SEM (CB-SEM) and variance-based SEM, commonly known as PLS-SEM.

In the present study, PLS-SEM was employed using Smart PLS software version 4.1.0.1, as it is widely recognised for its suitability in exploratory and predictive research models. Compared to CB-SEM, PLS-SEM is preferred for prediction-oriented studies and theory development due to its flexibility in handling complex models, non-normal data distribution and relatively smaller sample sizes (16, 17).

A pilot study was initially conducted with 30 respondents to assess the clarity, reliability and suitability of the research instrument. The pilot sample was used only for preliminary testing and refinement of the questionnaire and was not included in the final model estimation.

The final PLS-SEM analysis was carried out using data collected from 240 respondents. The adequacy of the sample size was determined based on the recommendations available in PLS-

SEM literature, which suggest that PLS-SEM can effectively handle small to medium sample sizes while maintaining acceptable predictive accuracy (18). Therefore, the final sample size of 240 respondents was considered adequate for evaluating the measurement and structural models in the present study.

Results

Socio-economic characteristics of the farmers

The current research investigated the socio-economic characteristics of farmers by utilising factors such as age, education, occupation status, farm size, annual income, farming experience and cosmopolitanism. The acquired information was evaluated, categorised and recorded. Statistical methods such as frequency, percentage, mean and standard deviation were utilised to analyse the results.

Table 1 exhibits that the majority of bio-inoculant users are middle-aged farmers (41.7 %), followed by young farmers (33.3 %). This shows that bio-inoculants are more often used by farmers during their productive years, when they may be more receptive to innovative agricultural approaches. Bio-inoculant users come from a varied spectrum of educational backgrounds. The majority (62.5 %) have had at least a secondary education, with 25 % having finished it. This shows that education may have a role in bio-inoculant acceptance, perhaps as a result of greater knowledge and comprehension of current agricultural processes (Table 1).

Bio-inoculant users are full-time farmers, with a quarter doing agriculture as a supplementary occupation. This suggests that bio-inoculants are predominantly used by people whose livelihoods

Table 1. Socio-economic characteristics of bio-inoculant adopters (n = 240)

Sl.no	Category	Frequency	%
Age			
1.	Young (18–35 years)	80	33.33
	Middle (35–50 years)	100	41.77
	Old age (above 50 years)	60	25.00
Education			
2.	Illiterate	20	8.33
	Primary	40	16.77
	Middle	50	20.88
	Secondary	60	25.00
	Higher secondary	40	16.77
	Collegiate	30	12.55
Occupational status			
3.	Agriculture as main occupation	180	75
	Agriculture as subsidiary occupation	60	25.0
Farm size			
4.	Small	44	18.3
	Medim	103	42.9
	Big	56	23.3
Annual income			
5.	Low	80	33.33
	Medium	100	42.99
	High	60	25.00
Farming experience			
6.	Low	70	33.33
	Medium	110	45.88
	High	60	25.00
Cosmopolitanism			
7.	Low	80	33.33
	Medium	100	41.77
	High	60	25.00

rely on agriculture. Medium-sized farms account for 42.9 % of the sample, followed by large farms (23.3 %) and small farms (18.3 %). This shows that bio-inoculant adoption may be more possible or appealing for medium to large-scale farmers, presumably owing to variables such as resources, risk tolerance or economies of scale. The income distribution generally corresponds to the farm size distribution. The biggest group is made up of medium-income farmers, indicating that bio-inoculant usage is not confined to high-income farmers but is available to people of all economic levels. Farmers with medium levels of expertise make up the biggest group of bio-inoculant users. This shows that some agricultural expertise may be useful when adopting novel approaches such as bio-inoculants, but it is not confined to the most experienced farmers (Table 1).

The majority of bio-inoculant users have a medium to high degree of cosmopolitanism. This might imply that exposure to larger social networks, information sources or urban influences may impact the adoption of new agricultural methods such as bio-inoculants. According to the research, bio-inoculant usage is most frequent among middle-aged, educated farmers who own medium-sized farms and have moderate levels of income, experience and cosmopolitanism. This profile suggests a group of farmers who are established enough to adopt new approaches while still being open to innovation.

Adoption level of the farmers towards bio inoculants

Adoption behaviour of bio-inoculants was analysed among different categories of farmers in different agro-climatic zones of Tamil Nadu. It was found that medium-sized-holding farmers adopted 42.91 % of bio-inoculants technologies in crops followed by large and small holding farmers. Women farmers adopted 15.41 % of bio-inoculants in crop cultivation, which was very minimal in case of adoption of bio inoculants in Tamil Nadu state. This may be due to the fact that medium to large sized land holding farmers are ready to take risks and afford new technologies for adoption in crop cultivation when compared to other categories of farmers in Tamil Nadu. In addition to that medium and large size holding farmers with educational backgrounds are recognised as opinion leaders in the village and used to adopt eco-friendly agricultural technologies for promoting sustainable farming (Table 2).

As far as crop-wise analysis is concerned, it was found that the majority of millet-growing farmers adopted a significant percentage of bio-inoculants, followed by paddy and hill banana. Millet growers used to choose eco-friendly agricultural practices, which include adoption of bio-inoculants. Paddy and hill banana require bio-inoculants as a measure to improve the soil microbial population and minimise the chemical residues in the end products. Hence, paddy and banana growers also adopted a significant percentage of bio-noculants in Tamil Nadu (Table 2).

Variation in adoption behaviour across farmer categories

The analysis further indicates that adoption behaviour varies across different farmer categories. Medium farm holders exhibited the highest adoption level (42.9 %), followed by large farmers (23.3 %), while small farmers showed relatively lower adoption (18.3 %). This suggests that farmers with moderate resource availability are more inclined to adopt bio-inoculants, as they possess sufficient financial capacity and risk-bearing ability while remaining open to innovation.

Similarly, adoption behaviour varied across crop types, with millet growers showing relatively higher adoption compared to other crops. This may be attributed to the compatibility of bio-inoculants with low-input cropping systems. In contrast, adoption among other crop growers appears to be influenced by specific agronomic needs and perceived benefits.

Educational differences also play a role in adoption behaviour, as a higher proportion of adopters had secondary education and above. This indicates that education enhances farmers' ability to understand and evaluate new agricultural technologies.

Factors that directly or indirectly influence the adoption of bio-inoculants

The factors that directly or indirectly influence the adoption of bio-inoculants were studied using the PLS-SEM software with the following steps.

Develop the conceptual model

Assessment of the proposed model

Structural model assessment

Development of conceptual model

The PLS-SEM analysis was carried out to find out the factors which directly or indirectly contribute towards the adoption of bio-inoculants among the different categories of farmers. The PLS-SEM software was run by feeding data related to attributes of innovation which were proposed by IDT. A separate scale was computed to find out the adoption attributes of bio-inoculants. The data pertaining to attributes of innovation and adoption of bio-inoculants were fed into PLS-SEM software to understand the factors which directly or indirectly contribute to the adoption of bio-inoculants. From the PLS-SEM output, it was possible to further categorise the overall factors which influence adoption and the negative factors which hinder adoption were finalised (Fig. 1).

Assessment of the proposed model

Measurement model assessment using factor loadings

The factor loadings of all indicators were examined to assess the indicator reliability of the measurement model. The loading values ranged from 0.772 to 0.916, which exceeded the recommended threshold value of 0.70 as suggested by previous reports (18). This indicates that all the indicators had a strong level of association with

Table 2. Category wise distribution of the respondent according to the adoption behaviour of bio-inoculants (based on farm size) (n=240)

Farmers category	Scale (ha)	cereals		Vegetables		Hill Banana		Millets		Oilseeds		Pulses		Total	Percentage %
		No	%	No	%	No	%	No	%	No	%	No	%		
Small	1-2	12	20	4	13.3	6	20	14	23.3	3	10	5	16.6	44	18.3
Medium	4-10	24	40	12	40	17	56.6	32	53.3	10	30	8	26.6	103	42.9
Large	>10	16	26.6	9	30	3	10	9	15	13	43.3	6	20	56	23.3
Women	-	8	13.3	5	16.6	4	13.3	5	8.33	4	13.3	11	36.6	37	15.4
Total		60		30		30		60		30		30		240	100

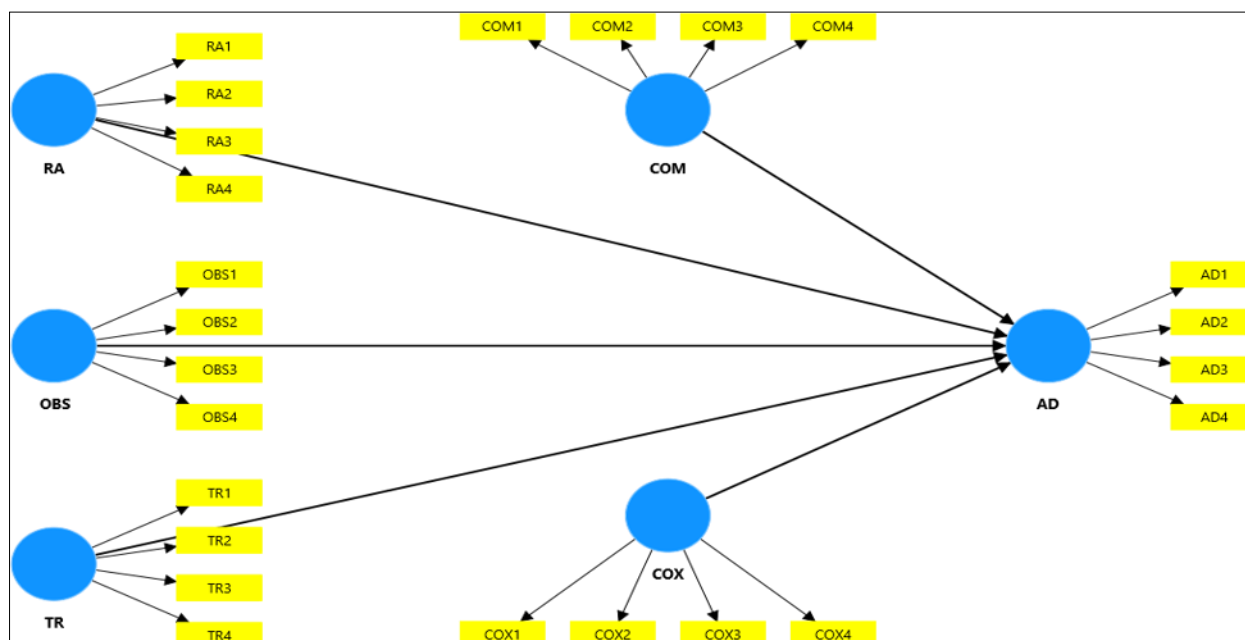


Fig. 1. Conceptual framework based on innovation diffusion theory showing relationships between innovation attributes and adoption behaviour.

Table 3. Assessment of factor loadings of constructs and indicators

Constructs	Indicators	Factor loadings
Relative Advantage (RA)	RA1	0.814
	RA2	0.862
	RA3	0.823
	RA4	0.831
Observability (OBS)	OBS1	0.839
	OBS2	0.855
	OBS3	0.810
	OBS4	0.792
Trialability (TR)	TR1	0.789
	TR2	0.855
	TR3	0.832
	TR4	0.895
Compatibility (COM)	COM1	0.885
	COM2	0.809
	COM3	0.916
	COM4	0.906
Complexity (COX)	COX1	0.873
	COX2	0.893
	COX3	0.825
	COX4	0.772
Adoption (AD)	AD1	0.893
	AD2	0.861
	AD3	0.872
	AD4	0.888

their respective latent constructs (Table 3).

Among the constructs, relative advantage (RA) recorded factor loading values ranging from 0.814 to 0.862 (Table 3), indicating that all four indicators adequately represented the construct. The indicators of observability (OBS) showed loading values between 0.792 and 0.855 (Table 3), confirming satisfactory contribution of each item towards measuring the construct.

The factor loading values of Trialability (TR) ranged from 0.789 to 0.895 (Table 3), demonstrating strong indicator reliability. Compatibility (COM) exhibited comparatively higher loading values ranging from 0.809 to 0.916 (Table 3), indicating a very strong relationship between the indicators and the latent construct.

Similarly, the indicators of Complexity (COX) recorded loading values between 0.772 and 0.893 (Table 3), while Adoption (AD) showed loading values ranging from 0.861 to 0.893 (Table 3). Since all the indicators exceeded the acceptable threshold value, the constructs achieved adequate convergent validity and indicator reliability. Therefore, all the indicators were retained in the final model and no items were removed during the model refinement process.

Construct reliability and validity

The measurement model findings show that all constructs in the study have high reliability and convergent validity. High Cronbach's alpha values (all more than 0.8) across constructs indicate high internal consistency, implying that the items within each construct consistently assess the same fundamental notion. The composite reliability ratings for all constructs exceed 0.9, suggesting a high degree of dependability. This implies that the constructs are consistently assessed and the items within each construct are substantially connected. The AVE values for all constructs surpass 0.5, indicating convergent validity. This suggests that the constructs account for a significant percentage of the variation in their indicators, implying that the indicators are accurately representative of their respective constructs (Table 4).

The AD construct, with a Cronbach's alpha of 0.902 and an AVE of 0.772 (Table 4), demonstrates that farmers' adoption of bio-inoculants is accurately assessed and captures a significant amount of variation from its indicators. This emphasises the necessity of knowing the elements that influence adoption when designing successful interventions. The COM construct is highly reliable and valid, having a Cronbach's alpha of 0.903 and an AVE of 0.774 (Table 4). This suggests that the compatibility of bio-inoculants with conventional agricultural techniques is an important consideration for adoption.

The COX construct has a Cronbach's alpha of 0.864 and an AVE of 0.71 (Table 4), indicating that complexity is a significant barrier to adoption. Simplifying technology and offering user-friendly instructions may assist in alleviating this difficulty. Observability (OBS) and RA are critical for adoption, as seen by their high

Table 4. Reliability and convergent validity of constructs

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
AD	0.902	0.903	0.931	0.772
COM	0.903	0.925	0.932	0.774
COX	0.864	0.877	0.907	0.71
OBS	0.848	0.884	0.894	0.679
RA	0.853	0.854	0.901	0.694
TR	0.872	0.973	0.908	0.712

dependability ratings. To spread the use of bio-inoculants, farmers must perceive concrete advantages and verifiable outcomes. The TR construct, with a Cronbach's alpha of 0.872 and an AVE of 0.712 (Table 4), suggests that farmers value the capacity to test bio-inoculants on a limited scale before completely implementing them. This shows that pilot initiatives and demonstrations may be successful in increasing acceptance (Table 4).

Outer loadings

These loadings represent the strength of the relationship between the latent variable and its indicators, and they are used to assess the reliability and validity of the measurement model (19, 20). As stated by the previous researchers (19, 20), the outer loading should be > 0.60, which shows that the study construct indicators' loadings were higher than all of their cross-loadings. Among the 24 items, all items are loaded adequately on their latent variables and the path weights were more than 0.7.

AD1 to AD4 have loadings ranging from 0.861 to 0.893. These high loadings demonstrate that these indicators significantly reflect the adoption construct, implying that respondents regularly see these indicators as representative of adoption. COM1 through COM4 have loadings ranging from 0.809 to 0.916. This reveals a strong link between the indicators and the compatibility construct, implying that the indicators accurately assess the construct. COX1 through COX4 have loadings ranging from 0.772 to 0.893. The somewhat lower loading for COX4 (0.772) still satisfies the acceptable threshold, but it implies that this indicator is significantly less representative of the complexity construct than others.

The loadings for OBS1 through OBS4 range from 0.792 to 0.855, showing a robust measurement of the observability construct. RA1 through RA4 have loadings ranging from 0.814 to 0.862. These substantial loadings show that the indicators were reliable measurements of the relative advantage construct. TR1 to TR4 have loadings between 0.789 and 0.895. These loadings suggest that the indicators are reliable measurements of the trialability construct.

Heterotrait-Monotrait ratio (HTMT)

The HTMT ratio is a statistic that compares the average correlations between indicators of distinct constructs (heterotraits) to those of the same construct (monotraits). If the HTMT value is less than 0.90, there is discriminant validity between two reflective constructs (16). The findings reveal that all of the HTMT ratios between the study model components for RA, COM, COX, TR and OBS are smaller than the 0.90 threshold, indicating that the measurement models demonstrate discriminant validity (16).

The correlation coefficient between AD and RA is 0.351 (Table 5), showing a positive association. This shows that bio-inoculants are adopted mostly because of their perceived advantages. Farmers are more willing to use bio-inoculants if they observe significant benefits over conventional approaches. The

Table 5. Discriminant validity using HTMT ratio

	AD	COM	COX	OBS	RA	TR
AD						
COM	0.182					
COX	0.587	0.212				
OBS	0.172	0.068	0.508			
RA	0.351	0.075	0.063	0.203		
TR	0.075	0.335	0.180	0.177	0.052	

correlation coefficient between AD and COM is 0.182 (Table 5), showing a weakly favourable link. This shows that when bio-inoculants become more compatible with current agricultural techniques, their adoption will increase. The correlation coefficient between AD and COX is 0.587 (Table 5), suggesting a moderate to strong positive association. This shows that as the complexity of bio-inoculants reduces, their adoption rises drastically. Simplifying technology and making it easy to comprehend and use may significantly increase adoption rates. The correlation coefficient between AD and OBS is 0.172 (Table 5), showing a weakly favourable association. This means that the more visible the advantages of bio-inoculants, the more likely they are to be embraced by farmers, even if the effect is little. The correlation coefficient between AD and TR is 0.075 (Table 5), showing a very modest positive link. This shows that the capacity to test bio-inoculants on a limited scale prior to complete adoption has no effect on their overall adoption (Table 5).

Fornell-Larcker criterion

The Fornell-Larcker criterion was used in this study in order to determine the variables' discriminant validity. To meet the requirement, a latent variable must have a higher variance with its assigned indicators than with any other latent variable. The results are shown in Table 6. The discriminant validity of the constructs was considered established because this criterion was met. We can determine if each of our conceptual models has construct validity by combining convergent and discriminant validity.

The correlation coefficient between AD and RA is 0.308 (Table 6), showing a somewhat good association. Farmers are more willing to use bio-inoculants if they see evident benefits over conventional approaches. The correlation coefficient between AD and COM is -0.17 (Table 6), showing a mild negative link. This means that bio-inoculants that are more compatible with conventional agricultural techniques may have a little lower uptake. This unexpected conclusion may need more inquiry to determine the underlying causes. The correlation coefficient between AD and COX is 0.532 (Table 6), showing a favourable link. As the complexity of bio-inoculants lowers, their acceptance rises dramatically, underscoring the need for simplifying the technology to encourage adoption. The correlation coefficient between AD and OBS is 0.16 (Table 6), showing a weakly positive association. Observable advantages of bio-inoculants help to boost their acceptance. The correlation coefficient between AD and TR is -0.075, showing a mild negative association. This shows that trialability has no influence on adoption (Table 6).

Table 6. Discriminant validity using Fornell–Larcker criterion

	AD	COM	COX	OBS	RA	TR
AD	0.879					
COM	-0.17	0.88				
COX	0.532	-0.036	0.842			
OBS	0.16	-0.026	0.457	0.824		
RA	0.308	-0.059	0.029	0.159	0.88	
TR	-0.075	0.297	-0.162	-0.168	-0.034	0.844

Model evaluation criteria and structural model fit

The measurement and structural models were evaluated using established threshold criteria. Internal consistency reliability was confirmed as Cronbach's alpha and composite reliability values exceeded the recommended threshold of 0.70, while convergent validity was established with AVE values above 0.50. Indicator reliability was ensured as outer loadings were greater than 0.70 (acceptable above 0.60). Discriminant validity was verified using the HTMT ratio (values < 0.90) and the Fornell–Larcker criterion. The structural model showed a coefficient of determination (R^2) value of 0.41 for adoption behaviour, indicating moderate explanatory power. Effect size (f^2) was assessed using thresholds of 0.02 (small), 0.15 (medium) and 0.35 (large), indicating the relative contribution of each construct. Predictive relevance (Q^2) was evaluated using the blindfolding procedure and values greater than zero confirmed that the model has adequate predictive capability.

Structural model assessment

P-values range from zero to one, with lower numbers indicating a lower likelihood of the null hypothesis being true (21, 22). When the t -value is significant (higher than 1.65 at 0.05, one-tailed test), the related p -value indicates statistical significance, with smaller p -values (closer to zero) providing stronger evidence against the null hypothesis. With regards to the path coefficients, trialability towards adoption is non-significant. The other latent variables, namely complexity, compatibility, relative advantage and observability, have an effect on the adoption of bio-inputs. Complexity has the

strongest path (0.598) in the model followed by RA (0.309), Trialability (0.051), compatibility (-0.150) and observability (-0.158) (Fig. 2).

There is a strong negative association between compatibility and adoption. Adoption of bio-inoculants grows as their compatibility with current techniques declines (t -value = 2.182, $p < 0.05$). This paradoxical finding suggests that farmers may be more ready to accept bio-inoculants that represent a shift or improvement over their current ways than those that simply fit into existing practices. There is a substantial positive correlation between complexity and adoption. A t -value of 7.910 ($p < 0.001$) suggests that simplifying bio-inoculants leads to higher adoption rates. Simplifying technology and making it more user-friendly are critical steps toward increasing adoption rates. There is a strong negative link between observability and adoption. The t -value of 2.725 ($p < 0.01$) indicates that as the observability of bio-inoculants declines, adoption rises. This surprising finding suggests that farmers may be affected by reasons other than apparent advantages when opting to use bio-inoculants.

There is a strong positive association between relative advantage and adoption. A t -value of 3.745 ($p < 0.001$) indicates that the perceived advantages of bio-inoculants over conventional approaches considerably increase their adoption behaviour. Highlighting the evident benefits of bio-inoculants may help increase adoption rates. The t -value of 0.743 ($p > 0.05$) indicates that there is no significant link between trialability and adoption. This shows that the capacity to test bio-inoculants on a small scale has no meaningful influence on their overall acceptance.

As a result, the study's hypotheses were examined, with an emphasis on path coefficients, t -values and p -values. Table 7 demonstrates that relative advantage (p -value 0.000), lack of complexity (p -value 0.000) and observability (p -value 0.006) all have a substantial impact on bio-input uptake (p -value 0.000, $p < 0.01$). Thus, these relationships are significant at the 1% level implying that a 99% relative benefit influences the uptake of bio-inputs. This is

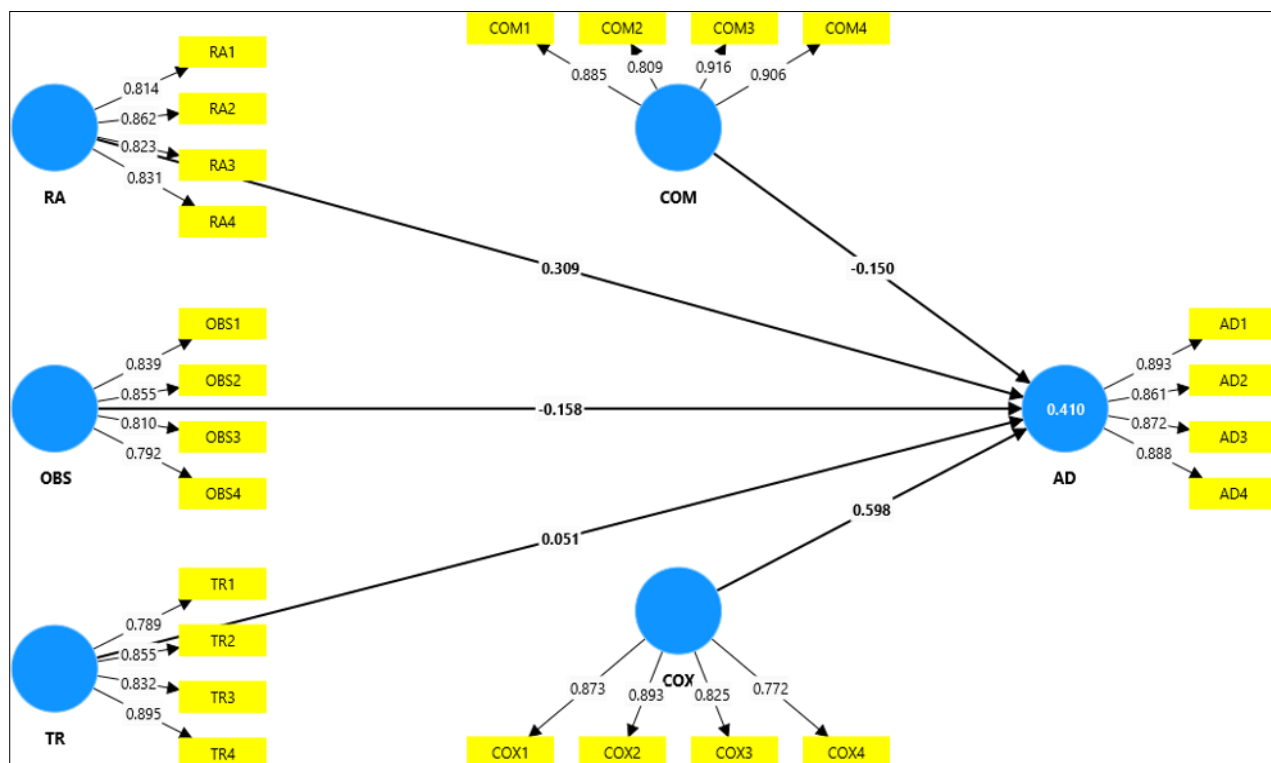
**Fig. 2.** Structural model results showing path coefficients and significance levels of factors influencing adoption of bio-inoculants.

Table 7. Structural model path coefficients

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T Statistics (O/STDEV)	p values
COM-> AD	-0.150	-0.156	0.069	2.182	0.029
COX-> AD	0.598	0.585	0.076	7.910	0.000
OBS-> AD	-0.158	-0.139	0.058	2.725	0.006
RA-> AD	0.309	0.306	0.082	3.745	0.000
TR->AD	0.051	0.044	0.069	0.743	0.458 (NS)

congruent with compatibility, which has a positive impact on bio-input adoption and is significant at 5 % (p -value = 0.029, $p < 0.05$), indicating that 95 % compatibility influences bio-input adoption. Trialability does not significantly impact bio-input adoption ($p = 0.458$, $p < 0.01$). The results emphasise the significance of decreasing complexity and stressing the relative benefits of bio-inoculants in order to enhance their adoption by farmers. The unanticipated negative connections between compatibility, observability and adoption need more inquiry to understand the underlying mechanisms (Table 7).

Previous research has shown that new goods or services must have better functional performance in order to be accepted (22, 23). Beyond direct economic gains, advancements should provide other benefits such as time savings, decreased pain and speedy outcomes (12). Our research analysis supports this, revealing a positive and substantial association between relative advantage and views regarding the use of bio-inoculants. This highlights the significance of relative advantage in shaping adoption attitudes due to its many advantages.

The research found a positive correlation between compatibility and bio-inoculant acceptance, aligning with results on the importance of compatibility in technology adoption (12). This compatibility may result in a variety of advantages, including greater crop yields, higher output quality, lower crop failure risk, better soil health compared to chemical fertilisers, easier management procedures, lower environmental pollution and support for sustainable agriculture. The compatibility of bio-inoculants with farmers' techniques increases their chances of adoption.

Our results contradict the previous reports claim that complexity limits the adoption of new technologies (12). Instead, decreased complexity is associated with increased adoption of bio-inoculants. Bio-inoculants are simple to comprehend and use; and they integrate well with traditional farming operations. Bio-inoculants are easier to apply and comprehend, which reduces perceived complexity and facilitates farmer acceptance.

Early adopters are more prepared to accept risks and often conduct early experiments (12). However, early and late majority farmers may embrace bio-inoculants based on direct observation of early adopters rather than undertaking their own studies. Our results show that the majority of farmers fall into the early or late majority groups, which has a detrimental influence on trialability and bio-inoculant uptake. The results show a non-significant relation with the adoption behaviour of bio-inoculants, implying that as more farmers see successful usage by early adopters, their demand for trial decreases.

Perceived observability has a strong impact on attitudes towards bio-inoculant usage. Non-adopters who see the product in action may overcome perceptual hurdles that would otherwise inhibit adoption (24). The apparent advantages of bio-inoculants,

such as healthier crops and higher yields, help farmers understand and appreciate their importance, generating favourable attitudes and increasing adoption rates. Thus, there exists a significant impact of attributes of innovation on the adoption of bio-inoculants. The alternate hypothesis (H1) was accepted and the null hypothesis (H0) was rejected. The present study provides empirical evidence on the adoption behaviour of bio-inoculants among farmers in Tamil Nadu by integrating IDT with PLS-SEM. The discussion interprets the findings by explicitly linking socio-economic characteristics, adoption levels and innovation attributes with the observed statistical results.

These additional analyses provide deeper insights into the variation in adoption behaviour across farmer categories and highlight the practical relevance of innovation attributes in influencing adoption decisions.

Coefficient of determination (R^2)

The coefficient of determination (R^2) was used to evaluate the explanatory power of the structural model. The R^2 value for the endogenous construct adoption was found to be 0.410, indicating that 41.0 % of the variation in adoption behaviour was explained by RA, observability, trialability, compatibility and complexity. The obtained R^2 value indicates moderate explanatory power of the model (21).

Effect size (f^2)

The effect size (f^2) was assessed to determine the individual contribution of each exogenous construct towards the endogenous construct. The results revealed that Trialability (0.458) had a comparatively large effect on adoption, whereas RA and compatibility exhibited small to medium effects. Observability and complexity showed relatively smaller effects on adoption behaviour. This indicates that trialability played a major role in influencing the adoption behaviour of respondents.

Predictive relevance (Q^2)

The predictive relevance (Q^2) of the structural model was evaluated using the blindfolding procedure. The Q^2 value obtained for the adoption construct was greater than zero, indicating that the model possessed satisfactory predictive relevance. Hence, the model demonstrated adequate capability in predicting the endogenous construct.

Constraints hindering the adoption of bio-inoculants among farmers

The study identified several constraints affecting the adoption of bio-inoculants among farmers (Table 8). The constraints are presented below.

Lack of knowledge and confidence

All the respondents (100 %) reported a lack of knowledge and confidence as a major barrier to the adoption of bio-inoculants (Table 8). This indicates that farmers are not adequately aware of the benefits, application methods and effectiveness of bio-inoculants,

Table 8. Constraints hindering adoption of bio-inoculants (n = 240)

Sl.no	Particulars (n = 240)	Frequency	Percentage	Rank
1.	Lack of knowledge and confident	240	100 %	1
2.	Non-availability of bio-fertilisers in time	140	58.33 %	5
3.	Lack of visibility of change due adoption of bio-inoculants in the crops	200	83.33 %	2
4.	Un assured quality of bio-inoculants	180	75 %	3
5.	High cost of bio-inoculants	160	66.67 %	4

which significantly restricts their adoption.

Lack of visibility of change due to adoption

A majority of the respondents (83.33 %) expressed concern that the effects of bio-inoculants are not immediately visible (Table 8). This suggests that farmers perceive delayed or unclear outcomes from the use of bio-inoculants.

Unassured quality of bio-inoculants

About 75 % of the respondents indicated that the quality of bio-inoculants is not assured (Table 8). This reflects farmers' doubts regarding the reliability and consistency of bio-inoculant products available in the market.

High cost of bio-inoculants

The high cost of bio-inoculants was reported as a constraint by 66.67 % of the respondents (Table 8). This indicates that financial limitations play a significant role in restricting adoption.

Non-availability of bio-inoculants in time

More than half of the respondents (58.33 %) reported that bio-inoculants are not available at the required time (Table 8). This highlights issues related to the supply chain and distribution of bio-inoculant products.

Discussion

Socio-economic characteristics and adoption pattern

The socio-economic profile of bio-inoculant adopters (Table 1) reveals that middle-aged farmers (41.77 %) constitute the largest adopter group, followed by young farmers (33.33 %). This indicates that adoption is highest among farmers who possess adequate farming experience while still remaining open to innovation. This finding aligns with IDT, which suggests that individuals with balanced risk perception and experience are more likely to adopt new technologies (12). Similar adoption behaviour has been reported in earlier studies, where middle-aged farmers were more inclined to adopt eco-friendly technologies due to their ability to evaluate risks and benefits effectively.

Education also plays a crucial role in adoption. Nearly 62.55 % of adopters had secondary education or above, suggesting that formal education enhances farmers' ability to understand the benefits, application procedures and long-term impacts of bio-inoculants. This supports the argument that educated farmers are more receptive to knowledge-intensive innovations. These findings are consistent with earlier studies which reported that education and access to information significantly influence the adoption of agricultural innovations (25–27).

Farm size further influenced adoption behaviour. Medium farm holders (42.9 %) constituted the highest proportion of adopters, followed by large farmers (23.3 %), while small farmers accounted for only 18.3 % (Table 1). Medium and large farmers

generally possess better financial capacity, access to information and higher tolerance for experimentation, enabling them to adopt bio-inoculants more readily. Income distribution followed a similar pattern, with 42.99 % of adopters belonging to the medium-income category, indicating that adoption is not restricted to high-income farmers but is more prevalent among economically stable households.

Adoption level across farmer categories and crops

The overall adoption level of bio-inoculants among the sampled farmers was 42.91 %, indicating a moderate level of diffusion across Tamil Nadu. Category-wise analysis (Table 2) shows that medium farm holders adopted the highest proportion of bio-inoculants (42.9 %), followed by large farmers (23.3 %). In contrast, women farmers accounted for only 15.41 % of adopters, reflecting gender-based constraints such as limited access to resources, extension services and decision-making power.

Crop-wise analysis reveals that millet growers exhibited the highest adoption, followed by paddy and hill banana farmers (Table 2). Millets, being traditionally low-input crops, are more compatible with eco-friendly practices such as bio-inoculant usage. In contrast, paddy and hill banana farmers adopted bio-inoculants primarily to improve soil microbial activity and reduce chemical residues, indicating that adoption is also influenced by crop-specific requirements.

Influence of innovation attributes on adoption behaviour

The structural model results (Table 7, Fig. 2) reveal that four innovation attributes significantly influenced adoption behaviour, while trialability showed no significant effect. These findings are interpreted within the framework of IDT.

Relative advantage

Relative advantage had a positive and significant effect on adoption ($\beta = 0.309$, $t = 3.745$, $p < 0.001$). This indicates that farmers adopted bio-inoculants when they perceived clear benefits over chemical inputs, such as improved soil health, yield stability and reduced input costs. This finding strongly supports diffusion theory, which identifies relative advantage as a key determinant of innovation adoption (12). Similar results have been reported in previous studies, where perceived economic and agronomic benefits significantly influenced farmers' adoption decisions (22, 23).

Complexity

Complexity emerged as the strongest determinant of adoption ($\beta = 0.598$, $t = 7.910$, $p < 0.001$). The positive relationship indicates that as perceived complexity decreases (i.e., ease of use increases), adoption increases significantly. This highlights the importance of simplifying technologies and providing user-friendly application methods. This finding is consistent with earlier studies, which emphasise that lower perceived complexity enhances adoption of agricultural technologies (13, 14).

Compatibility

Compatibility showed a significant negative relationship with adoption ($\beta = -0.150$, $t = 2.182$, $p = 0.029$), which contradicts the assumptions of classical diffusion theory (12). This unexpected finding may be explained by contextual factors in the study area. Farmers may perceive bio-inoculants not as a continuation of existing practices but as a shift away from chemical-intensive agriculture. In such cases, innovations that offer visible transformation and improvement may be preferred over those that merely align with existing systems. Similar context-specific deviations have been observed in earlier studies (23), suggesting that perceived transformational value may outweigh compatibility in influencing adoption behaviour.

Observability

Observability also showed a significant negative relationship with adoption ($\beta = -0.158$, $t = 2.725$, $p = 0.006$). While diffusion theory suggests that visible results enhance adoption (12), the findings of this study indicate that bio-inoculant benefits are not immediately observable, as they primarily improve soil health over time. Consequently, farmers may rely more on social learning mechanisms such as peer networks, farmer groups and extension services rather than direct observation. This finding is supported by earlier studies which highlight the role of trust-based knowledge systems and collective learning in technology adoption (24, 25).

Trialability

Trialability did not significantly influence adoption ($\beta = 0.051$, $t = 0.743$, $p = 0.458$). This suggests that farmers may not require small-scale experimentation before adoption. Instead, they may rely on shared experiences and observed outcomes from other farmers. This finding is consistent with diffusion theory, which suggests that in later stages of adoption, trialability becomes less influential as farmers depend more on social proof and established practices (12).

Practical implications of structural model results

The structural model results provide important practical insights into farmers' adoption behaviour. The positive and significant influence of relative advantage indicates that farmers are more likely to adopt bio-inoculants when clear economic and agronomic benefits are evident. This suggests that extension strategies should focus on demonstrating tangible benefits such as cost reduction and yield stability.

The strong influence of complexity highlights that simplifying application procedures and providing clear technical guidance can significantly improve adoption. This underscores the need for user-friendly technologies and effective training programmes.

The negative relationship observed for compatibility suggests that farmers may perceive bio-inoculants as a shift from conventional practices rather than a complementary input. This implies that awareness campaigns should emphasise both the benefits and practical integration of bio-inoculants into existing farming systems.

Similarly, the negative influence of observability indicates that the benefits of bio-inoculants are not immediately visible, which may reduce farmer confidence. This highlights the importance of demonstration plots, farmer field schools and peer learning to showcase long-term benefits.

The non-significant effect of trialability suggests that farmers rely more on shared experiences and social learning rather than

individual experimentation, indicating the importance of farmer networks and extension services in promoting adoption.

Explanation of unexpected relationships

The negative relationships observed for compatibility and observability with adoption behaviour represent a deviation from the classical assumptions of IDT, which posits that higher compatibility and observability generally promote adoption (12). However, such contrasting results have been reported in context-specific studies where the perceived nature of innovation differs from conventional expectations (23, 24). In the present study, farmers may perceive bio-inoculants as a transformative shift rather than a compatible extension of existing chemical-based practices. This perception may reduce the influence of compatibility, as farmers are more motivated by the potential for visible improvement rather than alignment with current practices. Similarly, the negative effect of observability may be attributed to the delayed and less visible outcomes associated with bio-inoculants, as their benefits are often realized over time through improved soil health rather than immediate crop response. In such contexts, farmers tend to rely more on experiential knowledge, peer networks and extension services rather than direct observation. These findings highlight the importance of contextual and behavioural factors in shaping adoption decisions and suggest that the influence of innovation attributes may vary across different agricultural settings.

Constraints hindering the adoption of bio-inoculants among farmers

Lack of knowledge and confidence

The finding that 100 % of respondents reported a lack of knowledge and confidence as a barrier highlights the critical role of awareness in adoption behaviour. Farmers are underinformed about the benefits, application techniques and effectiveness of bio-inoculants, which leads to hesitation and reluctance in adoption. This finding is consistent with earlier studies, which emphasise that inadequate knowledge significantly affects the adoption of sustainable agricultural technologies (25). Addressing this constraint requires targeted training programmes, demonstration activities and effective extension services to improve farmers' understanding and confidence.

Lack of visibility of change due to adoption

The lack of visible results, reported by 83.33 % of respondents, indicates that farmers expect immediate outcomes from agricultural inputs. However, bio-inoculants primarily improve soil health and microbial activity over time, which may not produce instant visible effects. This delayed response can reduce farmer confidence and discourage adoption. Similar findings have been reported in previous studies, which highlight that delayed or unclear results can act as a major barrier in adopting eco-friendly technologies (26). Demonstration plots and field-level evidence can help farmers observe the long-term benefits more clearly.

Unassured quality of bio-inoculants

The concern regarding unassured quality, expressed by 75 % of respondents, reflects farmers' lack of trust in the consistency and effectiveness of bio-inoculant products. Variations in product quality can lead to inconsistent results, further discouraging adoption. This finding is in line with earlier studies, which stress the importance of quality assurance in promoting agricultural innovations (25). Establishing standardised production processes, certification systems and proper labelling can enhance farmer trust and improve

adoption rates.

High cost of bio-inoculants

The high cost of bio-inoculants, reported by 66.67 % of respondents, indicates that financial constraints continue to influence farmers' decision-making, especially among small and marginal farmers. Although bio-inoculants are environmentally beneficial, their perceived cost may limit adoption. This finding is consistent with previous studies, which identify cost as a major barrier to the adoption of sustainable agricultural practices (26). Financial support mechanisms such as subsidies, credit facilities and group-based purchasing systems can help overcome this constraint.

Non-availability of bio-inoculants in time

The issue of non-availability, reported by 58.33 % of respondents, highlights the importance of timely access to agricultural inputs. Delays in availability can disrupt farming operations and discourage adoption. This finding is supported by earlier studies, which emphasise that efficient supply chains and distribution networks are essential for promoting agricultural technologies. Strengthening local distribution systems and improving logistics can ensure timely availability of bio-inoculants.

Policy implications

The findings of this study have important policy implications for promoting bio-inoculant adoption. Strengthening agricultural extension services is essential to improve farmers' awareness and technical knowledge. Training programmes, farmer field schools and demonstration plots can help reduce perceived complexity and enhance confidence in using bio-inoculants.

Furthermore, improving the availability and quality of bio-inoculants is crucial to build trust among farmers. Ensuring timely supply, standardisation and certification of bio-inoculant products can encourage wider adoption. In addition, promoting farmer networks and peer learning platforms can enhance knowledge sharing and support collective adoption of sustainable agricultural practices.

Conclusion

This research emphasises the importance of bio-inoculants in supporting sustainable agriculture in India. The findings reveal that innovation attributes, particularly relative advantage, significantly influence the adoption behaviour of farmers, while compatibility showed a negative relationship, indicating that farmers may perceive bio-inoculants as a shift from conventional practices rather than a complementary input. The study further highlights that 41.9 % of the farmers adopted bio-inoculants in Tamil Nadu, indicating a moderate level of diffusion with considerable benefits derived from their use.

These findings directly address the objectives of the study by empirically examining the influence of innovation attributes on adoption behaviour. The study makes a novel contribution by applying a theory-driven approach using IDT and PLS-SEM to analyse adoption behaviour across diverse agro-climatic zones, which has been limited in earlier research that largely focused on descriptive analysis.

Despite their well-documented advantages in improving soil health and crop yield, the use of bio-inoculants among Indian

farmers remains limited due to several constraints, including lack of knowledge and awareness, inconsistent product quality and inadequate support from agricultural extension services.

To address these limitations, focused educational initiatives must be implemented to enhance awareness and provide practical knowledge on the effective use of bio-inoculants. Strengthening extension services, improving product quality through standardisation and ensuring timely availability are essential to build farmer confidence and promote adoption. Addressing these challenges can significantly enhance the adoption of bio-inoculants and contribute to sustainable agricultural development by improving environmental health, economic viability and social well-being of farming communities.

Limitations and future research directions

Despite its contributions, the study has certain limitations. The use of non-probability sampling techniques may limit the generalisability of the findings and the study is cross-sectional in nature. Additionally, the analysis focuses on selected innovation attributes and does not include broader institutional or policy-related factors.

Future research may incorporate additional variables such as institutional support, market access and policy incentives to provide a more comprehensive understanding of adoption behaviour. Comparative studies across regions and longitudinal research can further strengthen the findings, while the use of probability sampling techniques and qualitative approaches may improve generalisability and provide deeper insights into farmers' decision-making processes.

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Authors' contributions

VPB contributed to the conceptualisation of the research work, development of methodology, field investigation, data collection, formal analysis, interpretation of results and preparation of the original manuscript draft. MH contributed to statistical analysis, economic interpretation of the findings, validation of results and critical review of the manuscript. LSM provided technical guidance related to agricultural entomology aspects, supported the literature review process and assisted in manuscript editing. KV contributed to research design, methodological refinement, supervision and critical review of the manuscript. JK was involved in data curation, field coordination, documentation and formatting of the manuscript. MSR contributed to economic analysis, validation of findings and review of the results and discussion sections. NS contributed to overall supervision, conceptual guidance, manuscript review, editing and final approval of the manuscript prior to submission. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

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Ethical issues: None

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