UNDERSTANDING THE SUPPLY CHAIN FOR BIO-PESTICIDES IN PUNJAB'S RICE-WHEAT CROPPING SYSTEM: THE ROLE OF DEALER ATTITUDES AND MARKET DYNAMICS

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ABSTRACT

The Rice-Wheat Cropping System (RWCS) of Punjab, Pakistan, is the cornerstone of the nation's food security but faces severe sustainability challenges due to over-reliance on chemical pesticides. While bio-pesticides offer an environmentally sustainable alternative for Integrated Pest Management (IPM), their adoption remains limited. A critical, yet under-researched, barrier is the efficacy of the supply chain and the role of agro-dealers, who are the primary link between manufacturers and farmers. This study examines the supply chain of bio-pesticides in Punjab's rice-wheat cropping system, focusing on the influence of dealer attitudes and market dynamics on farmer adoption. A quantitative survey was conducted with 150 farmers and 100 dealers, employing structured questionnaires and Likert-scale items to measure awareness, adoption, perceptions, and supply chain factors. Findings reveal that farmers exhibited high awareness of environmental benefits (Mean = 4.45, SD = 0.50, Rank 1) and types of bio-pesticides (Mean = 4.20, SD = 0.62, Rank 2), while adoption was highest for seasonal usage frequency (Mean = 3.85, SD = 0.91, Rank 1) and lowest for participation in training programs (Mean = 2.88, SD = 1.12, Rank 5). Dealers perceived bio-pesticides as effective (Mean = 4.25, SD = 0.55) and profitable (Mean = 4.10, SD = 0.60). Market dynamics showed pricing competitiveness (Mean = 4.00, SD = 0.60) and supply chain efficiency (Mean = 3.95, SD = 0.58) as critical factors. Barriers such as high cost (Mean = 4.10, SD = 0.60) and low awareness of purchase channels (Mean = 3.95, SD = 0.65) were identified, alongside facilitators including affordable pricing and timely availability. Chi-square tests indicated age (X^2 = 6.42, p = 0.040) and education (X^2 = 7.85, p = 0.020) significantly influenced adoption. Pearson correlations showed positive associations between awareness, adoption, and supply chain facilitators (r = 0.54–0.68, p < 0.01). The study highlights the importance of developing integrated strategies to enhance awareness, dealer engagement, and supply chain efficiency, thereby promoting sustainable pest management.

Keywords: Bio-pesticides, Rice-Wheat System, Punjab, Dealer Attitudes, Market Dynamics, Adoption, Supply Chain, Awareness

1. INTRODUCTION

Rice-wheat layer cropping system is a is predominant in Punjab , vital for national food security, livelihoods and social-economic stability of agricultural communities (Government of Punjab, 2025). Nevertheless, the pest infestation has also become a limiting factor to the productivity of these crops and can impose considerable losses in yields and damages to the economy when uncontrolled (Chakraborty et al., 2023). Farmers mostly rely on chemicals to manage pests,although these artificial chemicals may help in controlling the population of these pests, there have been serious environmental, health and economic concerns caused by their careless use. The excessive use of chemical pesticides pollutes soil and water, contaminates food with pesticide residues, has negative effects on other living organisms, and causes the pests to become resistant to cultivated crops, diminishing the sustainability of the cropping system in the long run (Custom Market Insights, 2024).

In this regard, bio-pesticides have has emerged to be as an alternative. Bio-pesticides are based on extracts of plant material, microbes, or natural organisms that offer environmentally sustainable, targeted, and less toxic way to manage pests(Deshmukh and Kulkarni, 2023). They incorporation into rice-wheat systemcan help achieve the goal of sustainable Integrated Pest Management (IPM) However, the benefits of their use do not appear to be well exploited in Punjab, mainly due to a lack of awareness, accessibility and limited availability (Faldu et al., 2023). Their adoption

among farmers depends upon the supply chain efficiency and the attitude of the major intermediaries (dealers and agro-input retailers).

The bio-pesticides supply chain includes manufacturers, wholesalers, , and end-users.Dealers play a crucial role in ensuring timely availability and flow of information about such products, because are the intermediator between the manufacturers and the end-users (farmers)., They have a huge impact farmers' decisions about purchasing inputs. So, their views regarding the profitability of bio-pesticide products, their performance, market demand are important (Gohel et al., 2023). Theyhave connections and influence over farmers, so their interests in the chemical pesticides or bio-pesticides have impacts on farmers . Dealers that have positive attitudes towards bio-pesticides, help create their awareness among farmers, offer technical guidance and availability of such products that will trigger their usage.

Market forces are also crucial in making decisions regarding the bio-pesticide supply chain. Availability, cost of the product, and dealer involvement are influenced by pricing, price competition among the suppliers, rules, and demand elasticity. Soaring prices and unreliable supply chain system can lead to minimal or no incentives to dealers, which leads to a decrease in adoption among farmers (Kachroo et al., 2023). Moreover, the level of trust that farmers place in dealers and the credibility of Bio-pesticides is also influenced by the market structure; and this is one of the most important predictors as far as the adoption decisions in the rice-wheat system are concerned.

Given the multiple factors influencing the adoption of bio-pesticides, understanding both dealer attitudes and market dynamics is essential for designing interventions that strengthen the supply chain and improve accessibility. Enhancing the efficiency of bio-pesticide distribution not only supports sustainable pest management but also contributes to environmental conservation, less health risks associated with chemical pesticides, and overall better agricultural productivity.

The present study seeks to analyze the supply chain for bio-pesticides in Punjab's rice-wheat cropping system, with a specific focus on how dealer attitudes and market dynamics influence availability, accessibility, and adoption at the farmer level. By investigating these factors, the research aims to provide actionable insights for policymakers, extension agencies, and agro-industries to promote sustainable crop protection technologies and improve the adoption of bio-pesticides. The specific objectives of the study are: to examine the awareness and adoption patterns of bio-pesticides among farmers, to analyze the attitudes of dealers toward profitability and results of bio-pesticides and to identify key barriers and facilitators within the bio-pesticide supply chain.
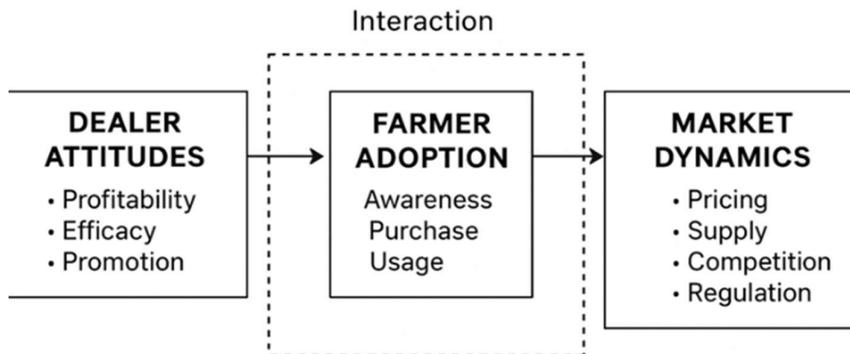

Fig. 1: Interaction among farmer adoption, dealer attitude and market dynamics (Self-computed).

2. MATERIALS AND METHODS

2.1. Research Design

This study employed a quantitative research design to examine the awareness and adoption patterns of bio-pesticides among rice-wheat farmers, the attitudes of dealers toward bio-pesticides, market dynamics, and key supply chain barriers and facilitators in Punjab. The quantitative approach enabled the collection of measurable data from a large sample and facilitated statistical analysis to identify trends, relationships, and significant factors affecting bio-pesticide utilization.

2.2. Study Population

The population of the study consisted of rice-wheat farmers and bio-pesticide dealers in Punjab. A stratified random sampling technique was used to ensure adequate representation across different districts, farm sizes, and dealer types. A total of 150 farmers and 100 dealers were selected as respondents, which was considered sufficient for generalizable quantitative analysis. Farmers were selected from districts with high rice-wheat cultivation, while dealers were chosen to represent both urban and rural distribution channels.

2.3. Data Collection

Data were collected using structured questionnaires administered separately to farmers and dealers. The farmers' questionnaire contained closed-ended items to measure awareness, adoption frequency, sources of information, and perceived barriers or facilitators to bio-pesticide use. Likert-scale items (1 = strongly disagree to 5 = strongly agree) were included to assess perceptions of efficacy and reliability. The dealers' questionnaire included items on attitudes toward bio-pesticides, perceived profitability, market potential, supply chain constraints, pricing, and regulatory influences. The instruments were pre-tested on a pilot sample of 20 farmers and 10 dealers to ensure clarity and reliability. Internal consistency of the Likert-scale items was evaluated using Cronbach's alpha (α), calculated as:

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{k} \sigma_i^2}{\sigma_T^2}\right)$$

Where K is the number of items, σ_i^2 is the variance of each item, and σ_T^2 is the variance of the total score. Items with $\alpha \geq 0.7$ were considered reliable. Data were collected through face-to-face interviews conducted by trained enumerators. Respondents were briefed on the study objectives and assured of confidentiality. Questionnaires were coded to maintain anonymity, and data collection spanned 6–8 weeks.

2.4. Data Analysis

The collected data were entered into SPSS Version 26 for analysis. Descriptive statistics such as frequencies, percentages, means ($\overline{X}$), and standard deviations (SD) were computed to summarize awareness, adoption patterns, and dealer attitudes. The mean and standard deviation were calculated as:

$$\overline{X} = \frac{\sum_{i=1}^{n} Xi}{n}, \ SD = \sqrt{\frac{\sum_{i=1}^{n} (Xi-\overline{X})^2}{n-1}}$$

Inferential statistics, including chi-square tests (X^2), was applied to examine relationships between demographic variables (e.g., age, education, farm size) and adoption of bio-pesticides.

$$X^2 = \sum \frac{(O-E)^2}{E}$$

Where:
O = observed frequency,
E = expected frequency.

Barriers, facilitators, and market dynamics were ranked based on mean scores to identify the most influential factors. Additionally, Pearson correlation coefficients (**r**) were calculated to assess the strength and direction of relationships between awareness, adoption, and supply chain factors using the formula:

$$r = \frac{\sum(X-\overline{X})(Y-\overline{Y})}{\sqrt{(X-\overline{X})^2 (Y-\overline{Y})^2}}$$

Ethical considerations were strictly followed, and informed consent was obtained from all respondents. Participants were assured of their right to withdraw at any stage, and all data were securely stored and used exclusively for research purposes. While this quantitative approach provided reliable and generalizable insights, it did not capture in-depth qualitative experiences, which is acknowledged as a limitation of the study.

3. RESULTS AND DISCUSSION

3.1. Demographic Characteristics

According to the findings in Table 1, the majority of farmers and dealers were male (94.7% and 95.0%, respectively). This reflects gender differentials in farming and agro-input enterprises in Punjab, where men are primarily responsible for farming and business functions, while women are largely in supportive positions rather than decision-making roles. Previous research has shown that men are the dominant gender in agricultural input supply chains (Fortune Business Insights, 2025; Kaur, 2024).

With respect to age distribution, the highest proportion 34.7% of the farmers belonged to the age group of 41-50 years, followed by 30% in the age group of 30-40 years, while 23.3% were above 50 years of age. In contrast, dealers were relatively young with 35% in the 30-40 year age category, and 28% in 41-50 year age group. These results suggest that the likelihood of older people with more experience being in farming is highest, and that younger people are more likely to be in agro-input businesses. According to Khimani et al. (2023), the younger population is more active in the marketing and distribution segment due to their preference for adopting innovative practices and business models. The educational level was also a significant factor in this study, with a difference between the farmers and the dealers. Of the farmers, 20% had no formal education, 23.3% had primary education and 30% had secondary education. Only one out of ten was university educated or above. On the other hand, dealers were relatively well-educated with 42% having at least a bachelor's degree, and 25% having an intermediate level of education. This difference implies the requirement for higher levels of education for dealers to run their businesses, execute financial transactions, and manage agricultural regulations as reported by Kumar et al. (2021). Past research has clearly

demonstrated that education is a key factor that affects the awareness of sustainable agricultural practices and adoption of new technologies (Kumar & Kumar, 2021).

Table 1: Demographic Characteristics of Farmers and Dealers (n = 250)

Characteristics	Categories	Farmers (n = 150)	%	Dealers (n = 100)	%
Gender	Male	142	94.7	95	95.0
	Female	8	5.3	5	5.0
Age (Years)	< 30	18	12.0	20	20.0
	30 – 40	45	30.0	35	35.0
	41 – 50	52	34.7	28	28.0
	> 50	35	23.3	17	17.0
Education Level	No formal education	30	20.0	5	5.0
	Primary (Grade 1–5)	35	23.3	8	8.0
	Secondary (Grade 6–10)	45	30.0	20	20.0
	Intermediate (Grade 11–12)	25	16.7	25	25.0
	Bachelor's or higher	15	10.0	42	42.0
Farming Experience (Years)	< 10	25	16.7	–	–
	10 – 20	52	34.7	–	–
	21 – 30	48	32.0	–	–
	> 30	25	16.7	–	–
Business Experience (Years)	–	–	–	< 5	20
	–	–	–	5 – 10	35
	–	–	–	11 – 15	28
	–	–	–	> 15	17
Farm Size (Acres)	< 5	40	26.7	–	–
	5 – 10	55	36.7	–	–
	11 – 15	30	20.0	–	–
	> 15	25	16.6	–	–

Results also exhibited that 34.7% had 10-20 years, 32% had 21-30 years, 16.7% had <10 years and 16.7% had >30 years of experience respectively. The distribution shows most farmers to be well experienced, which is consistent with traditional rice-wheat farming in Punjab where farming expertise are passed down from generation to generation (Marrone, 2023). On the other hand, dealers' business experience ranged from 5 to 10 years (35%), with 28% of 11-15 years, 20% of less than 5 years and 17% of more than 15 years of experience. It reflects a relatively mature market with many entrants-a situation typical of emerging trends in the bio-pesticide supply chains noted by Mottaleb et al. (2023). In terms of farm size, the 36.7% of farmers (36.7%) have the 5-10 acre of farm, followed by 26.7% with less than 5 acres, 20% with 11-15 acres and 16.6% having more than 15 acres. This speaks the predominance of small and medium size farms in Punjab, which matches with the finding of Muduli et al. (2024) in which most agricultural households in the geography have small land-holdings. In general the demographic analysis revealed that farmers are older, less educated and have a high level of farming experience, while dealers are younger, more educated and are relatively new to the bio-pesticide business. Such demographic variations are important for bio-pesticide adoption and diffusion. For instance, more educated dealers can play a vital role in spreading awareness and educating the farmers about sustainable pest management practices (Ali et al. 2019). Similarly, the low participation of women is evidence of the necessity for special policies that will encourage measures that are gender inclusive in both agricultural and agro-input enterprises.

3.2. Farmers' Awareness of Bio-pesticides

4. The data indicate that farmers had the highest awareness of the environmental benefits of bio-pesticides (Mean = 4.45, SD = 0.50, Rank 1), suggesting strong recognition of their role in reducing environmental harm. Knowledge of different types of bio-pesticides was also relatively high (Mean = 4.20, SD = 0.62, Rank 2), showing familiarity with available options. Awareness of cost-effectiveness compared to chemical pesticides ranked third (Mean = 3.90, SD = 0.68), reflecting perceptions of bio-pesticides as economically viable alternatives. Moderate awareness was observed in knowledge of proper application methods (Mean = 3.85, SD = 0.70, Rank 4) and market availability (Mean = 3.80, SD = 0.72, Rank 5). Lower awareness levels were noted for bio-pesticide efficacy (Mean = 3.65, SD = 0.78, Rank 6), potential side effects on crops and soil (Mean = 3.55, SD = 0.81, Rank 7), and regulatory guidelines for use (Mean = 3.40, SD = 0.85, Rank 8). This highlight the knowledge gap among farmers about the method of utilization of bio-pesticides, that may hinder effective adoption. These findings align with previous research indicating that while farmers often recognize the environmental and economic benefits of bio-pesticides, gaps in technical knowledge and regulatory understanding can limit their widespread use (Muduli et al., 2024; Panda & Sharma, 2025). Addressing these gaps through farmer training and improved extension services can enhance bio-pesticide adoption

and sustainable crop management.

Table 2: Awareness of Bio-pesticides among Rice-Wheat Farmers in Punjab (n = 150)

Awareness Indicators	Mean	SD	Rank
Awareness of environmental benefits of bio-pesticides	4.45	0.50	I
Knowledge of different types of bio-pesticides	4.20	0.62	2
Awareness of cost-effectiveness compared to chemical pesticides	3.90	0.68	3
Knowledge of proper application methods	3.85	0.70	4
Knowledge of market availability	3.80	0.72	5
Awareness of bio-pesticide efficacy	3.65	0.78	6
Awareness of potential side effects on crops and soil	3.55	0.81	7
Knowledge of regulatory guidelines for bio-pesticide use	3.40	0.85	8

4.1. Farmers' Adoption Patterns of Bio-pesticides

The adoption of bio-pesticides among farmers is a critical factor in promoting sustainable agricultural practices and reducing reliance on chemical pesticides.in Punjab.

Table 3 findings reveal that frequency of use of bio-pesticides in the crop season ranked highest (Mean = 3.85, SD = 0.91), indicating that a majority of farmers regularly use bio-pesticides, although not uniformly across all farms. The area of farm under bio-pesticide application (Mean = 3.60, SD = 0.97) was ranked second, suggesting that while bio-pesticides are applied, coverage is often limited to specific plots or high-value crops. Timely application according to recommended practices (Mean = 3.42, SD = 1.02) ranked third, highlighting gaps in precise application timing, which can influence efficacy. The use of bio-pesticides as a replacement for chemical pesticides (Mean = 3.15, SD = 1.08) was moderate, reflecting partial substitution behavior among farmers. Lastly, participation in training or awareness programs (Mean = 2.88, SD = 1.12) ranked lowest, underscoring the need for enhanced capacity-building initiatives to improve adoption and correct usage of bio-pesticides. These results align with previous studies indicating that farmer adoption is influenced not only by awareness and knowledge but also by accessibility, perceived efficacy, and availability of training (Panda et al., 2022; Panda et al., 2023; Police et al., 2023).

Table 3: Adoption Patterns of Bio-Pesticides among Rice-Wheat Farmers (n = 150)

Adoption Indicator	Mean	SD	Rank
Frequency of using bio-pesticides in crop season	3.85	0.91	I
Area of farm under bio-pesticide application	3.60	0.97	2
Timely application of bio-pesticides as per recommendations	3.42	1.02	3
Use of bio-pesticides as a replacement for chemical pesticides	3.15	1.08	4
Participation in training or awareness programs on bio-pesticides	2.88	1.12	5

4.2. Dealers' Attitudes toward Bio-pesticides

The findings of Table 4 indicate that dealers perceive bio-pesticides as highly effective in controlling pests (Mean = 4.25, SD = 0.55, Rank 1) and recognize their profitability (Mean = 4.10, SD = 0.60, Rank 2), suggesting strong incentives to promote these products. Market potential was also rated positively (Mean = 3.90, SD = 0.65, Rank 3), indicating optimism regarding future demand. Dealers showed moderate willingness to recommend bio-pesticides to farmers (Mean = 3.80, SD = 0.70, Rank 4) and moderate confidence in the quality and safety of these products (Mean = 3.70, SD = 0.72, Rank 5), highlighting areas where additional training and quality assurance could strengthen their role in promotion. Overall, the data suggest that while dealers recognize the benefits and market opportunities of bio-pesticides, enhancing their technical knowledge and confidence can further improve adoption rates among farmers. These findings are consistent with previous research emphasizing the importance of dealer attitudes in facilitating sustainable agricultural practices and the adoption of eco-friendly inputs (Police et al., 2023; Panda & Sharma, 2025).

Table 4: Attitudes of Dealers toward Bio-Pesticides (n = 100)

Attitude Indicators	Mean	SD	Rank
Perception of bio-pesticide efficacy	4.25	0.55	I
Perception of profitability from bio-pesticides	4.10	0.60	2
Market potential for bio-pesticides	3.90	0.65	3
Willingness to recommend bio-pesticides to farmers	3.80	0.70	4
Confidence in quality and safety of bio-pesticides	3.70	0.72	5

4.3. Market Dynamics of Bio-pesticides

The results in Table 5 indicate that factor of efficiency of the supply chain and distribution was taken into account with the highest score (Mean = 3.95; SD = 0.58; Rank 1). This indicates that logistics is a suitable function to meet products availability. Cost competitiveness of bio-pesticides was also perceived positively (Mean = 4.00, SD = 0.60,

Rank 2), suggesting factors relating to cost are important determinants of adoption. The third and fourth highest rankings were again dependent on factors specific to farmers' needs (distribution: Mean = 3.75 SD = 0.68 Rank 4) and availability in a local market (Mean = 3.85 SD = 0.65 Rank 3). Lower average scores for competition with chemical pesticides (Mean = 3.50, SD = 0.70, Rank 5) and regulatory support and guidelines (Mean = 3.40, SD = 0.75, Rank 6) indicating potential challenges in the marketing of bio-pesticides related to competition in the market and regulatory oversight. These results suggest that improving supply chain efficiency, greater market availability, and better regulatory support could help in greater uptake of bio-pesticides by farmers. These findings complement the findings of earlier studies outlining the critical role of market factors and regulatory institutional framework in the adoption and distribution of green agricultural inputs (Sahu & Pathak, 2023; Tudi et al., 2021).

Table 5: Market Dynamics of Bio-Pesticides (n = 100)

Market Dynamics Indicators	Mean	SD	Rank
Ease of distribution and supply chain efficiency	3.95	0.58	1
Pricing competitiveness of bio-pesticides	4.00	0.60	2
Availability of bio-pesticides in local markets	3.85	0.65	3
Farmers' demand influencing market distribution	3.75	0.68	4
Level of competition with chemical pesticides	3.50	0.70	5
Regulatory support and guidelines for bio-pesticides	3.40	0.75	6

4.4. Barriers and Facilitators in the Bio-pesticide Supply Chain

According to Table 6, The findings reveal that affordability of bio-pesticides is both a critical barrier and facilitator (Mean = 4.10, SD = 0.60, Rank 1), indicating that pricing strongly affects farmers' decisions. Low awareness of purchase channels and knowledge of sources were also important, highlighting the role of information in improving access (Mean = 3.95, SD = 0.65, Rank 2). Timely availability, accessibility in local markets, and adequate dealer guidance emerged as additional key factors influencing both barriers and facilitators (Ranks 3–5), suggesting that logistical efficiency and support services are vital for adoption.

Lower-ranked barriers included regulatory restrictions and lack of variety/brands, whereas supportive regulatory policies and availability of multiple options were noted as facilitators (Ranks 7–8), indicating that policy frameworks and product diversity can further enhance utilization. These findings align with prior studies emphasizing that both structural and informational aspects of the supply chain determine the successful adoption of eco-friendly agricultural inputs (Panda & Sharma, 2025; Muduli et al., 2024).

Table 6: Key Barriers and Facilitators in the Bio-Pesticide Supply Chain among Rice-Wheat Farmers in Punjab (n = 150)

Barriers	Mean	SD	Rank	Facilitators	Mean	SD	Rank
High cost of bio-pesticides	4.10	0.60	1	Affordable pricing of bio-pesticides	4.10	0.60	1
Low awareness of purchase channels	3.95	0.65	2	Farmer knowledge of sources and purchase channels	3.95	0.65	2
Limited timely availability	3.85	0.70	3	Timely supply of bio-pesticides	3.85	0.70	3
Poor accessibility in local markets	3.75	0.72	4	Availability in local markets	3.75	0.72	4
Inadequate dealer guidance	3.65	0.75	5	Adequate dealer knowledge and guidance	3.65	0.75	5
Limited presence of distributors	3.55	0.78	6	Presence of supply chain intermediaries	3.55	0.78	6
Regulatory restrictions	3.40	0.80	7	Supportive regulatory policies	3.40	0.80	7
Lack of variety/brands	3.30	0.82	8	Availability of multiple brands/options	3.30	0.82	8

4.5. Inferential Analysis
4.5.1. Chi-square Test

Table 7 indicates that adoption was significantly associated with age (X^2 = 6.42, df = 2, p = 0.040) and level of education (X^2 = 7.85, df = 2, p = 0.020), this means that younger farmers and higher educated farmers were more likely to adopt bio-pesticides. In contrast, agricultural size (X^2 = 5.30, df = 2, p = 0.070) was not statistically significantly related, indicating that agricultural size was not an important determinant in adoption decision-making in this sample. These findings are consistent with the previous study that education and age level are the key determinants of the innovation adopting propensity of farmers, while farm size may not be a significant characteristic (Muduli et al., 2024; Faldu et al., 2023). These results can be used to target extension efforts to lower-educated or older farmers, to increase use of bio-pesticides.

Table 7: Chi-Square Test of Relationships between Demographic Variables and Adoption of Bio-Pesticides (n = 150)

Demographic Variable	Chi-Square (X^2)	Df	p-value	Significance
Age	6.42	2	0.040	Significant
Education	7.85	2	0.020	Significant
Farm size	5.30	2	0.070	Not Significant

Notes: df = degrees of freedom; p-value < 0.05 indicates a statistically significant relationship.

3.7.2. Pearson Correlation Coefficients

Understanding how farmer awareness and adoption behaviour interact with supply chain factors is of great importance for intervention development for stimulating the use of bio-pesticides (Kaur, 2024).

As shown in Table 8, awareness was positively and significantly correlated with adoption (r = 0.68, p < 0.01), indicating that higher awareness of bio-pesticides is associated with increased adoption among farmers. Awareness also showed a positive correlation with barriers and facilitators (r = 0.54, p < 0.01), suggesting that better-informed farmers perceive supply chain facilitators more clearly and are better able to overcome barriers. Similarly, adoption was positively correlated with barriers and facilitators (r = 0.61, p < 0.01), highlighting that efficient supply chains and reduced barriers are associated with greater adoption of bio-pesticides. These findings are consistent with previous studies emphasizing that knowledge and awareness significantly influence adoption behavior, and that addressing supply chain barriers while enhancing facilitators can further support farmers in adopting sustainable agricultural practices (Kaur, 2024; Vachhani & Panigrahy, 2023).

Table 8: Pearson Correlation Coefficients (r) between Awareness, Adoption, and Barriers & Facilitators in the Bio-Pesticide Supply Chain (n = 150)

Variables	Awareness	Adoption	Barriers & Facilitators
Awareness	1	0.68**	0.54**
Adoption	0.68**	1	0.61**
Barriers & Facilitators	0.54**	0.61**	1

Notes: r = Pearson correlation coefficient; Significance: p < 0.01 (two-tailed).

CONCLUSION

This paper provides a systematic bio-pesticide supply chain analysis based on rice-wheat cropping system in Punjab state in which the crucial roles of farmers and dealer attitude and market dynamics have been highlighted for influencing farmer adoption. Findings indicate that the environmental and economic benefits of bio-pesticides are well known to farmers but lack of technical know-how, regulatory awareness and training are a major constraint for full adoption. Dealer perceptions of efficacy, profitability and market potential were identified as key enabling factors and these have exposed the role of dealers as intermediaries for sustainable pest management. A number of other characteristics affect accessibility and utilization, including market factors such as price, supply availability, competition and regulatory policies, of which efficiency in the supply chain and low cost are the most significant. From the analyses it was concluded that demographic variables (particularly age and education) have a significant influence on adoption, whereas farm size had a smaller influence. The high positive correlation value amongst awareness, adoption and supply chain facilitators indicates the need for knowledge transfer and removal of barriers to bio-pesticide adoption. Overall, this study suggests that integrated strategies that promote bio-pesticide adoption are required to raise awareness of farmers about availability and method of use. Further, there is required to engaging dealers and other stakeholders in order to deal with market constraints, and supply chain facilitation.

DECLARATIONS

Conflicts of Interest: Authors have no conflicts of interest.

Data Availability: Data will be available from the corresponding author upon request.

Ethics Statement: This work involved human data. The work was approved by the Institute of Agricultural Extension, Education, and Rural Development, University of Agriculture, Faisalabad, Pakistan.

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