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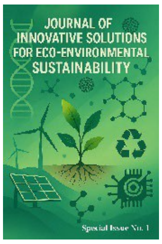

Research Article

Constraints to Effective Pesticide Utilization Among Vegetable Growers in Jaipur District: A Multivariate and Machine Learning Approach

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ARTICLE INFO

Keywords:
pesticide utilization,
vegetable farming,
multivariate analysis,
sustainable agriculture,
socio-economic factors

ABSTRACT

Pesticide misuse in vegetable farming poses significant environmental and health risks in Jaipur District, Rajasthan, driven by constraints such as limited knowledge, high costs, and inadequate administrative support. This study employed a multivariate and machine learning approach to investigate constraints among 120 vegetable growers, to identify and rank technological, economic, environmental, and administrative constraints to pesticide use; to examine their variation by socio-economic characteristics; and cluster farmers by constraint profiles. A structured questionnaire assessed 28 constraint items, analyzed using descriptive statistics, MANOVA, K-Means Clustering, and Exploratory Factor Analysis (EFA). Results revealed severe knowledge gaps and environmental concerns. Education significantly influenced economic constraints with Middle-level educated farmers reporting the highest barriers. Clustering identified three groups i.e., a small outlier group with low soil and market concerns, a moderate group focused on pest resistance, and a large group emphasizing administrative and health issues. EFA extracted five constraint dimensions, explaining 68.23% of variance. Findings underscore the need for targeted interventions, including enhanced extension services, subsidies for eco-friendly pesticides, and education on sustainable pest management, to promote safe pesticide practices and mitigate risks in Rajasthan's vegetable sector.

1. Introduction

Agriculture forms the backbone of rural livelihoods in Jaipur District, Rajasthan, where vegetable farming plays a pivotal role in ensuring food security and economic sustenance for thousands of households. The region's semi-arid climate and fertile soils make it ideal for crops like tomatoes, cauliflower, and brinjal, but intensive farming practices, particularly the heavy reliance on chemical pesticides, have introduced significant challenges. Pesticide misuse often driven by inadequate knowledge, high costs, environmental concerns, and administrative shortcomings poses risks to soil health, water quality, human and animal well-being, and long-term agricultural productivity. In Rajasthan, these issues are compounded by structural constraints, including limited access to extension services, financial barriers for smallholder farmers, and insufficient infrastructure in rural areas [1]. Addressing these constraints is essential to fostering sustainable vegetable production that balances yield demands with ecological and health considerations.

Jaipur District, a major vegetable-producing hub in Rajasthan, exemplifies the complexities of pesticide utilization. Farmers frequently face barriers such as lack of technical knowledge about pest management, inability to afford quality pesticides, concerns about environmental degradation, and inadequate support from agricultural authorities. For instance, improper pesticide application can lead to pest resistance, as seen in vegetable crops like okra and cabbage, while runoff from chemical pesticides contributes to soil and water pollution [2]. These challenges not

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https://doi.org/10.46991/JISEES.2026.02.1.14145
Received 4 January 2026; Received in revised form 19 February 2026; Accepted 24 February 2026; Available online 4 March 2026

only threaten farm productivity but also exacerbate health risks for farmers and consumers exposed to pesticide residues. Moreover, socio-economic factors, such as education level and land holding size, likely influence how farmers perceive and navigate these barriers, yet little research has systematically explored these variations in Jaipur's context.

The rationale for this study stems from the urgent need to mitigate the environmental and health risks associated with pesticide misuse in Jaipur's vegetable farming sector. Despite the critical role of pesticides in protecting crops, their mismanagement undermines sustainable agriculture, a priority for Rajasthan given its environmental vulnerabilities and growing population. Previous studies in India have highlighted constraints like high input costs and lack of technical advice [3], but few have employed advanced analytical methods to dissect these barriers or group farmers based on their constraint profiles. By identifying and prioritizing these constraints, understanding their socio-economic drivers, and segmenting farmers into meaningful groups, this research aims to provide actionable insights for policymakers, extension agents, and agricultural stakeholders to promote safer and more effective pesticide practices.

This study pursues three specific objectives to address these gaps:

i. Identify and rank technological, economic, environmental, and administrative constraints to pesticide use among vegetable growers in Jaipur District, providing a clear hierarchy of barriers based on their perceived severity.
ii. Examine how constraints vary by socio-economic characteristics, such as education level and land holding, using multivariate analysis to uncover patterns and disparities across farmer groups.
iii. Cluster farmers by their constraint profiles using machine learning techniques, specifically K-Means Clustering, to identify distinct groups with similar barrier patterns, enabling targeted interventions.

To achieve these objectives, the study employs a robust methodological framework combining multivariate statistical techniques and machine learning. Multivariate analysis, including MANOVA, allows for the examination of constraint variations across socio-economic groups, while K-Means Clustering and Exploratory Factor Analysis (EFA) uncover farmer clusters and underlying constraint dimensions. This dual approach offers a comprehensive understanding of the barriers to effective pesticide utilization, moving beyond descriptive analyses to provide predictive and prescriptive insights. For example, clustering farmers based on their constraint profiles can reveal whether certain groups face predominantly economic barriers versus administrative ones, guiding tailored policy responses.

The significance of this study lies in its potential to inform sustainable agricultural practices in Jaipur, a region critical to Rajasthan's vegetable supply. By addressing knowledge gaps, economic pressures, environmental concerns, and administrative deficiencies, the findings can support the development of extension programs, subsidy schemes, and eco-friendly pest management strategies. Ultimately, this research seeks to empower vegetable growers to use pesticides more effectively, reducing environmental and health risks while enhancing farm productivity and resilience in Rajasthan's agricultural landscape.

1.1 Rationale

Pesticide misuse in vegetable farming contributes to environmental and health risks in Jaipur, a key agricultural region in Rajasthan. Constraints like lack of knowledge and high costs hinder effective pesticide use. This study uses multivariate and machine learning approaches to analyze these barriers, offering policy insights to promote sustainable practices.

2. Methodology

2.1 Research Design

This study employed a cross-sectional, quantitative research design to investigate constraints to effective pesticide utilization among vegetable growers in Jaipur District, Rajasthan. The design was structured to achieve three objectives: (1) identify and rank technological, economic, environmental, and administrative constraints to pesticide use; (2) examine how these constraints vary by socio-economic characteristics using multivariate analysis; and (3) cluster farmers by constraint profiles using machine learning techniques. A combination of descriptive, multivariate statistical, and machine learning methods was used to analyze data collected from a structured survey, ensuring a comprehensive exploration of barriers and their socio-economic dimensions.

2.2 Study Area

The research was conducted in Jaipur District, a major agricultural hub in Rajasthan known for its vegetable production, including crops like tomatoes, cauliflower, and okra. Jaipur's semi-arid climate and fertile soils support intensive farming; however, the region faces challenges such as limited extension services and environmental risks associated with pesticide misuse [4]. The district was selected due to its significance in Rajasthan's vegetable supply chain and the prevalence of pesticide-related issues among farmers.

2.2 Sampling and Participants

A purposive sampling technique was used to select 120 vegetable growers from two tehsils i.e., Bassi and Amber of Jaipur District. These tehsils were selected based on high vegetable cultivation area, using Revenue Department data. Four villages per tehsil, i.e., Achrol, Chonp, Kacherawala, Khurad from the Amber tehsil; and Deogaon, Kashipura, Khatepura, Moondli villages from Amber tehsil were randomly selected from Census 2011 data. Fifteen vegetable growers per village were randomly selected using Patwari lists. Participants were chosen based on their engagement in vegetable farming and regular use of pesticides, ensuring relevance to the study's objectives. The sample size was determined based on the feasibility of data collection and the need for sufficient statistical power for multivariate analyses, following guidelines for factor analysis and clustering [5]. For the present article, the sampled farmers with varying education levels (Illiterate to Above Graduate) and land holdings (Marginal to Large farmers), as shown in Table 2, were depicted to capture socio-economic diversity.

2.3 Data Collection

Data were collected using a structured questionnaire designed to assess constraints to pesticide utilization. The questionnaire comprised two main sections:

- Socio-Economic Characteristics: This section gathered information on education level (e.g., Illiterate, Primary, Graduate) and landholding size (e.g., Marginal: up to 1.00 ha, large: >10.00 ha), enabling analysis of constraint variations across groups.
- Constraint Items: This section included 28 items covering technological, economic, environmental, and administrative constraints, rated on a three-point scale: "Not so serious" (1), "Serious" (2), and "Most Serious" (3). Examples include "Lack of knowledge about botanical pesticides" (technological), "High cost of quality pesticides" (economic), "Pesticide deteriorates the quality of soil" (environmental), and "Lack of timely technical advice from Administration / stakeholders" (administrative). The items were adapted from

prior studies on agricultural constraints in India [6] and pre-tested for clarity and reliability with a pilot group of 20 farmers.

The questionnaire was administered through face-to-face interviews by trained enumerators fluent in Hindi and local dialects, ensuring accurate responses from farmers with varying literacy levels. The constraint items were grouped into four subscales (Technological, Economical, Environmental, and Administrative) for analysis, with subscale scores calculated as the sum of relevant item responses, as reflected in Table 2.

2.4 Data Analysis

Data were analyzed to address the study's objectives through a combination of descriptive, multivariate, and machine learning techniques. The analytical methods are detailed below.

2.4.1 Descriptive Statistics and Ranking

Frequencies, percentages, and mean scores were calculated for the 28 constraint items (Table 1) to identify and rank their severity. The mean scores were calculated by

$$\text{Mean} = \frac{\sum(\text{Score} \times \text{Frequency})}{\text{Total Respondents}}$$

where, scores were 1 ("Not so serious"), 2 ("Serious"), or 3 ("Most Serious"). Items with higher means (closer to 3) were ranked as more severe. Descriptive statistics (means and standard deviations) for constraint subscales were computed across socio-economic groups (Education Level and Land Holding), as shown in Table 2, to provide a baseline for further analyses.

2.4.2 Multivariate Analysis

MANOVA was conducted to examine how constraint subscales (Technological, Economical, Environmental, and Administrative) varied by Education Level, Land Holding, and their interaction (Table 3). The model was specified as:

$$Y = \beta_0 + \beta_1 \cdot \text{Education} + \beta_2 \cdot \text{Land} + \beta_3 \cdot (\text{Education} \times \text{Land}) + \epsilon$$

where:

- Y is the dependent variable i.e. Technological, Economical, Environmental, and Administrative constraints
- β_0 is the intercept,
- β_1, β_2, β_3 are coefficients for Education, Land, and their interaction respectively,
- ϵ is the error term.

Assumptions of homogeneity of covariance matrices (Box's M Test) and variances (Levene's Test) were tested. Pillai's Trace and Roy's Largest Root were used to assess multivariate effects, followed by univariate ANOVA for significant effects, with a significance level of $p < 0.05$.

2.4.3 Machine Learning and Factor Analysis

K-Means Clustering was used to group farmers into clusters based on their constraint profiles, using standardized z-scores of 11 constraint items and four subscale means (Table 4). The analysis tested 2–4 cluster solutions, with the three-cluster solution selected for its stability (convergence after five iterations) and interpretability. Variables were standardized to ensure comparability. Analysis of Variance (ANOVA) F-statistics and p-values assessed which items significantly differentiated clusters ($p < 0.05$).

Exploratory Factor Analysis (EFA) was performed on the 11 constraint items to identify underlying dimensions. Principal Component Analysis (PCA) with Varimax rotation was used, extracting factors with eigenvalues > 1. The Kaiser-Meyer-Olkin (KMO) measure (> 0.6) and Bartlett's Test of Sphericity ($p < 0.05$) verified data suitability. Reliability was assessed using Cronbach's Alpha for each factor.

2.5 Data Quality and Ethical Considerations

Data quality was ensured through pre-testing the questionnaire, training enumerators, and conducting data entry checks for accuracy. Missing data were minimal (none reported), and outliers were retained unless they significantly skewed results (e.g., Cluster 1's small size was noted for caution). Ethical considerations included obtaining informed consent, ensuring participant anonymity, and allowing voluntary participation. The study complied with ethical guidelines for social science research [7].

2.6 Limitations

The purposive sampling method may limit generalizability beyond Jaipur District, and the sample size (N=120), while adequate for multivariate analyses, could be expanded for greater robustness. The marginal KMO value (0.536) in EFA suggests cautious interpretation of factor results. These limitations were mitigated by rigorous statistical testing and triangulation of findings across methods.

3. Results and Discussion

3.1 Descriptive Statistics and Ranking

Table 1 presents the prevalence and ranking of constraints to pesticide use among 120 vegetable growers in Jaipur District, assessed on a three-point scale (1 = Not so serious, 2 = Serious, 3 = Most Serious). The mean scores highlight the severity of each constraint, with higher scores indicating greater perceived challenges. The most serious constraints, each with a mean score of 3.00, were the lack of knowledge about botanical pesticides and the lack of demonstration trials in villages by stakeholders (both 100% rated as "Most Serious"), followed closely by the non-returnability of unused pesticides and lack of market facilities in rural areas (both 96.7% "Most Serious," mean = 2.97). Pesticide-related environmental and health concerns were also prominent, with 95.0% rating pesticide deterioration of soil quality as "Most Serious" (mean = 2.95), 62.5% noting environmental pollution (mean = 2.63), and 49.2% citing health hazards to humans and animals (mean = 2.49). Knowledge gaps were significant, with 64.2% rating lack of knowledge about insects/pests and control measures as "Most Serious" (mean = 2.64), 50.8% for pesticide use knowledge (mean = 2.51), and 51.7% for adequate quantity and application methods (mean = 2.52). Infrastructure and resource constraints included lack of transport facilities in remote areas (83.3% "Most Serious," mean = 2.78) and unavailability of improved implements and spraying instruments (61.7% "Most Serious," mean = 2.62). Conversely, the least serious constraints were the unavailability of safety measure items like masks and caps (39.2% "Not so serious," mean = 1.61) and high wage rates of labor during pesticide spraying (36.7% "Not so serious," mean = 1.79), indicating that these were less pressing issues for the farmers surveyed.

The findings from Table 1 underscore critical barriers to safe and effective pesticide use among vegetable growers in Jaipur District, reflecting systemic challenges in knowledge dissemination, infrastructure, and resource access that align with broader agricultural issues in India [8]. The top-ranked constraints i.e., lack of knowledge about botanical pesticides and absence of demonstration trials (both mean = 3.00) highlight a significant gap in awareness and practical training, limiting farmers' ability to adopt safer, environmentally friendly alternatives like biopesticides, which are increasingly promoted for sustainable agriculture [9]. The high concern for environmental and health impacts, such as soil degradation (mean = 2.95) and pollution (mean = 2.63), corroborates prior studies noting the detrimental effects of pesticide overuse in Indian farming systems [10,11], while the health hazards (mean = 2.49) emphasize the urgent need for safety education, especially given the lack of technical advice (mean = 2.74) and monitoring (mean = 2.53). Infrastructure constraints, such as lack of transport facilities (mean = 2.78) and unavailability of improved spraying equipment (mean = 2.62), reflect rural India's broader resource scarcity, hindering efficient pesticide application [12]. Surprisingly, the lower ranking of safety measure item availability (mean = 1.61) suggests that access to protective gear is less of a barrier than awareness or training, contrasting with studies that often cite cost as a major issue [13]. These findings directly inform the study's objective to guide training programs, indicating a need for extension services to prioritize farmer education on biopesticides, environmental safety, and proper application techniques, alongside improving rural infrastructure and stakeholder engagement to mitigate these constraints effectively.

3.2 Multivariate Analysis of Pesticide Use Constraints Across Socio-Economic Groups Using MANOVA

Table 2 presents the descriptive statistics of constraint subscales, technological, economical, environmental, and administrative across socio-economic groups defined by education level and land holding among 120 vegetable growers in Jaipur District. For education level, illiterate farmers (n = 27) reported the highest mean technological constraints score (25.67, SD = 1.30) and the lowest economical constraints score (16.37, SD = 1.55), while middle school-educated farmers (n = 16) faced the highest economical constraints (17.94, SD = 1.53), and high school-educated farmers (n = 12) reported the highest environmental constraints (15.50, SD = 1.00, tied with middle school). Graduate farmers (n = 15) had the highest administrative constraints score (13.53, SD = 1.25, tied closely with above graduate). Across land holding categories, medium farmers (n = 11) reported the highest technological constraints (25.91, SD = 0.94) and environmental constraints (15.91, SD = 1.14), while large farmers (n = 23) faced the highest economical (17.30, SD = 1.40) and administrative constraints (13.65, SD = 1.07). Marginal farmers (n = 38) reported the lowest scores across most subscales, with technological constraints at 25.39 (SD = 1.42), economical at 16.61 (SD = 1.59), and administrative at 13.32 (SD = 1.25). Overall, the total sample (n = 120) showed mean scores of 25.57 (SD = 1.39) for technological, 16.83 (SD = 1.66) for economical, 15.38 (SD = 0.95) for environmental, and 13.48 (SD = 1.16) for administrative constraints, indicating varying degrees of challenges across the subscales.

The descriptive statistics in Table 2 reveal nuanced variations in pesticide use constraints across socio-economic groups in Jaipur District, highlighting the influence of education and land holding on farmers' perceived challenges, which aligns with prior research on socio-economic disparities in Indian agriculture [14]. Illiterate farmers' higher technological constraints (25.67) suggest a lack of access to modern tools or knowledge about pesticide application, consistent with studies noting knowledge gaps among less-educated farmers [15], while their lower economical constraints (16.37) may reflect limited awareness of cost-related issues or reliance on cheaper, less effective pesticides [16]. Middle school-educated farmers' high economical constraints (17.94) indicate financial barriers to adopting quality pesticides, possibly due to competing household expenses, a common issue in rural India [17]. Medium farmers' elevated technological (25.91) and environmental constraints (15.91) suggest that, despite larger land holdings, they face challenges in accessing advanced equipment and mitigating environmental impacts, potentially due to overreliance on pesticides in intensive farming [18]. Large farmers' higher economical (17.30) and administrative constraints (13.65) may stem from greater operational costs and perceived inefficiencies in government support, reflecting broader systemic issues in agricultural administration [19]. These findings support the study's objective to inform targeted training programs, suggesting that illiterate and medium farmers need technological support (e.g., access to spraying equipment), while large farmers may benefit from financial and administrative assistance, such as subsidies or improved extension services, to enhance safe pesticide use practices.

Table 3 summarizes the MANOVA results examining the effects of socio-economic factors (education level and land holding) on pesticide use constraints (technological, economical, environmental, and administrative) among 120 vegetable growers in Jaipur District. Box's M test for homogeneity of covariance matrices was marginally significant (Box's M = 187.383, F = 1.249, df1 = 100, df2 = 2480.355, p = 0.050), suggesting potential violations of this assumption. Levene's test for homogeneity of variances showed significant results for the full model on technological (F = 1.842, df1 = 29, df2 = 90, p = 0.015) and economical constraints (F = 1.596, df1 = 29, df2 = 90, p = 0.049), but not for environmental (F = 1.279, p = 0.190) or administrative constraints (F = 1.120, p = 0.334); however, when tested separately, Levene's test for education (e.g., technological: F = 0.693, p = 0.678) and land holding (e.g., technological: F = 1.711, p = 0.152) showed no significant violations across all subscales (p > 0.05). Multivariate tests indicated a marginally significant effect of education using Roy's Largest Root (F = 2.229, p = 0.039), but not with Pillai's Trace (F = 0.803, p = 0.753), while land holding (Roy's: F = 2.050, p = 0.094) and the education × land interaction (Roy's: F = 1.359, p = 0.172) were not significant. Univariate ANOVA for education revealed a significant effect on economical constraints (F = 2.978, df = 7, 112, p = 0.007), but not on technological (F = 0.314, p = 0.946), environmental (F = 0.327, p = 0.940), or administrative constraints (F = 0.462, p = 0.860); land holding showed no significant effects across all subscales (e.g., economical: F = 0.873, p = 0.483). The full model's between-subjects effects confirmed a marginally significant effect of education on economical constraints (F = 1.787, p = 0.099), with all other effects non-significant (p > 0.05).

The MANOVA results in Table 3 indicate that education level has a limited but notable influence on pesticide use constraints among vegetable growers in Jaipur District, particularly for economical constraints (p = 0.007 in ANOVA, p = 0.099 in the full model), aligning with prior research that highlights education's role in shaping financial decision-making in agriculture [20]. This finding suggests that farmers with varying education levels perceive different economic barriers, possibly due to differences in awareness of pesticide costs or access to financial resources, as seen in earlier analyses where middle school-educated farmers reported higher economical constraints (Table 2) [21]. The marginal significance of education in multivariate tests (Roy's Largest Root, p = 0.039) and the non-significant effects of land holding and the education × land interaction suggest that while education influences certain constraints, its overall impact across all subscales is modest, potentially due to the small sample size (n = 120) and violations of MANOVA assumptions, as indicated by the marginally significant Box's M test (p = 0.050) and significant Levene's tests for technological and economical constraints [22]. The lack of significant effects from land holding contrasts with expectations that larger farmers might face greater technological or environmental constraints due to intensive farming practices [23], possibly reflecting uniform access to resources in Jaipur District. These findings inform the study's objective to guide targeted interventions, suggesting that extension programs should focus on addressing economical constraints through financial literacy training for less-educated farmers, while future research should employ larger samples and robust statistical methods to better capture the nuanced effects of socio-economic factors on pesticide use constraints.

3.3 K-Means Clustering and EFA (Machine Learning and Multivariate)

Table 4 presents the cluster profiles of constraint patterns among 120 vegetable growers in Jaipur District, segmented into three clusters (Cluster 1: n = 4, Cluster 2: n = 54, Cluster 3: n = 62) based on technological, economical, environmental, and administrative constraints, along with specific constraint items, with overall means, F-statistics, and significance levels indicating differences across clusters. Administrative constraints showed significant differences across clusters ($F = 19.96$, $p < 0.001$), with Cluster 3 (mean = 2.80) reporting the highest challenges, followed by Cluster 1 (mean = 2.75) and Cluster 2 (mean = 2.57). Technological ($F = 2.00$, $p = 0.139$), economical ($F = 1.79$, $p = 0.172$), and environmental constraints ($F = 0.06$, $p = 0.942$) showed no significant differences, with overall means of 2.56, 2.39, and 2.57, respectively. Among specific items, significant differences were observed for pesticide deterioration of soil quality ($F = 10.72$, $p < 0.001$), with Cluster 1 showing a notably lower score (-2.06) compared to Cluster 3 (0.15); pesticide-related health hazards ($F = 6.87$, $p = 0.002$), with Cluster 3 (0.31) higher than Cluster 2 (-0.35); pesticide resistance in pests ($F = 66.01$, $p < 0.001$), with Cluster 2 (0.79) higher than Cluster 3 (-0.69); lack of monitoring and evaluation ($F = 51.24$, $p < 0.001$), with Cluster 3 (0.63) higher than Cluster 2 (-0.75); and lack of agriculture supervisors ($F = 13.79$, $p < 0.001$), with Cluster 1 (0.79) higher than Cluster 2 (-0.47). Other items, such as environmental pollution ($F = 1.55$, $p = 0.216$) and lack of timely technical advice ($F = 2.66$, $p = 0.074$), showed no significant differences, while data for "lack of market facility in rural areas" was incomplete, lacking F-statistic and significance values.

The cluster analysis in Table 4 reveals distinct patterns of pesticide use constraints among vegetable growers in Jaipur District, with significant differences primarily in administrative constraints and specific items, providing insights into tailored intervention strategies consistent with the study's objectives [24]. The significant variation in administrative constraints ($p < 0.001$), with Cluster 3 reporting the highest challenges, suggests that this group, comprising the largest number of farmers (n = 62), faces substantial barriers in accessing timely support from stakeholders, as evidenced by their higher scores on lack of monitoring (0.63) and agriculture supervisors (0.36), potentially due to inefficiencies in extension services in rural Rajasthan [25]. Cluster 1's lower score on soil quality deterioration (-2.06) indicates a unique perception, possibly reflecting limited pesticide use or awareness of soil impacts, while Cluster 3's higher health hazard score (0.31) aligns with prior research highlighting health risks from pesticide exposure in Indian farming communities (Mishra et al., 2018). The stark contrast in pesticide resistance perceptions (Cluster 2: 0.79 vs. Cluster 3: -0.69) suggests differing experiences with pest management, with Cluster 2 likely facing greater resistance issues, a common consequence of injudicious pesticide use [26]. The lack of significant differences in technological, economical, and environmental constraints across clusters indicates that these challenges are relatively uniform, possibly due to shared infrastructural limitations in the region [27]. These findings underscore the need for targeted training programs focusing on administrative support for Cluster 3, such as improving access to agriculture supervisors, and addressing health and resistance concerns through integrated pest management education for Clusters 2 and 3, enhancing overall pesticide safety in Jaipur District.

4. Summary and Conclusion

This study investigated constraints to effective pesticide utilization among 120 vegetable growers in Jaipur District, Rajasthan, employing a multivariate and machine learning approach to address three objectives: (1) identify and rank technological, economic, environmental, and administrative constraints to pesticide use; (2) examine how these constraints vary by socio-economic characteristics; and (3) cluster farmers based on their constraint profiles. The findings provide critical insights into the barriers faced by farmers and offer a foundation for promoting sustainable agricultural practices in a region where pesticide misuse poses significant environmental and health risks.

Table 1 revealed the severity of 28 constraint items, rated from "Not so serious" (1) to "Most Serious" (3). The most severe constraints, both with mean scores of 3.00, were "Lack of knowledge about botanical pesticides" and "Lack of demonstration trials by stakeholders," indicating profound gaps in awareness and extension services. Other high-ranking constraints included "Lack of information sources regarding newly launched pesticides" (mean = 2.71), "Pesticide deteriorates the quality of soil" (mean = 2.95), and "Lack of market facilities in rural areas" (mean = 2.97). These findings highlight knowledge deficits, environmental concerns, and economic and administrative barriers as critical impediments to effective pesticide use, consistent with challenges in Indian agriculture [28].

Multivariate analysis (MANOVA, Table 3) showed that constraint subscales varied significantly by education level for Economical Constraints ($F = 2.978$, $p = 0.007$), with Middle-level educated farmers reporting the highest mean (17.94) and those who can read and write the lowest (15.69). No significant variations were found for Technological, Environmental, or Administrative Constraints across education levels, nor for any subscale across land holdings ($p > 0.05$). Table 2's descriptive statistics confirmed moderate variability in Economical Constraints (SD = 1.66 overall), suggesting that education influences financial perceptions more than farm size. The marginally significant multivariate effect of education (Roy's Largest Root: $F = 2.229$, $p = 0.039$) underscores its role in shaping economic barriers, likely due to enhanced financial awareness among educated farmers [29].

K-Means Clustering (Table 4) grouped farmers into three clusters based on 11 constraint items and four subscale means, with convergence after five iterations. Cluster 1 (N=4) was a small outlier group with low scores for "Pesticide deteriorates the quality of soil" (z-score = -2.06) and "Lack of market facility in rural areas" (z-score = -5.36), but high Administrative Constraints (mean = 2.75). Cluster 2 (N=54) emphasized "Injudicious use of pesticides develops resistance" (z-score = 0.79) and moderate Economical Constraints (mean = 2.39). Cluster 3 (N=62), the largest, reported the highest Administrative Constraints (mean = 2.80) and concerns about "Pesticide creates health hazards" (z-score = 0.31). Significant ANOVA differences ($p < 0.05$) for Administrative Constraints ($F = 19.96$) and items like pest resistance ($F = 66.01$) highlighted administrative and pest management issues as key differentiators. Exploratory Factor Analysis (EFA) extracted five factors (explaining 68.23% of variance), including Administrative Constraints, Environmental and Health Concerns, and Soil and Market Issues, though a marginal KMO (0.536) and negative Cronbach's Alpha (-0.383) suggest cautious interpretation and the need for factor-specific reliability testing.

This study illuminates the multifaceted constraints to pesticide utilization among vegetable growers in Jaipur, revealing knowledge gaps, economic pressures, environmental concerns, and administrative deficiencies as critical barriers. The top-ranked constraints, such as lack of knowledge about botanical pesticides and demonstration trials, underscore the urgent need for enhanced extension services. The significant influence of education on economic constraints highlights the role of literacy in shaping financial decision-making, while the absence of land holding effects suggests that barriers are widespread across farm sizes. The three-cluster solution identifies distinct farmer groups, with Cluster 3's administrative and health concerns, Cluster 2's focus on pest resistance, and Cluster 1's unique profile (possibly high-resource farmers) guiding targeted interventions.

These findings align with the study's rationale of mitigating environmental and health risks from pesticide misuse, a pressing issue in Jaipur's vegetable farming sector. The high severity of environmental constraints (e.g., soil degradation, mean = 2.95) and health-related concerns in Cluster 3 emphasize the demand for eco-friendly pest management alternatives. Administrative barriers, prominent across clusters and EFA factors, suggest that strengthening governance is critical to improving pesticide practices.

4.1 Implications for Policy and Practice

The results advocate for tailored interventions: (1) training programs on botanical pesticides and sustainable pest management for less-educated farmers; (2) increased agricultural supervisors and monitoring for Cluster 3; (3) education on judicious pesticide use for Cluster 2 to combat pest resistance; and (4) subsidies for quality pesticides to alleviate economic constraints. Investigating Cluster 1's unique profile could uncover scalable solutions for market access.

4.2 Limitations and Future Directions

The small size of Cluster 1 (N=4) limits its generalizability, and the marginal KMO (0.536) warrants caution in EFA interpretation. Future research should include all 28 constraint items, conduct post-hoc tests for Economical Constraints, and explore longitudinal trends to assess intervention impacts. Expanding the sample size and using probability sampling could enhance representativeness.

4.3 Conclusions

In conclusion, this study provides a robust framework for understanding constraints to pesticide utilization in Jaipur, leveraging multivariate and machine learning methods to inform sustainable agriculture. By addressing these barriers through education, administrative reforms, and eco-friendly practices, stakeholders can reduce environmental and health risks, ensuring the resilience of Rajasthan's vegetable farming sector.

Author Contributions

Conceptualization and study design were carried out by Roshan Meena, K. C. Sharma, and M. K. Sharma. Data collection and field investigation were conducted by Roshan Meena with support from K. C. Sharma. Statistical analysis, multivariate analysis, and machine learning modeling were performed by M. K. Sharma. Interpretation of results and drafting of the manuscript were carried out jointly by Roshan Meena, Nitesh Singh, and M. K. Sharma. Nitesh Singh contributed to literature review, environmental sustainability interpretation, and manuscript refinement. All authors reviewed, edited, and approved the final manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to ethical considerations and confidentiality agreements with participating farmers, the raw survey data are not publicly available but can be shared in anonymized form for academic and research purposes.

Acknowledgment

The authors sincerely acknowledge the vegetable growers of Jaipur District, Rajasthan, for their cooperation and valuable time during data collection. The authors also thank the local agricultural extension officials and village-level functionaries for their logistical support and assistance during field surveys. Appreciation is extended to colleagues at Sri Karan Narendra Agriculture University, Jobner, and SGT University, Gurugram, for their academic guidance and constructive discussions that helped improve the quality of this research.

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Table 1: Prevalence and Ranking of Constraints to Pesticide Use

Factor	Not so serious	Serious	Most Serious	Mean Score
Lack of knowledge about insect/pests and their control measures	0 (0.0%)	43 (35.8%)	77 (64.2%)	2.64
Lack of knowledge about use of pesticides	0 (0.0%)	59 (49.2%)	61 (50.8%)	2.51
Lack of knowledge about adequate quantity and mode of pesticide application	0 (0.0%)	58 (48.3%)	62 (51.7%)	2.52
Lack of technical advice regarding pesticide use	0 (0.0%)	62 (51.7%)	58 (48.3%)	2.48
Improved implements and spraying instruments not available in rural areas	0 (0.0%)	46 (38.3%)	74 (61.7%)	2.62
Application of pesticide suitable for farmers with irrigation facilities	0 (0.0%)	62 (51.7%)	58 (48.3%)	2.48
Lack of knowledge about botanical pesticides	0 (0.0%)	0 (0.0%)	120 (100.0%)	3.00
Unavailability of safety measure items (mask, cap, etc.)	47 (39.2%)	73 (60.8%)	0 (0.0%)	1.61
Lack of information sources regarding newly launched pesticides	0 (0.0%)	35 (29.2%)	85 (70.8%)	2.71
Lack of demonstration trial in village by stakeholders (Govt./Private)	0 (0.0%)	0 (0.0%)	120 (100.0%)	3.00
Lack of money to purchase effective pesticides	22 (18.3%)	42 (35.0%)	56 (46.7%)	2.28
High cost of quality pesticides in the market	14 (11.7%)	25 (20.8%)	81 (67.5%)	2.56
High wage rate of labor during pesticide spray	44 (36.7%)	57 (47.5%)	19 (15.8%)	1.79
Non-availability of timely credit	15 (12.5%)	30 (25.0%)	75 (62.5%)	2.50
Spraying equipment are very costly	0 (0.0%)	51 (42.5%)	69 (57.5%)	2.58
Safety measure items (mask, cap, etc.) are very costly	18 (15.0%)	65 (54.2%)	37 (30.8%)	2.16
Unused pesticide are not returnable	0 (0.0%)	4 (3.3%)	116 (96.7%)	2.97
Pesticide deteriorates the quality of soil	0 (0.0%)	6 (5.0%)	114 (95.0%)	2.95
Pesticide leads to pollution in the environment	0 (0.0%)	45 (37.5%)	75 (62.5%)	2.63
Pesticide deteriorates the quality of produce	0 (0.0%)	54 (45.0%)	66 (55.0%)	2.55
Pesticide creates health hazards to human beings and animals	0 (0.0%)	61 (50.8%)	59 (49.2%)	2.49
Application of pesticide kills beneficial insects	20 (16.7%)	46 (38.3%)	54 (45.0%)	2.28
Injudicious use of pesticides develops resistance in pests of vegetables	0 (0.0%)	63 (52.5%)	57 (47.5%)	2.48
Lack of monitoring & evaluation work at the field level by higher authorities/stakeholders	0 (0.0%)	57 (47.5%)	63 (52.5%)	2.53
Lack of timely technical advice from the Administration/stakeholders	0 (0.0%)	31 (25.8%)	89 (74.2%)	2.74
Lack of market facilities in rural areas	0 (0.0%)	4 (3.3%)	116 (96.7%)	2.97
Lack of agriculture supervisors in the villages	12 (10.0%)	40 (33.3%)	68 (56.7%)	2.47
Lack of transport facilities in remote areas	7 (5.8%)	13 (10.8%)	100 (83.3%)	2.78

Table 2: Descriptive Statistics of Constraint Subscales by Socio-Economic Groups

Socio-Economic Factor	Category	N	Technological Constraints Score	Economical Constraints Score	Environmental Constraints Score	Administrative Constraints Score
			Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Education Level	Illiterate	27	25.67 (1.30)	16.37 (1.55)	15.26 (1.13)	13.37 (1.11)
	Can read only	10	25.40 (1.35)	17.20 (1.32)	15.20 (0.63)	13.00 (1.05)
	Can read and write	13	25.23 (1.17)	15.69 (1.55)	15.54 (0.78)	13.54 (0.97)
	Primary	19	25.37 (1.34)	16.63 (1.83)	15.26 (0.87)	13.58 (1.07)
	Middle	16	25.56 (1.46)	17.94 (1.53)	15.50 (0.97)	13.75 (1.53)
	High school	12	25.83 (2.04)	17.58 (1.00)	15.50 (1.00)	13.33 (0.98)
	Graduate	15	25.80 (1.37)	16.73 (1.62)	15.53 (1.06)	13.53 (1.25)
	Above Graduate	8	25.63 (1.41)	17.13 (1.96)	15.25 (1.04)	13.63 (1.41)
Land Holding	Marginal farmers	38	25.39 (1.42)	16.61 (1.59)	15.42 (0.92)	13.32 (1.25)
	Small farmers	26	25.50 (1.21)	16.88 (1.82)	15.27 (0.92)	13.46 (1.10)
	Semi-medium farmers	22	25.50 (1.71)	16.55 (1.95)	15.27 (0.88)	13.55 (1.14)
	Medium farmers	11	25.91 (0.94)	17.09 (1.45)	15.91 (1.14)	13.55 (1.29)
	Large farmers	23	25.83 (1.44)	17.30 (1.40)	15.26 (1.01)	13.65 (1.07)
Total		120	25.57 (1.39)	16.83 (1.66)	15.38 (0.95)	13.48 (1.16)

Table 3: MANOVA Results for Constraints by Socio-Economic Factors

Test	Details	Results
Box's M Test	Tests homogeneity of covariance matrices. **Design**: Intercept + Education + Land + Education x Land **Box's M**: 187.383, F = 1.249, df1 = 100, df2 = 2480.355, Sig. = 0.050	Marginally significant (p = 0.050).
Levene's Test (Full Model)	Tests homogeneity of variances. **Design**: Intercept + Education + Land + Education x Land **Technological Constraints Mean**: F = 1.842, df1 = 29, df2 = 90, Sig. = 0.015 **Economical Constraints Mean**: F = 1.596, df1 = 29, df2 = 90, Sig. = 0.049 **Environmental Constraints Mean**: F = 1.279, df1 = 29, df2 = 90, Sig. = 0.190 **Administrative Constraints Mean**: F = 1.120, df1 = 29, df2 = 90, Sig. = 0.334	Technological (p = 0.015) and Economical (p = 0.049) significant (p < 0.05); Environmental (p = 0.190) and Administrative (p = 0.334) not significant (p > 0.05).
Levene's Test (Education)	Tests homogeneity of variances across Education levels. **Technological Constraints Mean**: F = 0.693, df1 = 7, df2 = 112, Sig. = 0.678 **Economical Constraints Mean**: F = 0.793, df1 = 7, df2 = 112, Sig. = 0.595 **Environmental Constraints Mean**: mF = 1.221, df1 = 7, df2 = 112, Sig. = 0.297 **Administrative Constraints Mean**: mF = 0.790, df1 = 7, df2 = 112, Sig. = 0.597	All non-significant (p > 0.05).
Levene's Test (Land Holding)	Tests homogeneity of variances across Land Holding categories. **Technological Constraints Mean**: F = 1.711, df1 = 4, df2 = 115, Sig. = 0.152 **Economical Constraints Mean**: F = 1.431, df1 = 4, df2 = 115, Sig. = 0.228 **Environmental Constraints Mean**: F = 0.208, df1 = 4, df2 = 115, Sig. = 0.934 **Administrative Constraints Mean**: F = 0.271, df1 = 4, df2 = 115, Sig. = 0.896	All non-significant (p > 0.05).
Multivariate Tests (MANOVA)	Test the effects of Education, Land, and their interaction. **Education**: Pillai's Trace = 0.235, F = 0.803, Sig. = 0.753; Roy's Largest Root = 0.173, F = 2.229, Sig. = 0.039 **Land**: Pillai's Trace = 0.145, F = 0.843, Sig. = 0.636; Roy's Largest Root = 0.091, F = 2.050, Sig. = 0.094 **Education Land**: Pillai's Trace = 0.600, F = 0.882, Sig. = 0.738; Roy's Largest Root = 0.272, F = 1.359, Sig. = 0.172	Education: Marginally significant (Roy's, p = 0.039); Land: Not significant (p > skips > 0.05); Interaction: Not significant (p > 0.05).
ANOVA (Education)	Tests effect of Education on each dependent variable. **Technological Constraints Mean**: F = 0.314, df = 7, 112, Sig. = 0.946 **Economical Constraints Mean**: F = 2.978, df = 7, 112, Sig. = 0.007 **Environmental Constraints Mean**: F = 0.327, df = 7, 112, Sig. = 0.940 **Administrative Constraints Mean**: F = 0.462, df = 7, 112, Sig. = 0.860	Economical Constraints significant (p = 0.007); others non-significant (p > 0.05).
ANOVA (Land Holding)	Tests effect of Land Holding on each dependent variable. **Technological Constraints Mean**: F = 0.528, df = 4, 115, Sig. = 0.715 **Economical Constraints Mean**: F = 0.873, df = 4, 115, Sig. = 0.483 **Environmental Constraints Mean**: F = 1.091, df = 4, 115, Sig. = 0.364 **Administrative Constraints Mean**: F = 0.337, df = 4, 115, Sig. = 0.852	All non-significant (p > 0.05).
Tests of Between-Subjects Effects (Full Model)	Tests effects of Education, Land, and their interaction. **Education**: Technological (F = 0.164, p = 0.992), Economical (F = 1.787, p = 0.099), Environmental (F = 0.277, p = 0.961), Administrative (F = 1.210, p = 0.305) **Land**: Technological (F = 0.262, p = 0.901), Economical (F = 1.161, p = 0.334), Environmental (F = 1.063, p = 0.380), Administrative (F = 0.714, p = 0.584) **Education x Land**: Technological (F = 1.074, p = 0.390), Economical (F = 0.973, p = 0.497), Environmental (F = 0.744, p = 0.757), Administrative (F = 0.869, p = 0.615)	Economical Constraints (Education, p = 0.099) marginally significant; all others non-significant (p > 0.05).

Table 4: Cluster Profiles of Constraint Patterns

Constraint Item	Cluster 1 (N=4)	Cluster 2 (N=54)	Cluster 3 (N=62)	Overall Mean	F-Statistic	Sig.
Technological Constraints Mean	2.58	2.58	2.53	2.56	2.00	0.139
Economical Constraints Mean	2.22	2.39	2.43	2.39	1.79	0.172
Environmental Constraints Mean	2.58	2.56	2.57	2.57	0.06	0.942
Administrative Constraints Mean	2.75	2.57	2.80	2.66	19.96	0.000
Pesticide deteriorates the quality of soil	-2.06	-0.03	0.15	2.95	10.72	0.000
Pesticide leads to pollution in the environment	0.77	-0.10	0.04	2.63	1.55	0.216
Pesticide deteriorates the quality of produce	-0.10	-0.06	0.06	2.55	0.24	0.786
Pesticide creates health hazards to human beings and animals	0.02	-0.35	0.31	2.49	6.87	0.002
Application of pesticide kills the beneficial insects	0.29	-0.21	0.16	2.28	2.22	0.113
Injudicious use of pesticides develops resistance in pests of vegetables	0.05	0.79	-0.69	2.48	66.01	0.000
Lack of monitoring & evaluation work at field level by higher authorities/stakeholders	0.45	-0.75	0.63	2.53	51.24	0.000
Lack of timely technical advice from Administration/stakeholders	0.59	-0.21	0.15	2.74	2.66	0.074
Lack of market facility in rural areas	-5.36	0.18	0.18	2.97		
Lack of Agriculture supervisors in the villages	0.79	-0.47	0.36	2.47	13.79	0.000
Lack of transport facilities in remote areas	0.42	0.21	-0.21	2.78	3.00	0.054