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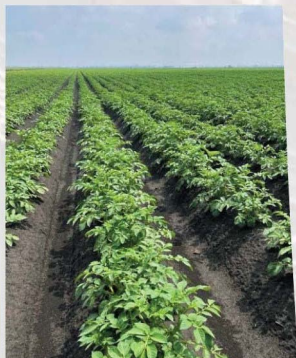
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DRIVERS OF CROP DIVERSIFICATION IN A SEMI-ARID REGION:  
EVIDENCE FROM VELLORE DISTRICT, SOUTH INDIA

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**Abstract:** Agricultural systems in the semi-arid tropics of India are increasingly susceptible to climate variability, posing significant challenges to productivity and rural livelihoods. This study examines the determinants of crop diversification in the Vellore district of Tamil Nadu, with a particular emphasis on climatic, socioeconomic, and institutional factors. The analysis integrates cross-sectional farm-level data with long-term climatic data spanning the period from 2001 to 2019. Crop diversification was quantified using the Herfindahl Index and Crop Diversification Index, and regression models were employed to identify key drivers of diversification and sustainability outcomes. The results indicate that climatic variables, such as rainfall and temperature, had a limited direct influence on diversification decisions. Conversely, institutional factors –particularly extension contact –emerged as more consistent drivers. Sustainability outcomes were significantly influenced by technology adoption, farm size, income stability, and climate perception. The findings suggest that diversification alone does not ensure resilience in semi-arid agricultural systems; rather, integrated institutional support and access to climate-smart technologies play a more critical role. This study contributes to the growing body of literature by demonstrating that crop diversification in semi-arid regions is shaped more by socioeconomic and institutional dynamics than by short-term climatic variability, offering important policy insights for similar agro-ecological contexts.

**Key words:** climate variability, crop diversification, sustainability, semi-arid tropics, technology adoption, agricultural resilience.

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## Introduction

The agricultural systems in the semi-arid tropics of India are critically endangered by climate change and variability. The increasing temperatures and altered precipitation patterns pose significant challenges to crop productivity in India, including the Vellore district in Tamil Nadu, where climate change has a profound impact on agriculture, particularly for smallholder farmers dependent on monsoon rainfall. Projections indicate that the yields of essential crops such as rice and maize may be adversely affected by an increase in annual maximum temperatures of up to 2.7°C and changes in rainfall patterns (Geethalakshmi et al., 2023). The agricultural resilience of the region is further compromised by irregular rainfall and adverse weather events, requiring the implementation of adaptive strategies to ensure food security (Baraj et al., 2024).

Vellore serves as a valuable site for understanding adaptive pathways, as it exemplifies many semi-arid tropical regions in South India. The challenges observed across semi-arid tropical regions are reflected in the district's conditions, including fragile soils, rain-fed agriculture, and small landholdings.

Since 2019, the Vellore district, now divided into Vellore, Tirupattur, and Ranipet, has experienced more frequent dry periods, rising temperatures, and variations in rainfall patterns. These changes threaten the sustainability of traditional monocropping systems, particularly those involving rice and groundnut cultivation. Rainfall variability affects the production of fruits and vegetables, with some regions experiencing growth while others face significant challenges (Karthick et al., 2024).

Recent climatic trends in the Vellore district indicate gradual changes in temperature and precipitation patterns, as well as an increasing frequency of extreme weather events. These events include recurrent droughts, delayed monsoon onset, short-duration high-intensity rainfall, and increased heat stress during critical crop growth periods. Such extreme events have significant implications for sowing decisions, crop yields, and risk management strategies among farmers in semi-arid regions. The growing variability and unpredictability of these events further complicate agricultural planning and underscore the necessity for adaptive strategies, such as crop diversification and technological adoption.

Crop diversification is increasingly recognised as a sustainable and risk-management strategy that can enhance farm incomes, reduce vulnerability, and protect ecological resources. The implementation of climate-resilient varieties, crop contingency plans, and precipitation harvesting is essential for mitigating adverse effects (Easwaran, 2023). This study uses a case-based approach to examine how smallholder farmers mitigate climate risks in this vulnerable agrarian environment through a combination of institutional access, diversification, and adaptation strategies. By positioning Vellore as representative of semi-arid tropical systems, a

more comprehensive understanding can be achieved without overextending empirical claims related to comparable agro-ecological zones worldwide and semi-arid tropical regions in South India.

Declining yields and increased risks for rain-fed agriculture have been linked to climate variability in the semi-arid tropics. This study investigates the key determinants of crop diversification in the Vellore district by integrating farm-level data with long-term climatic indicators. It specifically evaluates whether climatic variability or institutional and socioeconomic factors have a more significant impact on diversification decisions. Although crop diversification is widely promoted as a climate adaptation strategy, empirical evidence from semi-arid regions remains inconsistent (Primov et al., 2025). Some studies suggest that diversification may be more significantly influenced by socioeconomic and institutional determinants than by climatic variables. The necessity for localised solutions is underscored by the fact that various regions in Tamil Nadu require customised strategies to address specific climatic challenges (Varadan et al., 2017).

Research indicates that cultivation intensity and productivity are directly influenced by rainfall anomalies. Intra-seasonal rainfall variability is as crucial as total rainfall in South India, as it directly affects sowing decisions and crop survival, as highlighted by regional studies. The integration of climate data with farm-level variables in this approach provides a better understanding of the micro-macro dynamics involved in semi-arid tropic adaptation. The investigation avoids generalisation fallacies and facilitates more comprehensive inferences by establishing Vellore as a prototypical semi-arid tropic (SAT) district.

The Vellore district exemplifies a semi-arid tropic (SAT) region, distinguished by its unique climatic, agricultural, and socioeconomic characteristics. The district experiences low to moderate and highly variable rainfall, primarily influenced by the Southwest and Northeast monsoons, with frequent dry spells and delayed monsoon onset. This variability in rainfall, combined with relatively high temperatures, results in moisture stress conditions typical of SAT environments. Agriculturally, Vellore is characterised by smallholder farming systems that predominantly rely on rain-fed cultivation, particularly for crops such as groundnut, millets, and pulses, with paddy grown in irrigated areas. The prevalence of red loamy and black soils, limited irrigation coverage, and susceptibility to drought further reinforce its classification within the semi-arid tropics. From a socioeconomic perspective, farmers in the district face constraints such as limited access to irrigation infrastructure, credit, and market linkages, which are commonly observed across SAT regions. These conditions necessitate adaptive strategies such as crop diversification, technology adoption, and reliance on institutional support systems. Consequently, Vellore serves as a representative case for understanding agricultural adaptation and resilience in the semi-arid tropical regions of South India.

### Semi-arid tropics and smallholder vulnerability

Degraded natural resources, limited infrastructural support, pervasive rural poverty, and unreliable rainfall characterise the SAT of India, exacerbating agricultural risk exposure (Banerjee, 2015). Smallholder farmers, lacking irrigation and storage facilities, are disproportionately affected by the increasing frequency of extreme events such as droughts, unseasonal rainfall, and heat stress. Institutions such as the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) have been motivated to conduct case-based research in response to these challenges, highlighting the potential of sustainable intensification and conservation agriculture to enhance resilience (Kumara Charyulu et al., 2016; Jat et al., 2015b).

### Crop diversification and risk management

Crop diversification is widely recognised as an effective strategy for mitigating revenue volatility, market fluctuations, and production disruptions. National-level analyses affirm its role in enhancing system resilience, rural employment, and output growth (Gupta and Kannan, 2024; Hazra, 2001; Rahman and Mehnaz, 2024). It is acknowledged as a cost-effective and accessible approach to mitigating climatic risk, particularly for resource-limited producers in semi-arid regions. Diversification among pulses, millets, and horticultural commodities has been shown to improve both nutritional security and resilience in India. However, diversification is often impeded by a lack of institutional support, policies biased towards rice and wheat, and limited market access. Conversely, localised research, especially in semi-arid regions, highlights that institutional access frequently determines the success of adoption practices (Biswal and Bahinipati, 2025).

### Institutional drivers: extension, credit, and technology

The dissemination of climate information and the promotion of adaptive practices, such as water-saving irrigation and drought-tolerant varieties, are significantly influenced by access to extension services. Meta-analyses underscore the importance of institutional capacity and extension services in translating adaptive knowledge into practice, particularly in resource-constrained environments (Jodha et al., 2012; Nandi and Nedumaran, 2019; Rankoana, 2023). Investment in adaptation measures, such as mechanisation, agricultural insurance, and irrigation, is facilitated by access to credit, which alleviates liquidity constraints. The adoption of technology, particularly drought-tolerant crop varieties, integrated pest management, and precision farming tools, substantially enhances resilience in climate-vulnerable regions. Despite the emphasis on

institutional roles and diversification, there is a paucity of research integrating micro-level agricultural data with long-term climate trends in semi-arid tropic contexts.

#### Similar semi-arid tropic regions

In the literature on the semi-arid northern states, particularly Rajasthan and associated drylands, the primary focus is on water management, soil conservation, and policy-oriented resilience measures. These studies incorporate regional strategies and local case evidence relevant to semi-arid agriculture within the context of changing monsoon dynamics (Rathore, 2024). Practical adaptation mechanisms such as conservation agriculture, optimisation of sowing windows, deficit irrigation, and local farmer perceptions are emphasised in field experiments and vulnerability assessments conducted in Telangana, Andhra Pradesh, Tamil Nadu, and neighbouring semi-arid tropic zones. To propose site-specific interventions in the southern semi-arid tropic belt, these studies integrate crop modelling (AquaCrop, SIMDualKc), experimental trials (ICRISAT, farm plots), and household surveys (Anupaju and Kambhammettu, 2020a; Anupaju et al., 2020b; Banerjee, 2015; Barati et al., 2024; Jat et al., 2015a).

Through national and multi-state analyses, adaptation and mitigation frameworks pertinent to SAT agriculture in India are examined, drought and dryland susceptibility are mapped, and drought indices are compared across climatic zones (Garg et al., 2024; Jana, 2025; Saikanth et al., 2023; Surendran et al., 2019). Recent high-resolution drought datasets and index studies (2019–2025) provide spatially explicit evidence to prioritise regions and mandals for adaptation efforts (Jana, 2025; Surendran et al., 2019).

While these findings are rooted in the context of Vellore district, they are applicable to other semi-arid tropical regions characterised by small landholding farmers, limited irrigated agriculture, and climatic variability, including similar regions in South India and comparable agro-ecological zones globally. Consequently, the policy implications and adaptation strategies emerging from this study may provide useful insights for strengthening agricultural resilience in similar agro-ecological settings.

#### Theoretical background

The theoretical foundation of this study is based on the concepts of ecological economics, agricultural risk management, and the sustainable livelihoods framework.

Climate variability introduces production risk to agricultural systems. According to risk management theory, producers adopt strategies to mitigate

income fluctuations and yield variability. Crop diversification is an ex-ante risk mitigation strategy that enables producers to distribute climate and market risks across various crops (Hardaker et al., 2004).

Ecological economics highlights the interdependence of economic sustainability and ecological systems. Crop diversification correlates with agroecological principles by enhancing water use efficiency, soil fertility, and biodiversity (Altieri, 1995). This improves the adaptive capacity of semi-arid agricultural systems.

The Sustainable Livelihoods Framework (SLF), developed by the UK Department for Foreign, Commonwealth & Development Office (FCDO), argues that access to assets (natural, physical, financial, human, social) and vulnerability contexts influence livelihood outcomes. Scoones (1998) posits that crop diversification enhances resilience to shocks by stabilising incomes and decreasing dependence on climate-sensitive commodities (Scoones, 1998).

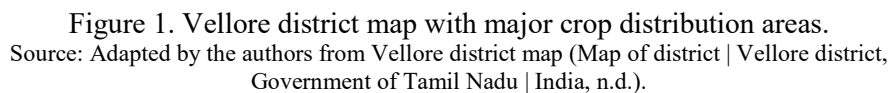
These theories collectively elucidate the rationale behind farmers' transition from monoculture to diversified cropping in response to economic pressures and climatic uncertainties.

## **Material and Methods**

### **Study area description**

Vellore district, as defined by its pre-2019 boundaries, is located in the semi-arid region of northern Tamil Nadu. The district is characterised by red loamy and black clayey soils, arid deciduous vegetation, and an agrarian economy reliant on the Southwest (SW) and Northeast (NE) monsoons. In certain areas of Vellore Taluk, black loam soil is predominant. The soil classification of the city also includes gravelly, stony, and sandy red soils. Vellore experiences a tropical savanna climate, according to the Köppen climate classification (Aw). These conditions make it representative of more extensive SAT challenges.

Vellore is a semi-arid region characterised by mixed soil types and monsoon-dependent agriculture. The map of the study area has been refined to include topographical features, principal agricultural zones, and the spatial representation of climatic data points used in the analysis. The map also highlights the major crop cultivation zones within the district. This enhancement facilitates a more comprehensive understanding of the agro-climatic conditions influencing agricultural practices within the district.



Climatic data on rainfall and temperature were obtained from the gridded datasets by the India Meteorological Department (IMD) for the period 2001 to 2019. This dataset is based on gridded observations from multiple meteorological stations throughout Tamil Nadu, ensuring both spatial consistency and reliability and did not utilise observations from individual meteorological stations directly. These gridded datasets provide spatially interpolated climatic estimates and are widely used in regional-scale climate analysis due to their spatial consistency and reliability.

The selection of grid points was based on the following criteria:

- (i) spatial overlap with the geographical boundaries of the Vellore district (pre-2019);

- (ii) representation of dominant agricultural land-use zones, particularly paddy, groundnut, and sugarcane cultivation areas;
- (iii) inclusion of both rainfed and irrigated regions to capture agro-climatic diversity, and
- (iv) continuity of data availability across the study period (2001–2019).

For each year, climatic values from the selected grid cells were aggregated using an area-weighted averaging approach, with weights assigned according to the proportion of each grid cell within the district boundary. This approach improves representativeness compared to simple arithmetic averaging by accounting for spatial heterogeneity.

This methodology ensures that the resulting variables accurately reflect the overall agro-climatic environment experienced by farmers across the district. The following variables were constructed for analysis: 1. total annual rainfall (mm), 2. southwest monsoon rainfall (June–September), 3. northeast monsoon rainfall (October–December), 4. mean annual maximum temperature (°C), and 5. mean annual minimum temperature (°C). In addition to mean values, inter-annual variability and trends in climatic variables were examined to better capture the variability and persistence of adverse weather conditions impacting agricultural systems. This aggregation method is widely used in district-level climate–agriculture research, particularly in situations where station-level data are either limited or unevenly distributed.

Table 1. Summary of climate variables (2001–2019).

| Variable                        | Mean  | Std Dev | Trend                      |
|---------------------------------|-------|---------|----------------------------|
| Southwest monsoon rainfall (mm) | 427.8 | 90.5    | Slight increase            |
| Northeast monsoon rainfall (mm) | 336.5 | 164.6   | High variability post-2015 |
| Total rainfall (mm)             | 890.2 | 227.7   | Fluctuating                |
| Maximum temperature (°C)        | 39.8  | 1.46    | Slight increase            |
| Minimum temperature (°C)        | 18.1  | 3.96    | Increasing variability     |

Source: Author's calculation using IMD data (2001–2019).

#### Measurement of crop diversification

Crop statistics for the period 2001–2019 were compiled using Tamil Nadu's Season and Crop Reports and the ICRISAT database, with additional production data provided by the Department of Economics and Statistics, Government of Tamil Nadu. The analysis focused on the primary commodities of the area, including paddy, sugarcane, groundnut, millets, and pulses.

Crop diversification was evaluated using the Herfindahl Index (HI) and the Crop Diversification Index (CDI), which quantify the degree of concentration and dispersion in cropping patterns.

The Herfindahl Index (HI) is calculated as follows:  $HI = \sum (P_i^2)$ ;

where  $P_i$  represents the proportion of area occupied by the  $i$ -th crop relative to the total cropped area. The HI values range from 0 to 1, with values approaching 1 indicating higher crop concentration (monocropping) and values nearing 0 signifying greater diversification.

The Crop Diversification Index (CDI) is derived as:  $CDI = 1 - HI$ .

The CDI also ranges from 0 to 1, with higher values reflecting greater diversification and lower values indicating crop concentration. These indices were calculated annually using crop area data for major crops in the district, including paddy, groundnut, sugarcane, millets, and pulses. These indices serve as the foundation for subsequent correlation and regression analyses aimed at investigating the determinants of crop diversification trends in the Vellore district.

#### Primary data

A structured primary dataset comprising 200 farmers was collected through field surveys conducted in selected villages within the Vellore district. A stratified sampling method was utilised to capture variations across different agro-climatic and socioeconomic conditions. Although agro-climatic conditions vary across the district, the use of aggregated district-level climatic indicators is justified given that farmers' decision-making is typically influenced by broader climatic trends rather than highly localised micro-variations. Furthermore, the sampling design incorporated multiple villages across different agro-climatic zones, thereby indirectly capturing spatial heterogeneity in farm-level responses. However, it is acknowledged that aggregation may mask micro-level climatic variations, which represents a limitation of the study. Future research may benefit from integrating higher-resolution climate data with location-specific farm observations. This dataset includes information on crop composition, irrigation methods, income levels, extension contact, climate perception, and access to credit.

#### Analytical framework

To investigate the relationship between climate variability and crop diversification, both trend and regression analyses were employed. Acknowledging that farmers' cropping decisions are shaped by accumulated climatic experience rather than immediate weather conditions, this study incorporates a temporal perspective in interpreting climatic influences. Climatic variables, such as rainfall and temperature, were analysed not only in terms of annual values but also in terms of their variability and persistence over time.

To explicitly account for climatic variability, additional variables were constructed, including the coefficient of variation (CV) for rainfall and

temperature, as well as short-term moving averages. These variables were incorporated into the regression analysis to capture the influence of variability beyond mean climatic conditions. The inclusion of variability measures did not significantly alter the results, reinforcing the limited role of climatic factors in influencing diversification decisions.

These measures capture inter-annual fluctuations and short-term persistence in climatic conditions, thereby reflecting variability patterns relevant to agricultural decision-making.

Although the statistical analysis employs annual data, the interpretation of results is grounded in the understanding that diversification decisions reflect adaptive responses to climatic patterns observed over preceding years, rather than immediate weather events. Multiple regression analysis was employed to identify the determinants of crop diversification, while sustainability outcomes were assessed using variables such as technology adoption, income variability, and farm characteristics.

A sample size of 200 farmers is considered adequate for conducting regression analysis and making statistical inferences. According to established econometric guidelines, a minimum of 10–15 observations per explanatory variable is recommended to ensure reliable parameter estimation (Hair et al., 2010). Given the number of independent variables included in the regression models, the sample size meets this requirement. Furthermore, similar farm-level studies in agricultural economics have employed comparable sample sizes to analyse diversification and adaptation behaviour in semi-arid regions, thereby affirming the robustness of the sample used in this study. Additionally, with a sample size of 200 observations, the study ensures sufficient statistical power and degrees of freedom for regression analysis, thereby reducing the risk of overfitting and enhancing the reliability of the estimated relationships.

## Results and Discussion

### Correlation analysis

The correlation matrix elucidates the relationship between climatic variables and crop diversification over an extended temporal framework. Farmers' decisions are influenced by cumulative climatic experiences rather than isolated annual conditions; thus, these correlations represent generalised associations rather than immediate causal linkages. The Crop Diversification Index (CDI) demonstrates a perfectly negative correlation with the Herfindahl Index ( $-1.00$ ), as anticipated. A moderate positive correlation is observed between CDI and minimum temperature ( $0.40$ ), while a weak negative correlation is found with total rainfall ( $-0.11$ ). Maximum temperature exhibits a negligible relationship ( $0.02$ ) (Figure 2).

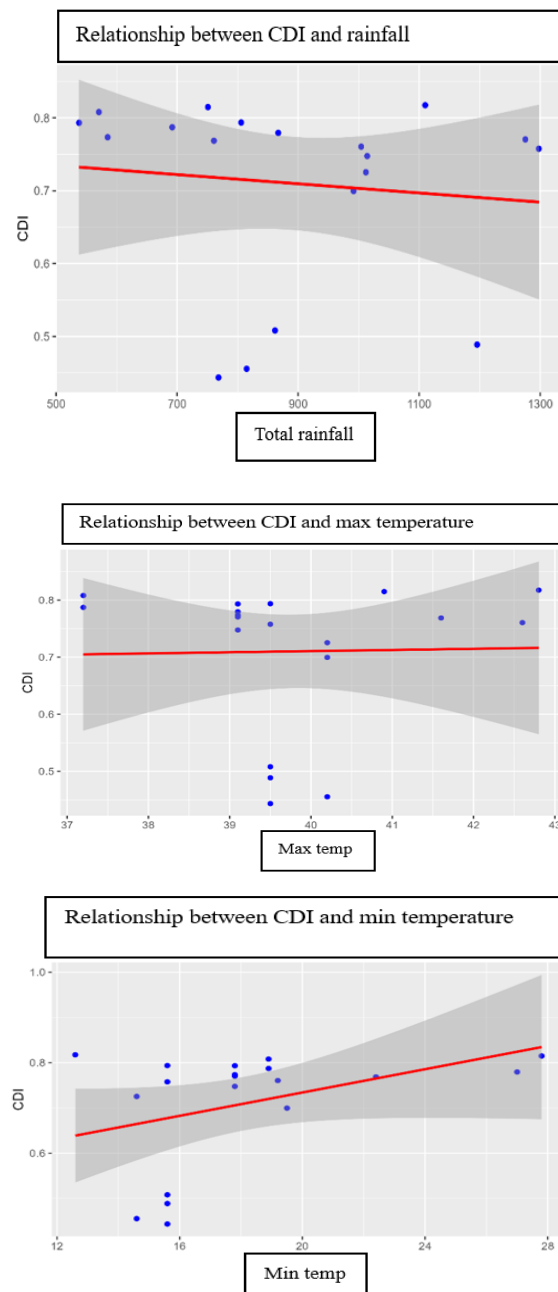


Figure 2. Relationship between CDI and rainfall, maximum and minimum temperature.

Source: Generated by the authors using EViews software based on secondary data.

These findings suggest that short-term climatic variations do not significantly influence diversification decisions. This aligns with existing studies in semi-arid regions, which indicate that farmers respond more strongly to long-term climatic risk patterns and institutional factors rather than to annual climatic fluctuations (Gupta and Kannan, 2024; Jodha et al., 2012).

In this study, short-term climatic variation refers to inter-annual fluctuations in climatic variables (rainfall and temperature) observed on a year-to-year basis, without accounting for longer-term trends or multi-year persistence. These variations capture immediate deviations from normal conditions but may not fully reflect the cumulative climatic experience that influences farmers' decision-making. In contrast, long-term climatic variability is interpreted as multi-year trends and persistent deviations, identified through moving averages and variability indices.

#### Regression analysis: CDI and climate variables

The regression analysis detailed in Table 2 substantiates the minimal influence of climatic variables on crop diversification. Both total rainfall and maximum temperature were statistically insignificant, indicating that annual variations alone did not directly impact farmers' decision-making processes. However, minimum temperature exhibited a positive but only marginally significant effect (coefficient = 0.0129,  $p = 0.09$ ). Given that the  $p$ -value surpassed the conventional 5% threshold, this finding should be interpreted with caution, as it likely signifies a weak or emerging trend rather than a robust causal relationship. Specifically, gradual increases in nighttime temperatures may influence cropping strategies over time.

Overall, these results suggest that climatic variables have limited explanatory power in isolation, supporting the argument that farmers' decisions are more influenced by cumulative experience and institutional contexts than by short-term conditions.

Table 2. Regression results for CDI and climate variables.

| Variable            | Coefficient | Std. Error | p-value |
|---------------------|-------------|------------|---------|
| Total Rainfall      | -0.000063   | 0.000137   | 0.650   |
| Maximum Temperature | 0.002014    | 0.021495   | 0.926   |
| Minimum Temperature | 0.012873    | 0.007261   | 0.094   |

Source: Author's calculation.

#### Determinants of diversification

The regression model incorporating socioeconomic and institutional variables (Table 3) explains only a limited portion of the variation in crop diversification.

Variables such as farm size, income, irrigation type, and climate perception were statistically insignificant, indicating that structural and climatic perceptions alone did not determine diversification behaviour. Extension contact was the only variable approaching statistical significance (coefficient = 0.0093,  $p = 0.055$ ), suggesting that farmers with greater access to extension services were more likely to adopt diversified cropping patterns.

The model's limited explanatory power (adjusted  $R^2 = -0.0139$ ) highlights that diversification decisions were shaped by complex and broader dynamics beyond observable farm-level characteristics. These findings align with previous studies that emphasise the significance of institutional support, market access, and policy incentives in influencing diversification strategies (Gupta and Kannan, 2024; Nandi and Nedumaran, 2019).

Table 3. Regression results for diversification determinants.

| Variable                    | Coefficient | Std. error | p-value |
|-----------------------------|-------------|------------|---------|
| Farm size (acres)           | -0.00794    | 0.01474    | 0.591   |
| Total annual income         | 1.84e-0.8   | 7.90e-07   | 0.981   |
| Irrigation type (canal)     | -0.00895    | 0.03711    | 0.810   |
| Irrigation type (mixed)     | 0.00812     | 0.04664    | 0.862   |
| Irrigation type (rainfed)   | -0.0208     | 0.03952    | 0.599   |
| Extension contact           | 0.00930     | 0.00481    | 0.055   |
| Climate perception (low)    | -0.00761    | 0.04175    | 0.855   |
| Climate perception (medium) | 0.00694     | 0.03347    | 0.836   |
| Access to credit            | 0.0408      | 0.02979    | 0.172   |

Source: Author's calculation.

### Determinants of sustainability

In contrast to crop diversification, sustainability outcomes are more systematically elucidated by the regression model (Table 4). Farm size exhibited a significant positive correlation with sustainability (coefficient = 0.0154,  $p < 0.01$ ), suggesting that larger landholdings facilitated the adoption of sustainable practices. Technology adoption emerged as the most influential determinant (coefficient = 0.00386,  $p < 0.001$ ), underscoring the critical role of modern inputs and climate-smart practices in enhancing resilience. Income variability demonstrated a strong negative effect (coefficient =  $-0.000268$ ,  $p < 0.001$ ). The model demonstrates strong explanatory power, with an adjusted  $R^2$  of 0.645, indicating that the selected variables accounted for nearly two-thirds of the variation in sustainability outcomes. This suggests that sustainability in semi-arid agricultural systems is systematically influenced by structural and institutional factors, particularly technology adoption and income stability, rather than by

random variation or unobserved factors alone. Climate perception also contributed, with moderate perception positively influencing sustainability ( $p < 0.05$ ). Notably, total income showed a negative relationship with sustainability, suggesting that higher-income farmers may prioritise market-oriented production over long-term ecological considerations.

The model demonstrated strong explanatory power (adjusted  $R^2 = 0.645$ ), indicating that sustainability was largely driven by structural and technological factors rather than climatic variability alone.

Table 4. Regression results for sustainability determinants.

| Variable                    | Coefficient | Std. error | p-value |
|-----------------------------|-------------|------------|---------|
| Farm size (acres)           | 0.0154      | 0.00516    | 0.003   |
| Total annual income         | -7.20e-07   | 2.77e-07   | 0.010   |
| Irrigation type (canal)     | 0.00495     | 0.01315    | 0.707   |
| Irrigation type (mixed)     | 0.00572     | 0.01637    | 0.727   |
| Irrigation type (rainfed)   | -0.00419    | 0.01394    | 0.764   |
| Extension contact           | -0.000729   | 0.00170    | 0.669   |
| Climate perception (low)    | 0.0320      | 0.01478    | 0.031   |
| Climate perception (medium) | 0.00875     | 0.01174    | 0.457   |
| Access to credit            | 0.00917     | 0.01051    | 0.384   |
| Diversification index       | -0.0342     | 0.02598    | 0.189   |
| Tech adoption (%)           | 0.00386     | 0.000228   | <0.001  |
| Income variability (%)      | -0.00268    | 0.000442   | <0.001  |

Source: Author's calculation.

The findings indicate a distinct divergence between the determinants of diversification and sustainability within semi-arid agricultural systems. While climatic and socioeconomic variables exerted a minimal influence on diversification, institutional factors - particularly extension contact - played a predominant role. This suggests that changes in cropping patterns were driven more by policy, market access, and knowledge dissemination than by direct environmental stimuli. In contrast, sustainability outcomes were primarily shaped by structural and technological factors, including farm size, technology adoption, and climate perception.

Notably, sustainability exhibited a negative relationship with higher total income. This implies that more affluent farmers may prioritise short-term profit through input-intensive or market-oriented monocropping – practices that often rely on chemical inputs and conflict with long-term ecological principles. This observation aligns with emerging evidence from semi-arid systems where higher-income farmers, often more integrated into commercialised production, prioritise immediate profitability over environmental considerations (Gupta and Kannan, 2024; Jodha et al., 2012). Ultimately, these results suggest that agricultural

resilience in regions such as Vellore depends less on diversification alone and more on a holistic combination of integrated institutional support, technological advancement, and income stabilisation mechanisms.

### Conclusion

This study examines the determinants of crop diversification in the Vellore district by integrating farm-level data with long-term climatic indicators from 2001 to 2019. The findings indicate that while climatic variability, particularly fluctuations in rainfall and temperature, affected overall agricultural conditions, its direct influence on crop diversification decisions was limited. Instead, diversification outcomes were more significantly shaped by institutional and socioeconomic factors, notably extension contact and access to resources.

Conversely, sustainability outcomes were substantially influenced by structural and technological factors, including technology adoption, farm size, income stability, and climate perception. These findings underscore a critical distinction: diversification alone does not ensure resilience. Instead, sustainability is enhanced when farmers are supported by robust institutional systems, stable incomes, and access to appropriate technologies.

From a policy perspective, the results suggest that strategies promoting diversification alone may not yield the anticipated resilience benefits in semi-arid agricultural systems. Instead, interventions should prioritise the following:

1. strengthening farmer-extension networks to improve awareness, knowledge dissemination, and adoption of adaptive agricultural practices;
2. promoting affordable and accessible climate-smart technologies to enhance productivity and resilience;
3. expanding financial support mechanisms, including crop insurance and minimum support price systems, to stabilise farm incomes and reduce risk exposure, and
4. encouraging cooperative approaches and collective action to enable small and medium farmers to adopt sustainable practices more effectively.

Overall, the findings indicate that achieving long-term resilience in semi-arid regions, such as Vellore, requires an integrated approach that encompasses institutional support, technological adoption, and income stabilisation measures, rather than relying solely on diversification. This study contributes to the broader understanding of agricultural adaptation by demonstrating that crop diversification is influenced more significantly by institutional and socioeconomic dynamics than by short-term climatic variability. Although the analysis is specific to Vellore, the insights are applicable to other semi-arid regions in South Asia and similar agro-ecological contexts, where enhancing institutional capacity and technological access can play a pivotal role in enhancing agricultural resilience.

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FAKTORI DIVERZIFIKACIJE USEVA U POLUSUŠNOM REGIONU:  
PRIMER OKRUGA VELOR, JUŽNA INDIJA

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R e z i m e

Poljoprivredni sistemi u polusušnim tropskim regionima Indije sve su podložniji klimatskoj varijabilnosti, što predstavlja značajne izazove za produktivnost i egzistenciju seoskog stanovništva. Ovo istraživanje ispituje faktore diverzifikacije useva u okrugu Velor u saveznoj državi Tamil Nadu, sa posebnim naglaskom na klimatske, socioekonomske i institucionalne faktore. Analiza kombinuje podatke prikupljene na nivou gazdinstava u jednom vremenskom trenutku sa dugoročnim klimatskim podacima za period od 2001. do 2019. godine. Diverzifikacija useva kvantifikovana je korišćenjem Herfindahlovog indeksa i indeksa diverzifikacije useva, dok su regresioni modeli primenjeni za identifikaciju ključnih faktora diverzifikacije i ishoda održivosti. Rezultati ukazuju na to da su klimatske varijable, poput padavina i temperature, imale ograničen direktan uticaj na odluke o diverzifikaciji. Nasuprot tome, institucionalni faktori – posebno kontakt sa savetodavnim službama – pokazali su se kao dosledniji pokretači. Na ishode održivosti značajno su uticali usvajanje tehnologije, veličina gazdinstva, stabilnost prihoda i percepcija klimatskih promena. Rezultati istraživanja sugerišu da diverzifikacija sama po sebi ne obezbeđuje održivost polusušnih poljoprivrednih sistema; naprotiv, integrisana institucionalna podrška i pristup klimatski pametnim tehnologijama imaju značajniju ulogu. Ova studija doprinosi sve brojnijim istraživanjima pokazujući da je diverzifikacija useva u polusušnim regionima više oblikovana socioekonomskom i institucionalnom dinamikom nego kratkoročnom klimatskom varijabilnošću, pružajući važne implikacije za javne politike u sličnim agroekološkim uslovima.

**Ključne reči:** klimatska varijabilnost, diverzifikacija useva, održivost, polusušni tropski regioni, usvajanje tehnologije, otpornost poljoprivrede.

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## A SYSTEMATIC REVIEW OF AFRICAN SWINE FEVER IN THE PHILIPPINES (2019–2025): SOCIO-ECONOMIC IMPACTS, STAKEHOLDER PRACTICES, AND MULTI-SECTORAL MANAGEMENT STRATEGIES

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**Abstract:** African swine fever (ASF) was first confirmed in the Philippines in September 2019, causing severe losses to the swine industry. This systematic review synthesised evidence on socio-economic impacts, biosecurity practices, and multi-sectoral management strategies from 2019 to 2025. Following PRISMA 2020 guidelines, four databases (Google Scholar, PubMed, Science Direct, and Web of Science) were searched, yielding 2,189 records. Eight studies met the eligibility criteria, and risk of bias was assessed using ROBINS-I, AXIS, and JBI tools. Industry losses totalled PHP 72–85 billion (2019–2022), with a 7.54-million-head decline in hog inventory. Smallholder incomes fell by 40–60%. Pre-ASF biosecurity compliance was critically deficient. A repopulation programme reached approximately 180,000 households with 28–35% income recovery, while multi-agency coordination showed significant implementation gaps. The included studies demonstrated moderate to high methodological quality, with a mean JBI-derived score of 7.7/10. The evidence indicates that ASF had severe and widespread impacts on the Philippine swine sector, disproportionately affecting smallholders. Effective future management requires One Health frameworks, enforceable biosecurity standards, equitable recovery programmes, and proactive surveillance infrastructure.

**Key words:** African swine fever, biosecurity, Philippines, socio-economic impact, stakeholder, systematic review.

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## Introduction

African swine fever (ASF) is a highly contagious haemorrhagic viral disease of domestic pigs and wild boar caused by the African swine fever virus (ASFV), the sole member of the family *Asfarviridae*. ASFV is a large, enveloped, double-stranded DNA virus that can persist in environmental matrices for extended periods. The disease is characterised by near-complete case fatality in naive populations infected with virulent strains, and no commercially licensed vaccine was available during the review period (2019–2025). Since the re-emergence of ASFV genotype II in Georgia in 2007, the pathogen has progressively spread across Eastern Europe and triggered a major epidemic across Asia that is estimated to have eliminated about half of China's domestic pig population within two years.

The Philippines confirmed its first ASF outbreak in the provinces of Rizal and Bulacan, Luzon, in September 2019. Despite the country's archipelagic geography, ASF spread from Luzon to the Visayas and Mindanao within three years. The Philippine swine industry is bimodal, comprising large commercial farms alongside nearly 2.6 million smallholder backyard raisers that together produce an estimated 60–70% of the national pork supply. This structure may have made the epidemic particularly destructive, as smallholdings are typically poorly equipped with biosecurity infrastructure and appear to have been disproportionately affected.

The DA-BAI, the Department of Agriculture's Bureau of Animal Industry, and the NTFAD, the National Task Force on Animal-borne Diseases, created in 2019, were at the core of the government response. The 2021 implementation of the National African Swine Fever Prevention and Control Program (NASFPCP) and the nationwide state of calamity declared through Proclamation No. 1143 (Duterte, 2021) further strengthened this response. Reported actions included the culling out of infected herds (stamping out), the establishment of quarantine and zoning areas, compensation arrangements, and a national pig repopulation programme. Despite the scale of the outbreak and the institutional response, no systematic review had yet synthesised the available evidence. The present review addresses this gap by integrating evidence across the socio-economic, biosecurity, and multi-sectoral management dimensions of the Philippine ASF experience.

This review has five objectives: (1) to synthesise evidence on the magnitude, distribution, and determinants of the socio-economic impacts of ASF across Philippine pig-industry stakeholders; (2) to document and critically evaluate stakeholder biosecurity practices, including pre-ASF baseline compliance and post-ASF protocol effectiveness; (3) to assess the design, implementation, reach, and equity of multi-sectoral management strategies, including surveillance, stamping-out, repopulation, and policy frameworks; (4) to appraise methodological quality using the ROBINS-I (*Risk of Bias in Non-Randomized Studies of Interventions*), *AXIS* (*Appraisal Tool for Cross-Sectional Studies*), and *JB* (*Joanna Briggs*

*Institute) tools*; and (5) to integrate the evidence into an exploratory account of economic impact and a conceptual multi-sectoral framework, while clearly distinguishing values reported in the primary studies from estimates derived by the authors for interpretive purposes.

## Material and Methods

### Protocol registration and eligibility criteria

The review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA 2020) guidelines (Page et al., 2021). The protocol was prospectively registered with the Open Science Framework prior to database searching. *The JBI Critical Appraisal Checklist was added to the original ROBINS-I and AXIS tools, and this was the only deviation from the prospectively registered protocol to strengthen quality assessment.* Eligibility criteria were developed using the PICOS framework. Regarding population, studies involving pig farmers, hog-industry stakeholders, consumers, policymakers, local government units (LGUs), and government agencies in the Philippines were included, while those not involving Philippine swine-industry stakeholders were excluded. For the intervention or phenomenon of interest, we included studies addressing socio-economic impacts, biosecurity practices, management strategies, policy responses, surveillance, and market impacts related to African swine fever (ASF) in the Philippines; purely virological or molecular studies without a socio-economic or management component were excluded. The comparison or scope required the Philippines (national or sub-national) or comparative studies that include the Philippines; studies from other countries without Philippines-specific data or analysis were excluded. Regarding the outcome or temporal scope, we included studies published from 2019 to 2025 (coinciding with ASF confirmation in Philippine territory) and excluded those published before 2019 or after March 2026 (the search cut-off). For study design, observational, cross-sectional, quasi-experimental, policy analyses, systematic reviews, and grey-literature reports were included. In contrast, editorials, letters without data, conference abstracts, and purely laboratory studies were excluded. Finally, regarding language, English and Filipino (Tagalog) articles with an English abstract were included; other languages without an available translation or English abstract were excluded.

### Information sources and search strategy

Systematic searches were conducted across four bibliographic databases in April 2026 (search window: 2019 – March 2026): Google Scholar (via Publish or

Perish v8.0), PubMed (via NCBI Advanced Search with MeSH terms), Science Direct (Open Access filter applied), and the Web of Science Core Collection. In Google Scholar, the search string was “African swine fever” AND “Philippines” AND “socio-economic”. In PubMed/MEDLINE, the search was (“African swine fever”[TIAB] OR ASFV[TIAB]) AND Philippines[TIAB] AND (“socio-economic” OR “economic impact” OR livelihood OR stakeholder OR biosecurity OR “management strategy”). In ScienceDirect, the search was “African swine fever” AND Philippines AND (“socio-economic” OR livelihood) AND (stakeholder OR “farmer practice” OR biosecurity) AND (“multi-sectoral” OR “management strategy”) with the Open Access filter applied. In Web of Science, the search was (“African swine fever” OR ASFV) AND Philippines AND (“socio-economic” OR “economic impact” OR livelihood OR stakeholder OR biosecurity OR “multi-sectoral” OR “management strategy”). These searches yielded 422, 418, 972, and 377 records respectively, totalling 2,189 records. Duplicate records across databases were identified and removed prior to screening.

#### Study selection and data extraction

All records were imported into a structured dataset. Titles and abstracts were screened against the PICOS criteria, and records that remained potentially eligible proceeded to full-text retrieval. Duplicate records were identified by matching record identifiers, DOIs, titles, and author names across the four database exports. A standardised extraction form captured study identifiers, geographic setting and period, design and population, sample size and recruitment, key variables and outcomes, principal findings, and quality-appraisal features. The extraction was performed and verified by three reviewers.

#### Quality assessment

Three complementary appraisal tools were applied. The Risk of Bias in Non-Randomised Studies of Interventions (ROBINS-I) tool (Sterne et al., 2016) was applied to observational, cross-sectional, quasi-experimental, and policy-evaluation studies across seven bias domains. The Appraisal Tool for Cross-Sectional Studies (AXIS; Downes et al., 2016) was applied to cross-sectional and survey designs. The Joanna Briggs Institute Critical Appraisal Checklist (Moola et al., 2020) was applied to all included studies as a unifying framework covering eight criteria, with overall ratings assigned as excellent ( $\geq 8/8$ ), good ( $\geq 6/8$ ), fair ( $\geq 4/8$ ), or poor ( $< 4/8$ ). To avoid redundancy, the three appraisals are reported together in a single consolidated summary (Table 2).

### Synthesis methods

The significant heterogeneity in methodology and context across the included studies did not permit a quantitative meta-analysis. A narrative synthesis approach was adopted, informed by the framework of Popay et al. (2006). Evidence was synthesised across six thematic domains, namely: (1) socio-economic impacts, (2) biosecurity practices, (3) surveillance and disease management, (4) policy and multi-sectoral response, (5) repopulation and recovery, and (6) market and supply-chain dynamics.

Results reported directly from the included studies and estimates made by the authors for the purpose of interpretation were clearly distinguished. Reported findings, including hog inventory trends, pork-price fluctuations, income-recovery rates, farm-survival outcomes and policy implementation observations, are attributed to their original sources. Conversely, other integrative quantitative summaries and cumulative economic burden estimates were developed through secondary synthesis of evidence from multiple studies. These derived estimates were generated to support the interpretation of general trends and should not be considered as equivalent to the primary observations reported in any single study. Caution was applied to all synthesised estimates, as the evidence base included only eight studies with different designs, geographic scope and populations. The emphasis was less on establishing causal relationships, and more on identifying recurring themes, areas of convergence and policy-relevant insights. The resulting synthesis was subsequently incorporated into a conceptual multi-sectoral framework designed to illustrate the relationships among biosecurity, surveillance, governance, market systems, and smallholder resilience within the Philippine ASF context.

## Results and Discussion

### Study selection

A total of 2,189 records were identified across the four databases. Title and abstract screening removed the large majority because of geographic mismatch or lack of ASF/swine relevance, leaving 14 potentially eligible records. After removal of four duplicate records, 10 unique records proceeded to full-text retrieval. Two records were excluded at full-text review because they concerned non-Philippine settings. Eight studies met all eligibility criteria and were included in the synthesis (Figure 1).

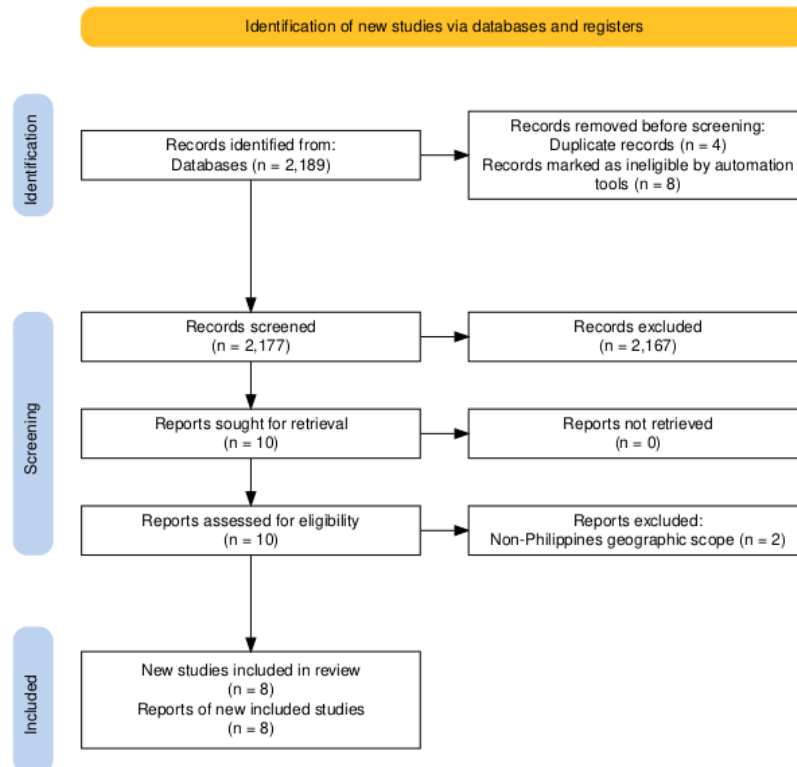


Figure 1. PRISMA 2020 flow diagram for study identification, screening, eligibility assessment, and inclusion across four bibliographic databases (Google Scholar, PubMed, Science Direct, and Web of Science; searches conducted in April 2026).

Source: Authors' analysis, adapted from the PRISMA2020 template of Haddaway et al. (2022).

#### Characteristics of included studies

The eight included studies spanned from 2020 to 2025 and comprised cross-sectional surveys ( $n = 2$ ), policy analyses ( $n = 2$ ), a prospective observational study ( $n = 1$ ), an ex-post quasi-experimental evaluation ( $n = 1$ ), a narrative review ( $n = 1$ ), and a comparative policy analysis ( $n = 1$ ). Five studies had national scope, two were subnational, and one was comparative across three Asian island nations (Table 1).

Table 1. Characteristics of the eight included studies.

| Author(s)                 | Year  | Design             | Setting            | Population              | Key outcomes                                             |
|---------------------------|-------|--------------------|--------------------|-------------------------|----------------------------------------------------------|
| Bañega et al.             | 2022  | Report             | Luzon region       | Industry-level          | Industry losses; price inflation; consumer impact.       |
| Bernardes and Peña        | 2020  | Cross-sectional    | Baybay City, Leyte | Smallholder farmers     | Biosecurity compliance; farm readiness; risk perception. |
| Bollido et al.            | 2022  | Survey             | Catbalogan, Samar  | Smallholder raisers     | Supply-chain restructuring; market access; livelihood.   |
| Hsu et al.                | 2024a | Observational      | Nationwide (PHL)   | Enrolled pig farms      | Repopulation success; protocol adherence; recovery.      |
| Portugaliza               | 2025  | Policy review      | National (PHL)     | Policy analysis         | Policy gaps; zonal quarantine; government response.      |
| Abao et al.               | 2025  | Ex-post evaluation | National (PHL)     | Programme beneficiaries | Income recovery; programme equity; beneficiary outcomes. |
| Fernandez-Colorado et al. | 2024  | Narrative review   | National (PHL)     | Published literature    | Surveillance; zero-prevalence; control measures.         |
| Hsu et al.                | 2024b | Comparative        | PHL, Taiwan, Japan | Island pig industry     | Transboundary management; island biosecurity; policy.    |

Source: Authors' compilation from the included studies.

### Risk of bias and quality assessment

Across the eight studies, ROBINS-I rated four as low overall risk of bias and four as moderate, the latter primarily reflecting non-probability sampling and limited confounder adjustment; no study was rated as serious or critical. AXIS appraisal placed most studies in the good category, with one rated fair–good and one (a grey-literature report) rated fair. The JBI appraisal was consistent with this pattern, rating two studies as excellent and the remainder as good or fair. The mean JBI-derived quality score across the eight studies was approximately 7.7 out of 10. The consolidated appraisal is presented in Table 2.

Table 2. Consolidated quality appraisal of the eight included studies. ROBINS-I overall risk of bias (low/moderate); AXIS overall rating; JBI overall rating and JBI-derived score (0–10 scale).

| Study                            | ROBINS-I | AXIS      | JBI score | JBI rating |
|----------------------------------|----------|-----------|-----------|------------|
| Bañega et al. (2022)             | Moderate | Fair      | 6.0       | Fair       |
| Bernardes and Peña (2020)        | Moderate | Good      | 7.2       | Good       |
| Bollido et al. (2022)            | Moderate | Fair–Good | 7.4       | Good       |
| Hsu et al. (2024a)               | Low      | Good      | 8.5       | Good       |
| Portugaliza (2025)               | Low      | Good      | 8.2       | Good       |
| Abao et al. (2025)               | Moderate | Good      | 7.7       | Good       |
| Fernandez-Colorado et al. (2024) | Low      | Good      | 9.0       | Excellent  |
| Hsu et al. (2024b)               | Low      | Good      | 8.6       | Excellent  |
| Mean                             | —        | —         | 7.7       | —          |

Source: Authors' appraisal using ROBINS-I (Sterne et al., 2016), AXIS (Downes et al., 2016), and JBI (Moola et al., 2020) tools.

### Synthesis by thematic domain

All quantitative values are reported directly from the included studies (Abao et al., 2025; Bañega et al., 2022; Bollido et al., 2022; Bernardes and Peña, 2020; Hsu et al., 2024a, 2024b; Fernandez-Colorado et al., 2024; Portugaliza, 2025).

### Socio-economic impacts

The national swine herd fell from 12.8 million head in 2019 to 7.8 million in 2021 (a 39% decline), partially recovering to 10.8 million by 2025 (Figure 2A). In Metro Manila, average pork retail prices peaked at PHP 290/kg, 53% above the pre-ASF baseline (Figure 2B). Annual economic losses peaked at USD 1.52 billion in 2021, and the swine-sector employment index (2019 = 100) fell to 67 in 2021 before recovering to 93 by 2025 (Abao et al., 2025). Taken together, these indicators show that ASF impacts extended beyond animal losses into rural livelihoods and broader economic activity. Income losses for smallholder raisers were 40–60% (Abao et al., 2025), and LGU capacity strongly mediated recovery: beneficiaries in well-resourced provinces recovered roughly twice as fast as those in poorly resourced localities. Governance quality thus emerges as an independent determinant of socio-economic resilience.

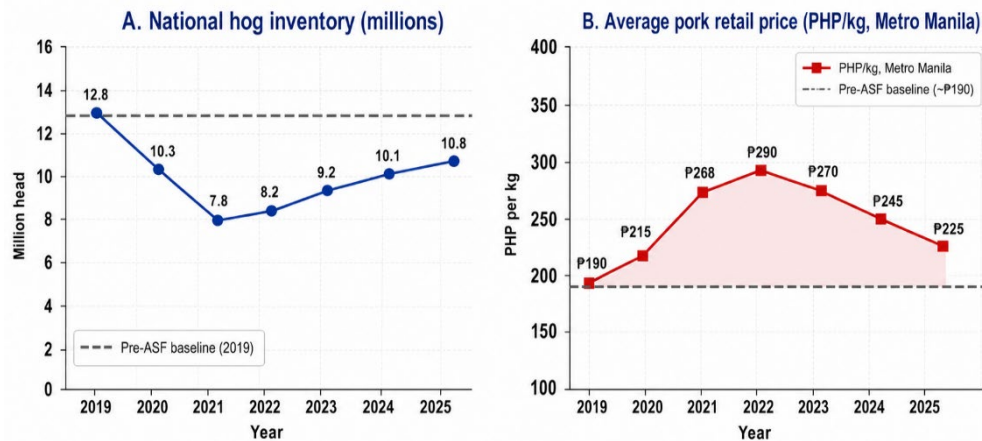


Figure 2. Time series trends of African swine fever impacts in the Philippines, 2019–2025. (A) National hog inventory (million head), declining by 39% from 2019 to 2021 and partially rebounding to 10.8 million in 2025. (B) Average pork retail price in Metro Manila (PHP/kg), with a peak of 53% above the pre-ASF baseline.

Source: Authors' synthesis based on Bañega et al. (2022), Bollido et al. (2022), Bernardes and Peña (2020); Hsu et al. (2024 a,b); Abao et al.(2025); Fernandez-Colorado et al. (2024) Portugaliza (2025).

### Biosecurity practices

In Leyte, perimeter fencing was present on only 60% of the smallholder farms, and disinfection footbaths were absent from most sites (Bernardes and Peña, 2020) with uncontrolled swill feeding still a common practice. By contrast, nationally administered, institutionally supported protocols provided a 6-month-farm survival rate of >70% following repopulation (Hsu et al., 2024a). Overall, these results suggest that successful biosecurity depends on adherence to protocols rather than the mere availability of infrastructure.

Philippine outbreaks are driven by ASFV genotype II (Fernandez-Colorado et al., 2024). Surveillance remains predominantly passive, with PCR/ELISA capacity concentrated in Metro Manila, causing confirmation bottlenecks of 5–10 days in more distant regions. At peak incidence, fewer than 30% of provinces conducted active zero-prevalence monitoring. The Philippine surveillance architecture lags behind Taiwan's prefectural-level active monitoring and Japan's MAFF system (Hsu et al., 2024b). Closing these gaps requires investment in risk-based active surveillance, expanded laboratory networks, wildlife-reservoir monitoring, and integrated data-management systems to enable rapid detection and response.

### Policy and multi-sectoral response

The stamping-out strategy was not entirely effective due to the non-participatory implementation of quarantine zones by LGUs, delayed and insufficient compensation, and gaps in accountability within the multi-agency structure of the NTFAD. Both Fernandez-Colorado et al. (2024) and Hsu et al. (2024b) recommended adopting an integrated One Health governance architecture, which forms the foundation of the conceptual framework presented below (Figure 3).

### Repopulation and recovery

The national pig repopulation programme reached approximately 180,000 beneficiary households, with an average income recovery of 28–35% relative to pre-ASF baselines, and the swine-sector employment index recovered from a nadir of about 67 in 2021 to roughly 93 by 2025 (Abao et al., 2025). The reported efficacy of the programme was about 72% and was higher where the validated protocol of Hsu et al. (2024a) was implemented with full biosecurity-compliance verification. One major equity issue was that, although the smallholders experienced higher proportional income losses, commercial operators accessed larger per-household subsidies. This mismatch between sheer financial need and access to programmes thus indicates an opportunity for a redesign that includes need-based eligibility scoring.

### Market and supply chain

Traditional pork supply channels were severely affected by ASF, with more informal routes for farm-to-market flows and illegal provincial cross-border movement of live animals (Bollido et al., 2022). Over the same period, pork price inflation was significantly higher than consumer prices as a whole. The extent of the subsequent impacts of these price spikes on consumer welfare and regional food security is still relatively poorly understood (Bañega et al., 2022). The cumulative direct herd loss (2019–2025) is estimated at USD 1.45 billion, but when including price effects, trade disruption, and employment losses, the total economic burden exceeds USD 3 billion, indicating that ASF is not merely a farm-level problem but a broader economic shock.

### Integrated conceptual framework

Bringing the six domains together, the authors developed a conceptual framework (Figure 3) that positions the ASF outbreak as a central driver extending to five response sectors: Epidemiology and Surveillance, Biosecurity Practices,

Government Policy, Smallholder Farmer Response, and the Market and Trade System, unified by an underlying One Health Integration layer and oriented towards the dual outcomes of improved farmer welfare and industry recovery. The framework is an interpretive synthesis rather than an empirically tested model; its most distinctive feature is the explicit placement of One Health Integration at the foundation of all response sectors, an emphasis supported by the convergent recommendations of Fernandez-Colorado et al. (2024), Hsu et al. (2024b), and Portugaliza (2025). In the Philippine ASF context, One Health is taken to encompass risk communication between animal- and human-health authorities, cross-sector economic coordination among agriculture, finance, and trade agencies, and multi-agency policy alignment across the Department of Agriculture, the Department of the Interior and Local Government, and local government units.

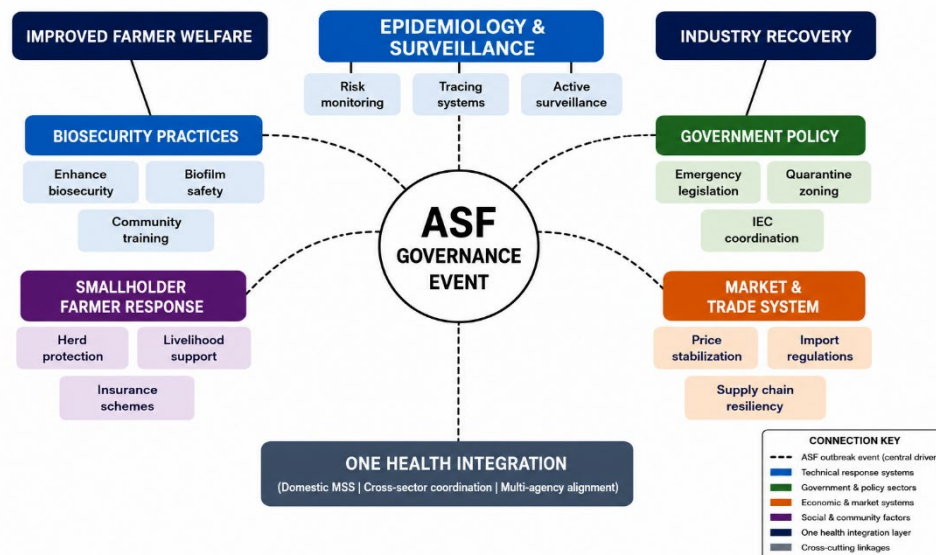


Figure 3. Conceptual multi-sectoral framework for ASF management in the Philippines. The ASF outbreak (central node) is linked to five response sectors and an underlying One Health integration layer. The framework was synthesised inductively by the authors from six thematic domains across the eight included studies and is interpretive rather than empirically validated.

Source: Authors' synthesis based on Fernandez-Colorado et al. (2024), Hsu et al. (2024a, 2024b), Portugaliza (2025) and Abao et al. (2025).

### Implications

The evidence synthesised across the six thematic domains points to four priority directions for policy and practice. First, biosecurity support may need to shift from voluntary guidance towards verifiable, institutionally supported protocols, building on the validated repopulation protocol of Hsu et al. (2024a), with accessible assistance for smallholder farms. Second, the surveillance architecture would benefit from transformation into an active, risk-based, decentralised network with provincial diagnostic capacity, real-time electronic reporting, wildlife-reservoir monitoring, and genomic sequencing. Third, governance reform to create a clearer One Health command structure – with collective accountability and defined metrics of success centres – seems warranted (Portugaliza, 2025; Hsu et al., 2024b). Fourth, the current repopulation programme should adopt fairness audits and need-based eligibility scoring (Abao et al., 2025).

These priorities are consistent with trends observed in other developing economies that have smallholder-influenced swine sectors. In such cases, where passive surveillance is the main monitoring method, compensation policies have often weakened farmer's incentives to report outbreaks (China 2018; Vietnam 2019–2020; Indonesia 2019–2022). Moreover, Hsu et al. (2024b) noted that Taiwan's island geography can paradoxically serve both as an escape and as a stronghold against ASF. To accomplish this, however, it is necessary to invest actively in border biosecurity, with tight restrictions on live animal and feed transfer between islands, alongside closely coordinated surveillance networks.

The findings presented in this review must be considered against its methodological quality. Although the ROBINS-I, AXIS, and JBI appraisal tools rated the included literature from fair to excellent, many reports are practice-based, drawing on observational data, survey responses, or policy reviews and grey literature. Such designs are inherently at risk of sampling restrictions, reporting biases, and particular contextual constraints. Nevertheless, the consistent convergence of results between independent research groups suggests that the central conclusions regarding on-farm biosecurity gaps, delayed surveillance, socio-economic impact, and governance capacity are robust. These findings provide a sound basis for informing further ASF prevention and control measures in the Philippines.

### Limitations

Several limitations apply. First, the prominence of grey literature reduces the standard quality assurances provided by peer review. Second, the absence of PubMed-indexed studies meeting the full eligibility criteria reflects a genuine evidence gap rather than a search inadequacy. Third, design heterogeneity

precluded quantitative meta-analysis. An additional limitation relates to the relatively small evidence base available for synthesis. Although the systematic search identified 2,189 records, only eight studies met all eligibility criteria. Thus, thematic conclusions were derived from a small number of studies with heterogeneous methodologies, geographic regions and stakeholder populations. A consistent direction of effect across the included papers supports the overall interpretation, though caution is required when extrapolating these specific estimates to the Philippine swine sector as a whole. Moreover, many of the quantitative metrics included in this review, such as the summary of comparative effectiveness estimates and cumulative economic burden estimates, were generated using a secondary synthesis of published data and should thus be interpreted as exploratory approximations rather than conclusive measures. Additional studies using standardised approaches, wider geographic sampling and longitudinal follow-up would strengthen the evidence base for ASF policy and management decisions in the Philippines.

### Conclusion

African swine fever (ASF) has become one of the most serious challenges facing the Philippine swine industry, affecting not only animal health but also the livelihoods of thousands of farmers and stakeholders throughout the pork value chain. These eight studies within our PRISMA 2020-based systematic review suggest that the disease has caused considerable economic losses, dramatic declines in local swine population numbers and major disruptions to pork marketing systems. Much of this hardship has been borne by smallholder producers, who generally lack the financial cushions available to larger agribusinesses during disease outbreaks.

The review highlights that many of the challenges faced during the ASF epidemic arose from weak existing biosecurity measures, surveillance systems and institutional collaboration. Although some provinces have successfully undertaken government-led initiatives for repopulation and recovery, this has occurred unevenly across regions. Reducing the burden – ranging from low local surveillance capacity and unequal access to support programmes to fragmented governance – remains an obstacle to controlling the disease and accomplishing sectoral recovery.

Stronger on-farm biosecurity, improved testing capacity and closer integration between state governments and producers are all part of a more resilient pork industry. Importantly, smallholders also need targeted support to be able to implement these steps. The direct links between animal health, rural livelihoods and sustainable agriculture are demonstrated by the practical viability of a One Health framework in managing transboundary diseases such as ASF. Even with a

modest range of literature available, the consistency of results across studies provides a firm foundation for policy development. Ongoing research should focus on long-term follow-up of farmer recovery, economic evaluations based on primary data, core measures of compliance with biosecurity practices and the interaction between local governance and ASF control outcomes. The information gathered here will play a critical role in closing these research gaps and ultimately helping to inform the sustainable recovery of the Philippine swine sector.

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SISTEMATSKI PREGLED AFRIČKE KUGE SVINJA NA FILIPINIMA (2019–2025): SOCIO-EKONOMSKI UTICAJI, PRAKSE ZAINTERESOVANIH STRANA I MULTISEKTORSKE STRATEGIJE UPRAVLJANJA

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R e z i m e

Afrička kuga svinja (AKS) prvi put je potvrđena na Filipinima u septembru 2019. godine, prouzrokujući velike gubitke u industriji svinja. U ovom sistematskom pregledu objedinjeni su rezultati istraživanja o socio-ekonomskim uticajima, biosigurnosnim praksama i multisektorskim strategijama upravljanja u periodu od 2019. do 2025. godine. U skladu sa smernicama PRISMA 2020, pretražene su četiri baze podataka (*Google Scholar*, *PubMed*, *ScienceDirect* i *Web of Science*), što je dalo ukupno 2.189 zapisa. Osam studija ispunilo je kriterijume podobnosti, a rizik od pristrasnosti procenjen je primenom alata ROBINS-I, AXIS i JBI. Ukupni gubici u sektoru svinjarstva iznosili su između 72 i 85 milijardi filipinskih pezosa (fil./tag. *piso ng Pilipinas – PHP*) u periodu 2019–2022, uz smanjenje fonda svinja za 7,54 miliona grla. Prihodi malih poljoprivrednika smanjeni su za 40–60%. Pre pojave AKS, usklađenost sa propisima o biosigurnosti bila je na izrazito niskom nivou. Programom obnove proizvodnje obuhvaćeno je približno 180.000 domaćinstava, uz oporavak prihoda od 28% do 35%, dok su u koordinaciji između različitih institucija utvrđeni značajni nedostaci. Uključene studije pokazale su umeren do visok metodološki kvalitet, sa prosečnom ocenom od 7,7/10 izvedenom na skali JBI. Rezultati ukazuju na to da je AKS imala ozbiljne i široko rasprostranjene uticaje na sektor svinjarstva na Filipinima, pri čemu su mali poljoprivrednici bili nesrazmerno više pogođeni. Efikasno upravljanje u budućnosti zahteva primenu pristupa „Jedno zdravlje” (engl. *One Health*), obavezujuće standarde biosigurnosti, pravične programe oporavka i proaktivno razvijenu infrastrukturu za nadzor.

**Ključne reči:** afrička kuga svinja, biosigurnost, Filipini, socio-ekonomski uticaj, zainteresovane strane, sistematski pregled.

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## ASSESSMENT OF NEEM AND MORINGA DIETARY ADDITIVES ON GROWTH TRAITS AND HORMONAL BALANCE IN WEST AFRICAN DWARF BUCKS

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**Abstract:** This study demonstrates the effects of neem (*Azadirachta indica*) and moringa (*Moringa oleifera*) leaf meal supplementation as feed additives on growth performance, hematological parameters, and hormone metabolism in West African Dwarf (WAD) bucks. Sixteen WA D bucks aged 8 to 12 months were randomly assigned to four dietary treatments (T<sub>1</sub> to T<sub>4</sub>) for 90 days. T<sub>1</sub> was the control (basal diet only), while T<sub>2</sub>, T<sub>3</sub>, and T<sub>4</sub> were fed on the basal diet supplemented with 10% neem leaf meal, 10% moringa leaf meal, and a mixture of 5% neem and 5% moringa leaf meal, respectively. Bucks in T<sub>3</sub> (moringa) and T<sub>4</sub> (blend) had significantly ( $P<0.05$ ) greater average daily gain and feed conversion ratio than those in T<sub>1</sub> and T<sub>2</sub>. The bucks in T<sub>3</sub> had the highest plasma testosterone concentration ( $3.52\pm0.15$  ng/mL) and the highest T<sub>3</sub> levels ( $2.21\pm0.08$  nmol/L), both significantly higher than those of the control group ( $P<0.05$ ). The results indicated that moringa affected growth performance and anabolic or metabolic hormonal status. It is concluded that pure or mixed moringa leaf meal combined with neem may be used as a natural feed additive to enhance this type of small ruminant productivity.

**Key words:** growth performance, hormonal balance, moringa leaf meal, neem leaf meal, testosterone, triiodothyronine.

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## Introduction

Small ruminants, particularly the West African Dwarf (WAD) goat, are important to the economy of humid and sub-humid West Africa (Olajide, 2017). They are a significant source of meat, milk, and income for smallholder farmers, thereby contributing greatly to household food security (Wodajo et al., 2020). The WAD goat breed, which is known for its trypanotolerance and ability to thrive in a harsh environment, constitutes an important genetic resource in the tropics (Okeniyi et al., 2025). Notwithstanding their indigenous ruggedness, the performance levels of these genetically enhanced goats are generally substandard and significantly lower than their genetic capacity (Magoro et al., 2022). This limitation is closely related to the high costs of feeds, as well as common nutritional deficiencies, especially during the long dry seasons, which restrict natural pasture provision both quantitatively and qualitatively (Assefa et al., 2024). This feed gap results in low growth, poor reproduction, and high disease susceptibility, the combined effect of which negatively affects WAD goat production profitability and sustainability (Olawoye et al., 2020). Therefore, the exploitation of low-cost, environmentally friendly, and accessible feed resources, which can be used as functional feed additives, is an emergent research field (Ndudzo et al., 2023).

Some of these are locally abundant plants such as *Azadirachta indica* and *Moringa oleifera*, that are well-known sources of crude protein, essential amino acids, valuable minerals, and bioactive phytochemicals, including flavonoids and polyphenols (Kumar et al., 2023). Moringa and neem leaves, widely studied in ruminant nutrition, are tropical tree species (Preez et al., 2023). Moringa is highly rated for its high nutritional value, providing 25–30% crude protein, essential amino acids,  $\beta$ -carotene, and major minerals such as calcium, iron, and zinc (Islam et al., 2021). In contrast, neem leaf meal is valued less for bulk nutrients and more as a highly potent source of bioactive limonoids, such as azadirachtin and nimbin, which have a strong anthelmintic and anti-methanogenic effect and have been shown to regulate rumen activity by reducing parasite load and enhancing energy utilization (Sarkar et al., 2021).

Although these independent effects have been identified, especially the nutritional and hormonal effects of moringa, there are still gaps in knowledge about the synergistic effects of neem when combined with the nutritional and hormonal impact of moringa, which is the focus of this study.

## Material and Methods

### Experimental site and animals

The experiment was conducted at the Goat Unit of Landmark University Teaching and Research Farm located in Omu-Aran, Kwara State, Nigeria. Eighteen (18) young West African Dwarf bucks, aged between 8 and 12 months, were purchased from Omu-Aran and surrounding areas. Sixteen male WAD bucks were used for the feeding trial, with an average initial body weight of  $12.5 \pm 0.5$  kg. The bucks were quarantined for two weeks and treated against internal parasites (using a broad-spectrum anthelmintic) and external parasites (ectoparasites) before the commencement of the experiment. All applicable institutional guidelines for the care and use of animals were followed.

### Experimental diet preparation and formulation

The basal diet consisted of a concentrate feed formulated using locally available ingredients (maize offal, wheat offal, palm kernel cake) as shown in Table 1, and chopped Guinea grass (*Panicum maximum*) offered ad libitum. Fresh leaves of neem and moringa were harvested, thoroughly washed, air-dried in the shade to preserve active components, and then milled into fine leaf meals.

Table 1. Standard-based neem and moringa leaf meal diet composition.

| Ingredients (%)        | T <sub>1</sub> | T <sub>2</sub> | T <sub>3</sub> | T <sub>4</sub> |
|------------------------|----------------|----------------|----------------|----------------|
| Maize offal            | 40.00          | 35.00          | 35.00          | 35.00          |
| Wheat offal            | 30.00          | 27.00          | 27.00          | 27.00          |
| Palm kernel cake       | 25.00          | 23.00          | 23.00          | 23.00          |
| Neem leaf meal         | 0.00           | 10.00          | 0.00           | 5.00           |
| Moringa leaf meal      | 0.00           | 0.00           | 10.00          | 5.00           |
| Bone meal              | 2.00           | 2.00           | 2.00           | 2.00           |
| Common salt            | 1.00           | 1.00           | 1.00           | 1.00           |
| Vitamin-mineral premix | 2.00           | 2.00           | 2.00           | 2.00           |

Source: Authors' formulation based on the Nigerian Institute of Animal Science Database (2020 edition).

Four experimental diets (T<sub>1</sub> to T<sub>4</sub>) were formulated as follows: T<sub>1</sub>: basal diet (control); T<sub>2</sub>: basal diet + 10% neem leaf meal (NLM); T<sub>3</sub>: basal diet + 10% moringa leaf meal (MLM); T<sub>4</sub>: basal diet + 5% NLM + 5% MLM (blend). These diets were analyzed as shown in Table 2. The percentage inclusions were based on the weight of the concentrate component of the diet. The diets were formulated to be isonitrogenous and isocaloric, according to the nutrient requirements for growing goats.

Table 2. Estimated proximate composition of the neem-moringa leaf meal-based diets.

| Parameters                      | T <sub>1</sub> | T <sub>2</sub> | T <sub>3</sub> | T <sub>4</sub> |
|---------------------------------|----------------|----------------|----------------|----------------|
| Crude protein (%)               | 16.02          | 16.15          | 16.20          | 16.18          |
| Metabolizable energy (MJ/kg DM) | 10.85          | 10.80          | 10.88          | 10.84          |
| Crude fibre (%)                 | 14.50          | 15.20          | 14.90          | 15.00          |
| Ether extract (%)               | 5.10           | 5.25           | 5.30           | 5.28           |
| Ash (%)                         | 7.80           | 8.40           | 8.30           | 8.35           |

Source: Authors' calculations from the Nigerian Institute of Animal Science Database (2020 edition).

A limitation of this study is that ingredient and diet compositions were estimated from standardized database values (NIAS, 2020) rather than direct laboratory analyses, which may not fully account for environmental and processing variations in the feed materials used.

#### Experimental design and procedure

The sixteen bucks were randomly assigned to four treatment groups, with four animals per treatment ( $n = 4$ ), following a completely randomized design (CRD). Bucks were housed individually in elevated pens. The adaptation period lasted 14 days, and the feeding trial lasted 90 days. The concentrate diets were provided in the morning, and Guinea grass was given in the evening.

#### Measurement of growth traits

Daily feed consumption was determined by recording the actual daily weight of feed offered and refused (orts). Individual body weight was measured weekly with a suspended digital weighing scale before the morning feeding during the trial. Initial and final body weights (IBW, FBW) were recorded in kilograms (kg). The average daily gain (ADG) was calculated in grams (g) as follows (Eq. 1):

$$ADG = \frac{\text{Final body weight} - \text{Initial body weight}}{\text{Number of experimental days}} \quad \text{Eq. (1)}$$

Feed conversion ratio (FCR), an indicator of feed efficiency, was calculated and expressed as the ratio of average daily feed intake (ADFI) in g to average daily gain (ADG) in g.

#### Hormonal assay

At the end of the trial (day 90), blood samples were collected from each buck by jugular vein puncture into heparinized tubes (approximately 10 mL). Plasma

samples were promptly separated by centrifugation at 3,000 r/min for 15 minutes and stored at -20°C until analysis. Plasma testosterone and triiodothyronine (T3) concentrations were measured using competitive enzyme-linked immunosorbent assay (ELISA) kits, following the manufacturer's instructions (MyBioSource and Enzo Life Sciences) at Manzanita Research Laboratories, Behind Opeyemi Filling Station, Ilorin, Kwara State, Nigeria. Each sample was analysed in duplicate for accuracy. The lower limits of detection were 0.05 ng/mL for testosterone and 0.01 nmol/L for T3.

#### Statistical analysis

The normality and homoscedasticity of all data were assessed first. Differences between least square means among the groups were analyzed using one-way ANOVA (Statistical Analysis System, version 9.4; SAS Institute Inc., Cary, NC, USA). The fixed effect for the dietary treatments was included in the statistical model. Means denoted by different superscript letters are significantly different according to Duncan's multiple range test (DMRT).  $P < 0.05$  was considered a significant difference. Data are expressed as means  $\pm$  SEM, as described by Bewick et al. (2004).

### Results and Discussion

There were clear dietary differences in the performance of the West African Dwarf (WAD) bucks when fed neem and moringa leaf meals, as indicated by final body weight (FBW), average daily gain (ADG) and feed conversion ratio (FCR) ( $P < 0.05$ ), but not by initial body weight (IBW) or average daily feed intake (ADFI) ( $P > 0.05$ ), as shown in Table 3. The similarity in IBW and ADFI suggests that the observed performance differences were due to dietary treatment rather than variation in intake or initial physiological differences (Chichester et al., 2021). Bucks fed 10% *Moringa oleifera* leaf meal (T<sub>3</sub>) achieved the highest FBW, while the neem–moringa blend (T<sub>4</sub>) also improved growth performance (FBW and ADG).

However, goats fed neem (10%, T<sub>2</sub>) showed no significant difference from the control group in ADG, suggesting a lesser effect on bucks' growth at 10% inclusion. The improved feed efficiency and nutrient conversion, as indicated by better FCR in T<sub>3</sub> ( $7.52 \pm 0.45$ ) and T<sub>4</sub> ( $8.11 \pm 0.45$ ), further support enhanced feed efficiency and nutrient conversion in the treated animals compared to the control animals (Davison et al., 2023). However, the total feed intake was recorded by treatment, but the individual dry matter intakes of the concentrate mixture and Guinea grass were not separately monitored, which prevented partitioning of total DM intake into forage and concentrate components.

The better performance in goats fed moringa was attributed to its high crude protein level, balanced essential amino acids, essential vitamins, minerals, and

abundant phytochemicals, which support rumen fermentation, microbial protein synthesis, and nutrient digestibility. Omotoso et al. (2024) reported that moderate inclusion of *Moringa oleifera* supplementation in goats (5% to 20%) can consistently enhance nutrient utilization, antioxidant activity, and growth efficiency. Similarly, small ruminants have been shown to gain more weight and improve feed efficiency when moringa is included in their diets as a feed additive, due to its effect on dry matter digestibility, fibre degradation, and nitrogen utilization efficiency (Kholif et al., 2018). These responses are often dose dependent, and the best results are achieved at a certain level, above which the physiological adaptations in the rumen cause an increase of marginal benefit (Kholif, 2023).

Table 3. Effect of neem and moringa dietary additives on growth performance of WAD bucks.

| Parameter    | T <sub>1</sub>     | T <sub>2</sub>     | T <sub>3</sub>     | T <sub>4</sub>     | SEM  | P-value |
|--------------|--------------------|--------------------|--------------------|--------------------|------|---------|
| IBW (kg)     | 12.55              | 12.48              | 12.60              | 12.50              | 0.21 | 0.98    |
| FBW (kg)     | 18.82 <sup>c</sup> | 19.36 <sup>c</sup> | 21.28 <sup>a</sup> | 20.65 <sup>b</sup> | 0.35 | <0.01   |
| ADG (g/day)  | 69.67 <sup>c</sup> | 76.44 <sup>c</sup> | 96.44 <sup>a</sup> | 89.56 <sup>b</sup> | 2.85 | <0.01   |
| ADFI (g/day) | 712.8              | 753.5              | 725.7              | 728.4              | 18.4 | 0.65    |
| FCR (g/g)    | 10.23 <sup>a</sup> | 9.85 <sup>a</sup>  | 7.52 <sup>c</sup>  | 8.11 <sup>b</sup>  | 0.45 | <0.05   |

<sup>a, b, c</sup> Means within the same row with different superscripts are significantly different ( $P < 0.05$ ).

Source: Authors' calculations based on experimental data.

The neem-only group (T<sub>2</sub>) showed no significant growth response, which is consistent with the presence of bioactive secondary metabolites such as alkaloids, flavonoids, and limonoids in the plant that could decrease the palatability and nutrient utilization when fed at higher dietary levels (Archa et al., 2026). Neem has antimicrobial and antiparasitic properties that have been shown to be favourable to animal health management, but higher inclusion levels can reduce feed efficiency through the formation of protein–tannin complexes and decreased nutrient degradation in the rumen (Taethaisong et al., 2023). Plant secondary compounds have been extensively documented to inhibit rumen fermentation and nutrient availability in ruminant diets based on herbage, especially when feeds contain high proportions of tannin-rich plants (Musati et al., 2025).

These results indicate that T<sub>4</sub> produced better results than any other treatment, indicating a complementary action between moringa and the functional phytochemicals present in neem, which has a superior nutritional profile (Muhammad and Aliyu, 2025). The moringa component may have helped to overcome the weak anti-nutritional factor in neem, and it enhanced the nitrogen availability and microbial activity in the rumen (Amad and Zentek, 2023). This synergistic effect is in line with the evidence that some nutrient-rich forages and

phytogenic plants can improve growth efficiency under intensive feeding systems and promote more stable rumen fermentation (Priyashantha et al., 2026).

Practically, the results suggest that the inclusion of 10% moringa leaf meal in the diet would be the optimal method of improving growth and feed efficiency in WAD bucks under semi-intensive production systems (Safwat et al., 2024). Neem leaf meal, which might be useful for health management such as parasite control, may not be optimal when used alone for maximizing growth performance, despite its benefits in this area. A combination of neem and moringa could provide an effective feeding strategy, offering moderate health-promoting phytochemicals alongside high-quality nutritional support (Ali, 2023). In smallholder livestock systems in the tropics, where conventional protein feed resources are expensive, moringa is a sustainable feed which is locally available and can be used to boost livestock productivity (Mendieta-Araica et al., 2011).

The plasma hormonal profile of the bucks (Table 4) showed that dietary supplementation with neem leaf meal, moringa leaf meal, and their combination significantly ( $P < 0.01$ ) affected the level of plasma testosterone and triiodothyronine ( $T_3$ ), indicating a significant change in the anabolic and metabolic activities of the experimental animals. Higher testosterone levels were noted in  $T_3$  than in  $T_1$ , suggesting that supplementation with *Moringa oleifera* improved the activity of the steroids and anabolic activity in bucks (Prabsattroo et al., 2015).

Table 4. Effect of neem and moringa dietary additives on plasma hormonal concentrations in WAD bucks.

| Hormone                   | T <sub>1</sub>    | T <sub>2</sub>    | T <sub>3</sub>    | T <sub>4</sub>    | SEM  | P-value |
|---------------------------|-------------------|-------------------|-------------------|-------------------|------|---------|
| Testosterone (ng/mL)      | 2.15 <sup>c</sup> | 2.31 <sup>c</sup> | 3.52 <sup>a</sup> | 2.95 <sup>b</sup> | 0.11 | <0.01   |
| Triiodothyronine (nmol/L) | 1.45 <sup>c</sup> | 1.53 <sup>c</sup> | 2.21 <sup>a</sup> | 1.98 <sup>b</sup> | 0.07 | <0.01   |

<sup>a, b, c</sup> Means within the same row with different superscripts are significantly different ( $P < 0.05$ ). n = 4 bucks per treatment.

Source: Authors' calculations based on experimental data.

Testosterone is one of the most important of the androgenic hormones, playing a direct role in protein accretion, muscle growth, nitrogen balance, and lean tissue gain in ruminants (Evans et al., 2022). The improvements in the hormonal response noted in the groups fed moringa are consistent with the earlier documented effects of *Moringa oleifera* on endocrine function and/or reproductive hormone production in male animals (Ogunlade et al., 2022), supporting the presence of bioactive compounds such as phytosterols, flavonoids, essential amino acids, vitamins, and trace minerals, including zinc.

In particular, zinc is essential for the biosynthesis of testosterone, as it is involved in steroidogenesis in the testicles and the activation of enzymes involved

in the formation of steroid hormones (Rotimi et al., 2024). In addition, the potent antioxidant effects of moringa could have minimized the oxidative stress in the testes, maintained the normal function of Leydig cells, and increased their capacity to secrete hormones (Monageng et al., 2023).

However, no significant difference between  $T_2$  and  $T_1$  indicates that the inclusion of 10% neem leaf meal alone may not have been adequate to support the anabolic hormonal activity necessary for achieving optimum growth performance. Presence of secondary metabolites such as tannins, limonoids, saponins, and azadirachtin in neem, which can have mild anti-nutritional effects, reduce feed palatability, or affect nutrient utilization efficiency at relatively high inclusion levels, may be associated with this observation (Sutradhar et al., 2025). Neem is known to have antimicrobial, antiparasitic, and immune-modulating effects that are beneficial to animal health, however, when fed at high levels, it can reduce the digestibility of nutrients and metabolic efficiency, thereby restricting growth-promoting endocrinological responses (Taethaisong et al., 2023). Interestingly, treatments  $T_4$  and  $T_2$  had significantly higher testosterone levels than  $T_1$ , which suggests a synergistic effect between neem and moringa leaf meal (Oloidi et al., 2026). This also indicates that the greater nutritional and antioxidant potential of moringa helped to offset any possible negative effects of neem supplementation and enhanced the physiological and anabolic status of the bucks under the environmental conditions of the current experiment (Ali, 2023).

There have been reports of similar synergistic effects among phytogetic feed additives, which improve nutrient metabolism, hormonal balance, and productive performance in small ruminants exposed to environmental and nutritional stressors (Kholif et al., 2021; Ali et al., 2025).

Similarly, the level of triiodothyronine, a biologically active thyroid hormone that controls BMR, mitochondrial activity, protein turnover, thermoregulation, and nutrient partitioning in animals, was significantly higher in  $T_3$  (Prates, 2025). Thus, the higher  $T_3$  levels suggest greater efficiency of metabolism and utilization of feed nutrients for tissue growth and energy production (Mazza, 2025). This finding is important because it may explain the better feed conversion ratio and growth response reported in the groups fed moringa, where thyroid hormones are closely associated with improved nutrient assimilation and metabolic adaptive characteristics (Saleh et al., 2025).

The increase in  $T_3$  and  $T_4$  in the moringa and mixed treatments indicates significant physiological effects that enhanced anabolic and metabolic activity in the experimental bucks. Both hormones were stimulated together, implying that the plants had a positive effect on their physiological status, which led to the expression of their growth potential, either via *Moringa oleifera* alone or in combination with neem (Pilotos et al., 2020). These results align with Eppe et al. (2026), who have reported that the optimal endocrine balance of anabolic and

thyroid hormones is essential for efficient growth, productive performance, and metabolic adaptation of male livestock species.

### Conclusion

The inclusion of *Moringa oleifera* leaf meal significantly improved the growth performance of the West African Dwarf bucks in this study, as the final body weight, average daily gain, and the feed conversion efficiency were improved. While there was no significant difference in feed intake, there was a considerable improvement in the metabolism and utilization efficiency of nutrients. The neem–moringa blend also had a positive effect, though less pronounced, whereas the use of neem leaf meal alone at 10% did not significantly increase growth performance compared to the control. This implies that its use at this rate is unlikely to be productive, possibly due to anti-nutritional factors. The observed gain in growth efficiency in moringa-fed animals can be physiologically explained by increased anabolic activity, which may be linked to greater nutrient availability and metabolic support conducive to a growth-promoting hormonal balance (growth hormone–insulin axis activity). However, neem inclusion may not sufficiently support such anabolic processes, since it may contain secondary metabolites that negatively affect nutrient utilization.

Finally, the study showed that *Moringa oleifera* leaf meal could be a more suitable phyto-genic feed resource to enhance the growth performance of WAD bucks, whereas neem could serve as a functional feed additive more suited to health benefits than growth maximization. A combination of neem and moringa is a possible balanced approach, but moringa was the main contributor to an increase in productivity in this study.

### Ethical approval

This paper was conducted in accordance with accepted protocols for animal handling and welfare in research. It was approved by the Landmark University Ethical Committee, approval number: LMUIREC/ACSC/037/2025.

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EFEKAT KORIŠĆENJA *AZADIRACHTA INDICA* I *MORINGA OLEIFERA* KAO  
ADITIVA U ISHRANI ZAPADNOAFRIČKIH PATULJASTIH JARČEVA NA  
OSOBINE PORASTA I HORMONSKU RAVNOTEŽU

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R e z i m e

U radu se ispituje efekat dodavanja u obroke za zapadnoafričke patuljaste jarčeve brašna od lista *Azadirachta indica* i *Moringa oleifera* na porast, hematološke parametre i hormonski metabolizam. Šesnaest zapadnoafričkih patuljastih jarčeva, uzrasta od 8 do 12 meseci, nasumično je raspoređeno u četiri režima ishrane (T<sub>1</sub> do T<sub>4</sub>) tokom 90 dana. Grupa T<sub>1</sub> je bila kontrolna (osnovni obrok), grupe T<sub>2</sub>, T<sub>3</sub>, i T<sub>4</sub> su hranjene osnovnim obrokom uz dodatak 10% brašna od lista biljke *Azadirachta indica*, 10% brašna od lista biljke *Moringa oleifera*, odnosno mešavine 5% *Azadirachta indica* i 5% *Moringa oleifera*, respektivno. Jarčevi u tretmanima T<sub>3</sub> (*Moringa oleifera*) i T<sub>4</sub> (mešavina) su imali značajno (P<0,05) veći prosečni dnevni prirast i bolju konverziju hrane u odnosu na životinje u tretmanu T<sub>1</sub> i T<sub>2</sub>. Jarčevi T<sub>3</sub> tretmana imali su najveću koncentraciju testosterona u plazmi (3,52±0,15 ng/mL) i najviše nivoe trijodotironina (2,21±0,08 nmol/L), koji su bili značajno viši nego u kontrolnoj grupi (P<0,05). Rezultati pokazuju da je dodatak brašna od lista *Moringa oleifera* uticao na porast i anabolički ili metabolički hormonski status. Zaključeno je da se brašno od lista *Moringa oleifera*, čisto ili u kombinaciji sa *Azadirachta indica*, može koristiti u cilju poboljšanja produktivnosti ove vrste sitnih preživara.

**Ključne reči:** performanse porasta, hormonska ravnoteža, brašno od lista biljke *Moringa oleifera*, brašno od lista biljke *Azadirachta indica*, testosteron, trijodotironin.

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EFFICACY OF INCREASED AZADIRACHTIN DOSES AGAINST  
*DIABROTICA VIRGIFERA VIRGIFERA* LARVAE IN  
HIGHLY INFESTED MAIZE FIELDS

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**Abstract:** The western corn rootworm (*Diabrotica virgifera virgifera* LeConte) is a significant maize pest in Hungary, particularly in monoculture systems. As many effective synthetic soil insecticides and seed dressings have been withdrawn, interest in environmentally friendly alternatives has grown. Among these, azadirachtin – an insecticide from the neem tree (*Azadirachta indica*) – offers long-lasting protection and reduced risk of resistance. We conducted multi-year field trials using seed-applied azadirachtin at doses ranging from 50% (0.022 mg/seed) to 300% (0.129 mg/seed), with 100% (0.043 mg/seed) as our previously recommended rate. In fields with moderate larval pressure, doses of 125–150% (0.053–0.065 mg/seed) prevented economic loss, although minor root damage occurred. In 2022, higher doses (200% and 300%) were tested under severe infestations (modified Iowa scale 3.93–5.10). Across sites, the 200% dose (0.086 mg/seed) showed the most favourable overall performance, reducing larval numbers and root damage while providing the best overall balance of efficacy and crop safety under high infestation pressure. In contrast, the 300% dose delayed development, likely due to poor germination under drought conditions, as the oil-rich formulation hindered water uptake. These findings underscore the need to tailor dosing to local conditions. Azadirachtin seed dressing is an effective and sustainable alternative to synthetic insecticides, with the 200% dosage showing the most favourable overall balance of efficacy and crop safety under high pest pressure.

**Key words:** *Diabrotica virgifera virgifera*, maize pests, azadirachtin, neem tree, biological control methods.

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## Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide, with a sown area of 140–160 million hectares. This extensive cultivation is due to a wide range of maize's uses. For example, it serves as fodder and feed for animals, it is a vital food source for humans, and has significant industrial applications. To achieve high yields and quality, particular attention must be paid to crop protection, especially against insect pests. One of the most damaging pests of maize today is the western corn rootworm (*Diabrotica virgifera virgifera* LeConte), whose larvae and adults are both capable of causing serious economic damage (Vörös and Ledóné Ábrahám, 2023). The larvae chew plant roots (Culey et al., 1992; Ferracini et al., 2021; Gyeraj et al., 2021), while the adults interfere with fertilisation by chewing back the pistils (Culey et al., 1992). Effective control must focus on reducing larval numbers, as this significantly lowers the emerging adult population (Spencer et al., 2009; Szalai et al., 2014).

Today, as more synthetic chemical agents are phased out under sustainable management policies, greater emphasis is being placed on biologically derived pest control methods. These alternatives do not cause long-term environmental harm, do not endanger beneficial organisms, and are not hazardous to the health of agricultural workers (Lengai et al., 2020). One such substance is azadirachtin, a compound extracted from the seeds of the neem tree (*Azadirachta indica*) (Chaudhary et al., 2017). Originally native to India, the neem tree is now widespread throughout much of Asia and Africa (Norten and Pütz, 1999). Azadirachtin acts against a broad range of insect pests, exerting its effects through multiple modes of action. It inhibits feeding, functions as a repellent, disrupts the moulting process by interfering with ecdysone hormone production, and acts as a growth regulator. Additionally, it affects reproduction by inhibiting egg-laying and causing fertility disorders (Brahmachari, 2004; Feng and Isman, 1995; González Coloma et al., 2010; Lengai et al., 2020; Morgan, 2009; Mulla and Su, 1999).

Furthermore, several studies have reported the antiviral and antimicrobial effects of neem extracts and azadirachtin against plant pathogens, further highlighting their broad-spectrum bioactivity and potential role in sustainable crop protection systems (Akinbode and Ikotun, 2011; Benhammou et al., 2025).

Based on these multifaceted effects, we began testing azadirachtin against the larvae of the western corn rootworm in 2020 using seed dressing techniques. In 2020 and 2021, we conducted trials in various Hungarian regions with different levels of larval infestation, aiming to determine whether azadirachtin was effective and, if so, which seed dressing doses were optimal. For these studies, we used Neemazal T/S (10 g/L azadirachtin) and Neemazal F (50 g/L azadirachtin), supplied by Bio-Products Division at Coromandel International(India), applying seed dressing doses ranging from 10% (0.043 mg/seed) to 150% (0.065 mg/seed)

of the recommended rate. The experiments showed that azadirachtin can be used effectively against larvae, with positive results observed at seed dressing doses above 50% (0.022 mg/seed). In areas with especially high larval pressure – where modified Iowa mean values were 3.55 and 4.42 – higher doses (125% [0.053 mg/seed] and 150% [0.065 mg/seed]) proved most effective (Vörös and Ledóné Ábrahám, 2023). In the present study, moderate larval pressure generally corresponded to mIS values of approximately 3.0–3.5, whereas severe infestation pressure exceeded the economic threshold of about 3.5 on the modified Iowa scale.

In Hungary's Great Plain region, where average root damage on the mIS reached 4.42, we observed signs of larval damage (gooseneck symptoms) in some plants even at the higher 125% and 150% seed dressing doses. Although no economic loss occurred, these symptoms prompted us to investigate whether even higher doses – 200% (0.086 mg/seed) and 300% (0.129 mg/seed) – could provide full protection in areas where pest pressure exceeds economic thresholds (typically mIS > 3.5, where root damage can begin to affect yield) (Vörös and Ledóné Ábrahám, 2023). At the start of our investigation, we hypothesised that the mild gooseneck symptoms observed in previous years under high larval pressure could be reduced or eliminated by increasing the seed dressing dose. To our knowledge, this is the first field-based evaluation in Hungary of elevated azadirachtin seed-treatment doses up to 300% under severe western corn rootworm infestation. This study presents the 2022 results from three different sites in Hungary, each representing a distinct level of larval infestation.

### Material and Methods

In our 2022 experiments, we tested a preparation containing azadirachtin at three sites in Hungary: Röjtökmuzsaj, Perkáta, and Tiszalök, using seed dressing technology against the larvae of the western corn rootworm. The product used in the study was Neemazal F (Bio-Products Division at Coromandel International, India). With an active ingredient content of 5% (50 g/L), this formulation allowed us to apply higher seed dressing doses than those used in previous years.

#### The experimental site in Röjtökmuzsaj

Röjtökmuzsaj is located in northwestern Hungary. The experimental area forms part of the pathology research station of the National Food Safety Office, where maize has been grown continuously, or nearly continuously, for 60 years to support ongoing plant pathology studies. This site was selected because the western corn rootworm population has steadily increased over the past few decades and is now considered well-established. This region is also one of the cooler and wetter

areas of the country, where maize plants are generally better able to recover from larval damage due to more favourable weather conditions.

The soil at this site is classified as meadow soil – a type of hardened clay soil – rich in humus (3.25%), slightly acidic (pH 6.87), well supplied with potassium, and moderately supplied with phosphorus.

#### The experimental site in Perkáta

The Perkáta site is located in central Hungary, within one of the country's most productive maize-growing regions. The soil is classified as chernozem, a type of medium-hardened plain soil characterised by a high humus content (3.5%), a weakly alkaline pH (7.2), and a good supply of potassium and phosphorus. This location was chosen based on reports from a local farmer, who noted that rootworm damage in the area has been consistently high each year.

#### The experimental site in Tiszalök

Tiszalök is situated in the northeastern region of Hungary. This part of the Great Plain was among the first areas in the country where the western corn rootworm was detected, and significant annual damage continues to be reported. The soil is medium-hardened meadow chernozem with a neutral pH (7.01), a high humus content (3.17%), and medium levels of potassium and phosphorus.

#### Conditions of application of experimental materials

The experiments were conducted in small plots measuring  $4 \times 6$  metres, arranged in four replications using a randomised block design. Each plot consisted of 24 square metres ( $4 \times 6$  metres) of maize.

We used the DKC 5141 hybrid maize (DEKALB/Monsanto) in all treated plots, as in previous years, with a weight of 360 g per 1,000 seeds. The seed dressing fluid volume was calculated at 12 L per 1,000 kg of seeds, resulting in 4.32 mL of dressing fluid applied to 360 g of seed.

Percentage dose values – or seed dressing dose levels – refer to the standard previously used with Neemazal T/S (1% azadirachtin, 10 g/L). A 100% dose, therefore, corresponds to undiluted Neemazal T/S. Seed dressing was done manually, which was appropriate given the small quantity of seed. The seeding rate was standardised at 70,000 seeds/ha, in line with typical field practices (Table 1). Maize was sown during the second half of April 2022 at all experimental sites, following local agronomic practice. The sowing sequence was Tiszalök, Perkáta, and Rőjtökmuzsaj, corresponding approximately to early, mid-, and late April sowing periods, respectively.

Table 1. Seed dressing dose parameters and azadirachtin content per seed and per hectare.

| Dose (%) | 1000-seed weight (g) | Neemazal F (mL) | Water (mL) | Azadirachtin (mg/seed) | Azadirachtin (g/ha) |
|----------|----------------------|-----------------|------------|------------------------|---------------------|
| 300%     | 360                  | 2.58            | 1.74       | 0.129                  | 9.03                |
| 200%     | 360                  | 1.72            | 2.60       | 0.086                  | 6.02                |
| 100%     | 360                  | 0.86            | 3.46       | 0.043                  | 3.01                |

Note: Doses refer to seed dressing doses based on the undiluted Neemazal T/S reference (10 g/L azadirachtin). Dressing volumes were calculated for 360 g of seed, equivalent to 1000 seeds of the DKC 5141 maize hybrid.

Source: Authors' calculation.

#### Assessment of treatment effectiveness

To evaluate the effectiveness of azadirachtin treatments, untreated control plots were established, which received no seed dressing. In addition, Force 1.5 G, containing the active ingredient tefluthrin, was applied at a dose of 15 kg/ha. This product is one of the most widely used soil insecticides among farmers for controlling western corn rootworm larvae.

The same observation and recording procedures were applied across all treatments. Larvae present in the root zone were counted, and the average number of larvae per plant was calculated. Root damage was assessed using a standardised root damage rating system.

Each year, larval monitoring was timed according to population forecasts, which were based on pheromone traps. These traps consisted of yellow sticky cards baited with sex pheromones. Once the first adult beetles appeared, sampling began immediately, as this indicated that larval development in the soil was nearing completion (L3 stage or pupation).

From each experimental plot, five maize plants were randomly selected and excavated with a 20 × 20 cm soil block. After excavation, the number of live larvae was recorded – both those shaken from the roots and those remaining in the soil cavity. No distinction was made between fully developed larvae, free pupae, or newly emerged adults.

In general, field sites were selected along an east-to-west geographic gradient, as larval development in the Great Plain region typically advances by one to two weeks compared to Transdanubian areas. Larval sampling and root damage assessments were conducted during the peak larval feeding period, between late June and mid-July.

The excavated roots were placed into labelled bags, transported to the laboratory, soaked in water, and then assessed for damage using the mIS – a standardised root damage rating system that ranges from 1 to 6 in half-point

increments, with higher values indicating greater loss of root mass due to larval feeding. Larval counts and root damage were recorded at regular intervals and analysed using statistical methods.

#### Statistical analysis

Data on larval counts and root damage were analysed using one-way analysis of variance (ANOVA) in SPSS Statistics for Windows, Version 16.0 (SPSS Inc., Chicago, IL, USA), to compare the means of independent treatment groups. Each treatment consisted of four replicated plots, with five plants per plot assessed for larval counts and root damage. Data were analysed separately for each site and year. Prior to analysis, assumptions of normality and homogeneity of variance were checked. The Tukey's honest significant difference (HSD) post hoc test was used for pairwise comparisons. Differences were considered statistically significant at  $p \leq 0.05$ .

### Results and Discussion

Across the investigated experimental sites (Röjtökmuzsaj, Perkáta, Tiszalök), azadirachtin treatments reduced larval abundance and root damage compared to the untreated control. Differences among treated plots were generally small, although the 200% seed dressing dose frequently resulted in lower root injury values across sites. In contrast, the 300% dose tended to show less consistent performance under drought-affected conditions.

#### Experiment at Röjtökmuzsaj (2022)

In Röjtökmuzsaj, a comparison of azadirachtin treatments with the positive and untreated controls reveals that the highest average number of larvae developed on the untreated control plot ( $2.95 \pm 1.15$  larvae/plant). Among the azadirachtin-treated areas, the highest average larval count per plant was observed in the 300% treatment ( $1.80 \pm 1.28$  larvae/plant), followed by the 100% ( $1.30 \pm 1.13$ ) and 200% ( $1.15 \pm 1.09$ ) treatments. The larval count in the Force 1.5 G treatment was  $1.40 \pm 1.00$  larvae/plant, which falls between the 300% and 100% seed dressing doses (Figure 1).

Our analysis confirmed that larval counts varied significantly between plots ( $p = 0.000$ ;  $F = 8.286$ ), as determined by one-way ANOVA. The Tukey's post hoc test showed that the untreated control plot had a significantly higher average larval count value than plots treated with 300% ( $p_{\text{Tukey}} = 0.015$ ), 200% ( $p_{\text{Tukey}} = 0.000$ ), and 100% ( $p_{\text{Tukey}} = 0.000$ ) azadirachtin, as well as Force 1.5 G ( $p_{\text{Tukey}} = 0.000$ ). There was no statistically significant difference between the managed plots.

Based on the comparison of treatments with azadirachtin at different seed dressing doses and controls (Force 1.5 G and untreated control), the most significant average root damage occurred in the untreated control plot ( $3.40 \pm 0.53$ ), followed by areas treated with 300% azadirachtin ( $2.05 \pm 0.54$ ), Force 1.5 G ( $1.70 \pm 0.44$ ), 100% azadirachtin ( $1.55 \pm 0.36$ ), and 200% azadirachtin ( $1.45 \pm 0.39$ ).

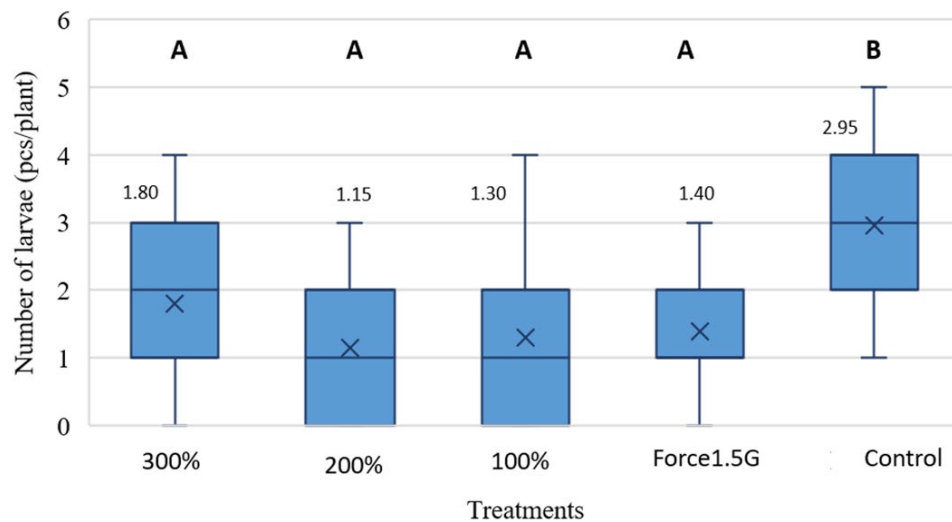


Figure 1. Average larval counts per plant in the various treatments at the Rőjtökmuzsaj site in 2022.

The central line represents the median, the “x” indicates the mean, the box shows the interquartile range, and the whiskers represent the minimum and maximum values. Different letters indicate statistically significant differences among treatments according to the Tukey’s HSD test ( $p \leq 0.05$ ).

Source: Authors’ calculations based on experimental data.

Compared to the control plot, all treatments showed lower modified Iowa (mIS) scale values. It is worth observing that the 300% dose did not outperform the lower seed dressing doses. This may be due to formulation-related effects on germination or early root development, especially under dry conditions (Figure 2).

ANOVA identified statistically significant differences in root damage across treatments ( $p = 0.000$ ;  $F = 61.092$ ). The Tukey’s post hoc test confirmed that the untreated control plot exhibited significantly higher root injury scores than those treated with 300% ( $p_{\text{Tukey}} = 0.000$ ), 200% ( $p_{\text{Tukey}} = 0.000$ ), and 100% azadirachtin ( $p_{\text{Tukey}} = 0.000$ ), as well as Force 1.5 G ( $p_{\text{Tukey}} = 0.000$ ).

The plot treated with 300% azadirachtin showed significantly higher root damage than those treated with 200% azadirachtin ( $p_{\text{Tukey}} = 0.001$ ) and 100%

azadirachtin ( $p_{\text{Tukey}} = 0.007$ ), but did not differ significantly from the Force 1.5 G plot ( $p_{\text{Tukey}} = 0.119$ ).

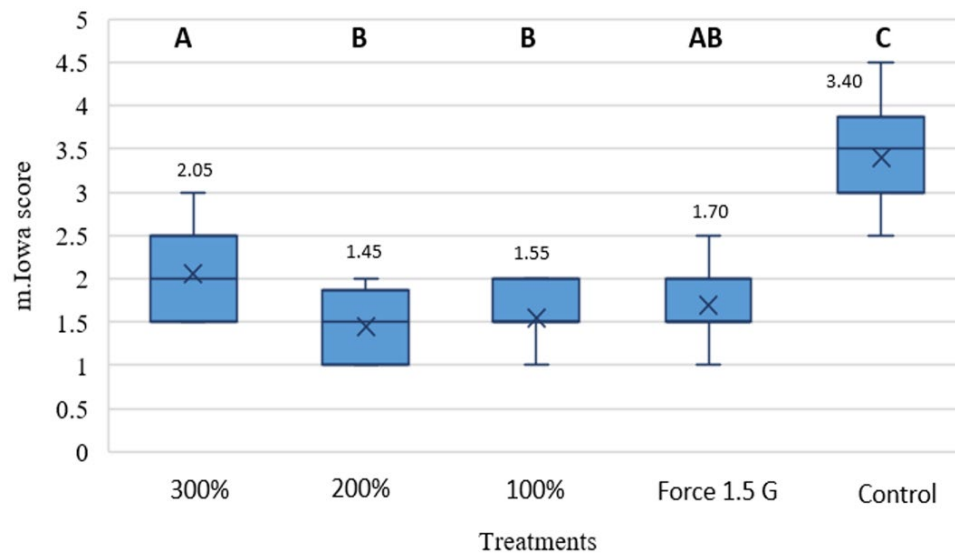


Figure 2. Average mIS scores per plant in the various treatments at the Röjtökmuzsaj site in 2022.

The central line represents the median, the “x” indicates the mean, the box shows the interquartile range, and the whiskers represent the minimum and maximum values. Different letters indicate statistically significant differences among treatments according to the Tukey’s HSD test ( $p \leq 0.05$ ).

Source: Authors’ calculations based on experimental data.

#### Experiment at Perkáta (2022)

At the Perkáta site, the highest average number of larvae per plant was recorded in the untreated control plot ( $3.20 \pm 2.46$  larvae/plant). All treated plots showed significantly lower larval counts. Among these, the 300% azadirachtin treatment ( $0.70 \pm 0.73$  larvae/plant) and Force 1.5 G ( $0.70 \pm 0.66$  larvae/plant) had the highest larval numbers, followed by the 200% ( $0.60 \pm 0.68$ ) and 100% ( $0.50 \pm 0.76$ ) azadirachtin treatments. Notably, even the 100% seed dressing dose performed slightly better than the standard chemical treatment, indicating its potential as a sustainable alternative under these field conditions (Figure 3).

Larval count data varied significantly across plots, as confirmed by ANOVA ( $p = 0.000$ ;  $F = 16.510$ ). The Tukey’s HSD post hoc analysis revealed that the untreated control differed significantly from every plot where an insecticide had been applied ( $p < 0.05$ ). In contrast, differences among the application groups

were not statistically significant. Overall, both azadirachtin and Force 1.5 G – regardless of seed dressing dose – substantially reduced larval abundance relative to the control.

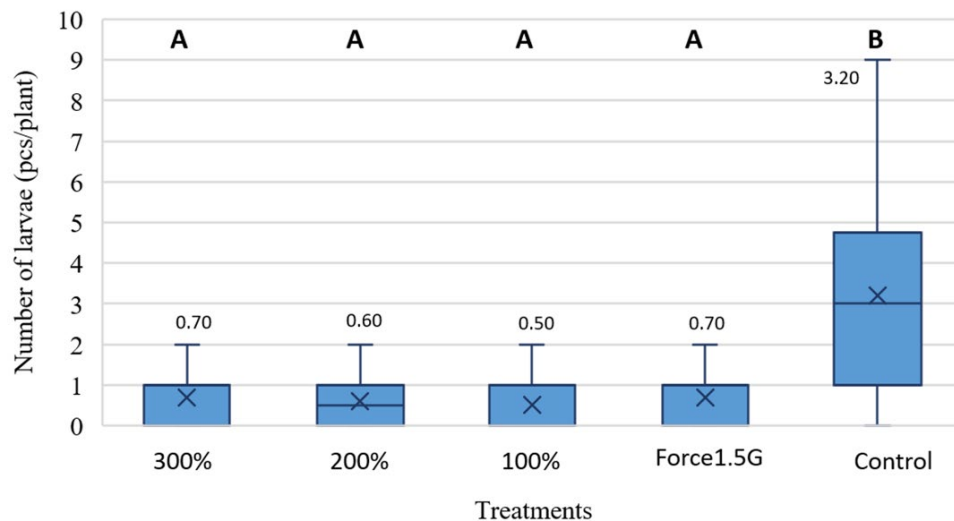


Figure 3. Average larval counts per plant in the various treatments at the Perkáta site in 2022.

The central line represents the median, the “x” indicates the mean, the box shows the interquartile range, and the whiskers represent the minimum and maximum values. Different letters indicate statistically significant differences among treatments according to the Tukey’s HSD test ( $p \leq 0.05$ ).

Source: Authors’ calculations based on experimental data.

In Perkáta, the highest average root damage was observed in the untreated control plot ( $3.93 \pm 1.23$ ), followed by those receiving 300% azadirachtin ( $2.08 \pm 0.49$ ), Force 1.5 G ( $1.80 \pm 0.57$ ), 100% azadirachtin ( $1.65 \pm 0.40$ ), and 200% azadirachtin ( $1.58 \pm 0.41$ ). In the control plot, the root chewing value exceeded the 3.5 mIS threshold, which is considered the limit of economic damage, whereas in all other plots, the values remained below this threshold (Figure 4).

Treatment effects differed significantly, as indicated by ANOVA ( $p = 0.000$ ;  $F = 39.989$ ). The Tukey’s post hoc test showed that the untreated control plot had significantly higher root damage scores than all treated plots: 300% azadirachtin ( $p = 0.000$ ), 200% ( $p = 0.000$ ), 100% ( $p = 0.000$ ), and Force 1.5 G ( $p = 0.000$ ). No statistically significant differences were observed among the treated plots, indicating that azadirachtin and Force 1.5 G were similarly effective across all tested seed dressing doses. Overall, root damage was significantly lower in all treated plots compared to the untreated control.

Thus, all seed dressing treatments – including Force 1.5 G and the varying seed dressing doses of azadirachtin – were equally or nearly equally effective in reducing larval counts and root damage compared to the untreated control.

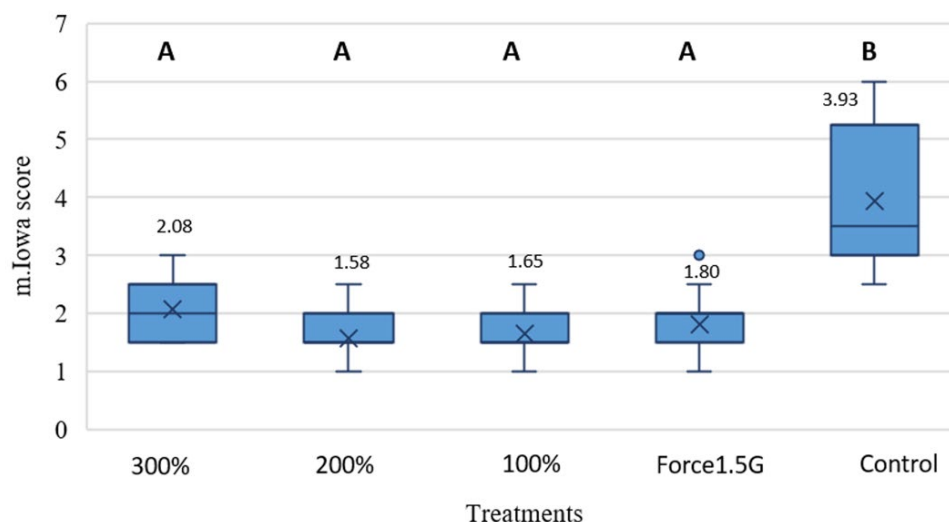


Figure 4. Average mIS scores per plant in the various treatments at the Perkáta site in 2022.

The central line represents the median, the “x” indicates the mean, the box shows the interquartile range, and the whiskers represent the minimum and maximum values. Different letters indicate statistically significant differences among treatments according to the Tukey’s HSD test ( $p \leq 0.05$ ).

Source: Authors’ calculations based on experimental data.

#### Experiment at Tiszalök (2022)

At the Tiszalök site, the untreated control plot had the highest average number of larvae per plant ( $3.90 \pm 2.13$ ), followed by the 300% azadirachtin treatment ( $2.15 \pm 1.23$ ), Force 1.5 G ( $1.85 \pm 1.31$ ), 200% azadirachtin ( $1.45 \pm 1.15$ ), and 100% azadirachtin ( $1.40 \pm 1.23$ ) (Figure 5).

ANOVA results ( $p = 0.000$ ;  $F = 9.955$ ) demonstrated marked variation in larval counts per plant across the treatment groups at the Tiszalök site. According to the Tukey’s post hoc test, the untreated control plot supported significantly more larvae than any of the application groups: 300% azadirachtin ( $p = 0.002$ ), 200% ( $p = 0.000$ ), 100% ( $p = 0.000$ ), and Force 1.5 G ( $p = 0.000$ ). However, differences among the insecticide-treated plots were not statistically significant. Taken together, these results show that all azadirachtin seed dressing doses, along with

Force 1.5 G, led to a noteworthy and comparable reduction in larval density compared to the untreated control.

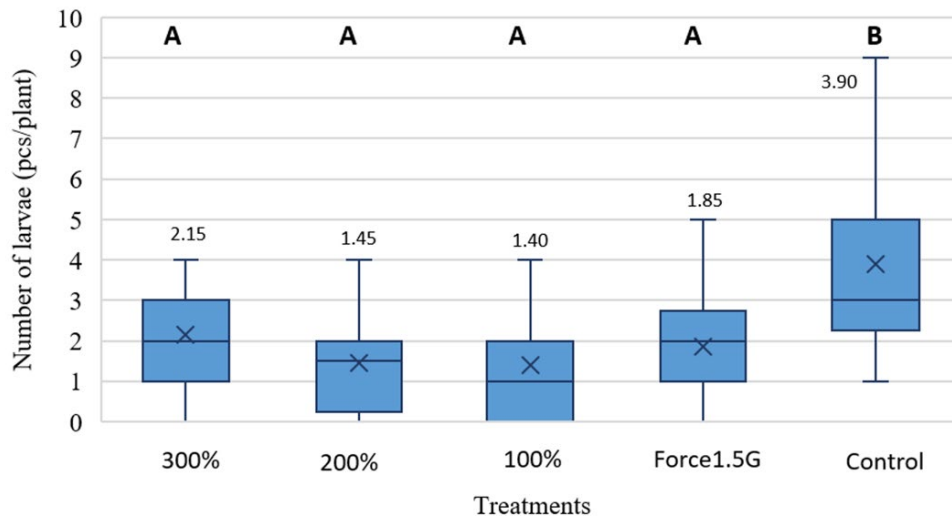


Figure 5. Average larval counts per plant in the various treatments at the Tiszalök site in 2022.

The central line represents the median, the “x” indicates the mean, the box shows the interquartile range, and the whiskers represent the minimum and maximum values. Different letters indicate statistically significant differences among treatments according to the Tukey’s HSD test ( $p \leq 0.05$ ).

Source: Authors’ calculations based on experimental data.

Regarding root damage, the untreated control plot had the highest average injury score ( $5.10 \pm 0.90$ ), well above the economic threshold of 3.5 on the mIS. In contrast, the treated plots remained below this threshold, with average scores of  $2.85 \pm 0.83$  (300% azadirachtin),  $2.30 \pm 0.89$  (Force 1.5 G),  $2.10 \pm 0.87$  (100% azadirachtin), and  $2.03 \pm 0.68$  (200% azadirachtin) (Figure 6).

Significant differences in root damage scores among treatments were confirmed by ANOVA ( $p = 0.000$ ;  $F = 47.117$ ). The Tukey’s post hoc test revealed that the untreated control plot had significantly higher injury values than all treated plots: 300% azadirachtin ( $p = 0.000$ ), 200% ( $p = 0.000$ ), 100% ( $p = 0.000$ ), and Force 1.5 G ( $p = 0.000$ ). In addition, the 300% azadirachtin plot had significantly higher root damage than both the 200% ( $p = 0.020$ ) and 100% ( $p = 0.044$ ) treatments.

These findings indicate that although all azadirachtin and Force 1.5 G treatments reduced larval populations and root damage compared to the control, the

300% dose showed marginally higher root damage than the lower azadirachtin doses, possibly reflecting the early developmental effects previously noted.

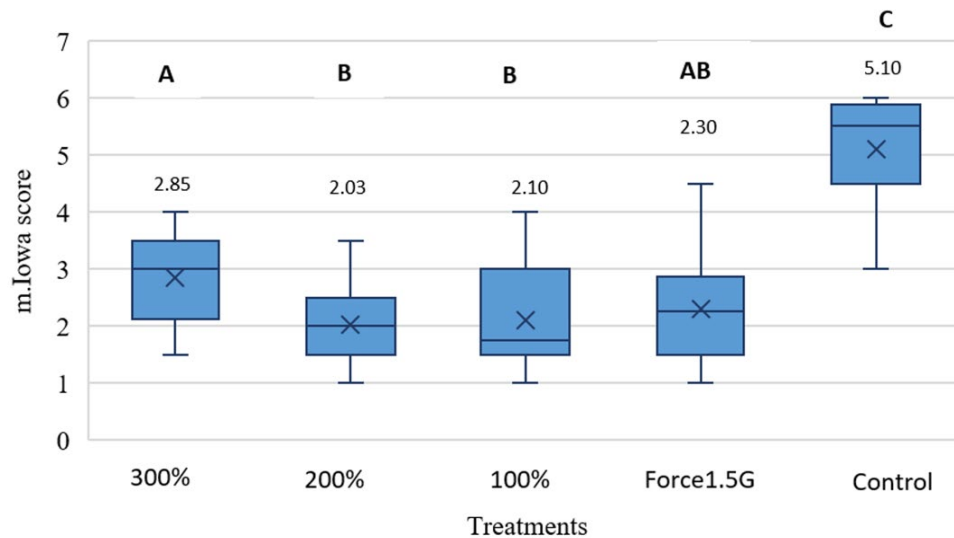


Figure 6. Average mIS scores per plant in the various treatments at the Tiszalök site in 2022.

The central line represents the median, the “x” indicates the mean, the box shows the interquartile range, and the whiskers represent the minimum and maximum values. Different letters indicate statistically significant differences among treatments according to the Tukey’s HSD test ( $p \leq 0.05$ ).

Source: Authors’ calculations based on experimental data.

Controlling *Diabrotica* larvae is challenging due to the long interval (5–8 weeks) between maize sowing and the emergence of larvae from overwintering eggs. This delay highlights the importance of biopesticides with extended activity, such as azadirachtin, which remain effective throughout the critical larval period. By maintaining consistent pressure on the pest population, these long-acting treatments reduce the likelihood that some larvae will survive sublethal exposure and contribute to the gradual development of resistance at the population level (Lengai et al., 2020). Our multi-year, multi-site field trials assessed the effectiveness of azadirachtin applied as a seed dressing under varying larval pressures. In 2020, we demonstrated in Gyömöre that azadirachtin significantly reduced root damage even under moderate infestation levels (mIS score: 3.23), with doses above 50% performing similarly to Force 1.5 G (Vörös and Ledóné Ábrahám, 2023). In 2021, we extended trials to Röjtökmuzsaj and Hajdúvid, where larval pressure was higher (mIS: 3.55 and 4.42, respectively). Visual field

inspections revealed slight stem tilting in plots treated with 50–150% of the recommended dose, suggesting that higher seed dressing doses may be necessary under heavy infestation. Based on these results, the 2022 trials focused on high-pressure sites and tested doses of 100%, 200%, and 300%. However, the extreme drought that year, especially in Röjtökmuzsaj and Tiszalök, affected the results. Limited rainfall after sowing (e.g., 30 mm in Röjtökmuzsaj) may have contributed to poorer germination and establishment, particularly at the 300% dose, which likely delayed emergence due to the heavy seed oil coating (Neemazal F contains 95% vegetable oil). This poorer establishment may have increased the vulnerability of young plants to more developed larvae (L2–L3 stages), which may partly explain the relatively higher root damage observed at this dose. Although some differences between treated plots were not statistically significant, trends in root damage suggest that 300% dosing may be less advantageous under drought conditions.

Even so, all azadirachtin treatments significantly outperformed the untreated control. These findings support our hypothesis that azadirachtin can provide long-term protection when applied at the appropriate seed dressing dose. In addition to its insecticidal activity, azadirachtin has also been reported to possess antiviral and antimicrobial properties against several plant pathogens (Akinbode and Ikotun, 2011; Benhammou et al., 2025). This broad-spectrum bioactivity further supports its potential role in integrated pest and disease management (IPDM) systems aimed at reducing reliance on synthetic pesticides. Unlike many conventional insecticides that act through a single target site, azadirachtin affects multiple physiological and behavioural processes in insects, including feeding, moulting, development, and reproduction. This multifaceted mode of action may contribute to a lower risk of resistance development in pest populations and supports its long-term value in sustainable crop protection strategies. Compared with many single-target synthetic insecticides, azadirachtin acts through multiple physiological pathways, which may also help lower the risk of resistance development in pest populations. Other studies have demonstrated azadirachtin's success against foliar pests (e.g., Li et al., 2003; Mancebo et al., 2002; Senthil et al., 2006), and more recent research shows promise against soil-dwelling pests as well. Xie et al. (1991) reported positive laboratory results using soil application against corn rootworm larvae, while our own field-based seed dressing approach is simpler and better aligned with large-scale practice.

Toepfer et al. (2021) found that azadirachtin granules (200–380 g/ha) offered effective protection under greenhouse conditions. However, granular formulations depend heavily on soil moisture. Our previous field trials with granules revealed the presence of undissolved material under dry conditions. In contrast, seed dressing ensures direct uptake of the active ingredient by the germinating plant, resulting in sustained protection at much lower application rates (1.54–9.03 g/ha).

A limitation of this study is that the direct comparison of the 200% and 300% seed dressing doses was conducted during only one growing season (2022), which was characterised by severe drought conditions. These environmental conditions may have influenced treatment performance, particularly under low soil moisture levels. In addition, although poorer emergence and establishment were observed at the higher dose, no direct germination or emergence measurements were performed. Therefore, the effectiveness of elevated azadirachtin doses may depend on local infestation pressure, soil moisture, and seasonal variability, highlighting the need for further multi-year field evaluations.

### Conclusion

Our multi-year field trials have demonstrated that azadirachtin, when applied as a seed dressing, provides effective and sustained protection against western corn rootworm (*Diabrotica virgifera virgifera*) larvae under varying levels of pest pressure. Unlike granular formulations, which heavily depend on soil moisture and may leave undissolved residues under dry conditions, seed dressing ensures the direct uptake of the active ingredient by the germinating plant, allowing for much lower application rates (1.54–9.03 g/ha) while maintaining reliable efficacy.

In the 2022 trials, conducted under high infestation conditions (average mIS: 3.93–5.10), the 200% seed dressing dose (0.086 mg/seed) showed the most favourable overall performance across sites. This treatment provided the best balance of efficacy and crop safety, particularly under high infestation pressure, significantly reducing larval feeding damage and helping to prevent the severe root damage typically observed under intense pest pressure.

Importantly, increasing the dose to 300% did not improve protection. On the contrary, the poorer performance observed at the 300% dose under dry weather conditions may have been associated with delayed seedling emergence caused by the heavier oil coating (NeemAzal F is 95% vegetable oil), potentially leaving plants more vulnerable to older larvae.

Azadirachtin also holds several practical and environmental advantages over conventional insecticides: it is cost-competitive, easy to apply via seed dressing, safe for beneficial organisms and workers, and permitted in organic farming systems.

In summary, a 200% azadirachtin seed dressing provides a simple, effective, and environmentally sustainable method for protecting maize from one of its most economically damaging pests.

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EFIKASNOST POVEĆANIH DOZA AZADIRAHTINA U SUZBIJANJU LARVI  
*DIABROTICA VIRGIFERA VIRGIFERA* U USEVU KUKURUZA SA  
VISOKIM STEPENOM INFESTACIJE

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R e z i m e

Kukuruzna zlatica (*Diabrotica virgifera virgifera* LeConte) predstavlja značajnu štetočinu u Mađarskoj, naročito u sistemu gajenja kukuruza u monokulturi. S obzirom na to da su mnogi efikasni sintetički insekticidi za tretiranje semena i primenu preko zemljišta povučeni iz upotrebe, povećan je interes za ekološki prihvatljive alternative. Među njima se izdvaja azadirachtin, insekticid poreklom iz drvenaste biljke *Azadirachta indica*, koji predstavlja obećavajuću opciju. Sproveli smo višegodišnja poljska ispitivanja efekata azadirachtina u suzbijanju kukuruzne zlatice primenjenog tretiranjem semena u dozama od 0,022 mg/semenu (50%) do 0,129 mg/semenu (300%), pri čemu je doza od 0,043 mg/semenu (100%) bila preporučena doza proizvođača. Na parcelama sa umerenom brojnošću larvi, doze od 0,053 do 0,065 mg/semenu (125–150%) značajno su smanjile ekonomske štete, iako su zabeležena manja oštećenja korena. Tokom 2022. godine, više doze (200% i 300%) testirane su u uslovima intenzivnih infestacija larvama kukuruzne zlatice (modifikovana Ajova skala 3,93–5,10). Na svim lokalitetima, doza od 0,086 mg/semenu (200%) pokazala je najpovoljnije ukupne performanse, posebno u smanjenju oštećenja korena, dok razlike u broju larvi među tretiranim parcelama generalno nisu bile statistički značajne. Nasuprot tome, doza od 0,129 mg/semenu (300%) bila je povezana sa slabijim razvojem biljaka u ranim fenofazama, u uslovima suše, verovatno zato što je formulacija bogata uljem ometala klijanje i apsorpciju vode. Ovi rezultati ukazuju na potrebu prilagođavanja doza lokalnim uslovima. Tretman semena azadirachtinom mogao bi da predstavlja efikasnu i održivu alternativu sintetičkim insekticidima, pri čemu doza od 0,086 mg/semenu (200%) pruža najbolji balans efikasnosti i bezbednosti za usev kukuruza u uslovima intenzivnog napada larvi kukuruzne zlatice.

**Ključne reči:** *Diabrotica virgifera virgifera*, štetočine kukuruza, azadirachtin, drvo nima, biološke metode suzbijanja.

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EARLY-STAGE MANAGEMENT OF BROWN PLANTHOPPER  
(*NILAPARVATA LUGENS* STÅL) THROUGH SEED TREATMENT:  
A PREVENTIVE STRATEGY IN RICE CULTIVATION

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**Abstract:** Early infestation by brown planthopper (BPH) is common in rice ecosystems. Foliar application of insecticides is normally practised but adversely affects natural enemies and the environment. This study evaluated the effects of insecticidal seed treatments using a randomised design with three replications at the Bangladesh Rice Research Institute from August 2024 to March 2025. Germination percentage varied significantly among treatments, with the highest germination in the untreated control (91.3%), while the lowest in cartap (65.0%). Neonicotinoid seed treatments maintained superior germination (>87%) and promoted seedling vigour. Seedling damage was highest in the untreated control (>81%) and cartap (>54%), whereas imidacloprid (9.00–12.33%) and thiamethoxam (2.67–5.33%) provided strong protection with <12% damage under both no-choice and choice tests. The dynamics of the BPH population further confirmed consistent suppression by imidacloprid and thiamethoxam across 28 days after sowing, while the control plots sustained the highest densities. Sweep collections showed higher pest abundance in untreated and cartap plots, whereas imidacloprid- and thiamethoxam-treated plots recorded significantly lower populations from the seedbed. Natural enemy abundance also varied, with untreated and isoprocarb plots harbouring more green mirid bugs, while spider populations were highest under imidacloprid treatment, suggesting relatively lower

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non-target impacts on natural enemies among the treatments. Overall, imidacloprid and thiamethoxam were most effective in enhancing seedling vigour and suppressing BPH, while maintaining a relatively higher field abundance of spiders compared with other treatments. These findings highlight the potential of seed treatments for early-stage BPH management, reducing reliance on foliar sprays.

**Key words:** rice, seed treatment, germination percentage, imidacloprid, neonicotinoids, natural enemy.

### Introduction

Rice (*Oryza sativa* L.; Family: Poaceae) is one of the most extensively cultivated staple cereal crops in many countries, and approximately one-third of the world's population primarily depends on it. In Bangladesh, it serves as the staple food, and is essential for ensuring food security, and is among the crops grown widely across the nation throughout the year. Rice is cultivated during the three different rice-producing seasons, namely – Boro (irrigated rice), Aus (monsoon rice), and Aman (rain-fed with additional irrigation). However, a number of factors, such as variety selection, cultural management practices, abiotic and biotic factors, and environmental conditions, affect rice production (Rana et al., 2025; Roy et al., 2025). Insect pests frequently infest rice fields during the rice-growing period. A wide variety of 232 harmful insect pest species and 375 beneficial arthropod species, including both predatory and parasitic species, are closely associated with rice farming in Bangladesh's rice ecosystem. According to recent studies, the brown planthopper (*Nilaparvata lugens* Stål), the white-backed planthopper (*Sogatella furcifera* Horváth), the gall midge (*Orseolia oryzae*), Wood-Mason, the rice leaf folder (*Cnaphalocrocis medinalis* Guenée), the green leafhopper (*Nephotettix virescens* Distant), and the rice hispa (*Diuraphis armigera* Oliver) are the most common pest species in Bangladesh (Islam and Catling, 2012; Roy et al., 2024).

Among these pests, infestation by the brown planthopper is very common in the rice ecosystem of Bangladesh. Through its stem-sucking behaviour, it weakens the plant and often appears on the lower part of the rice stem. BPH nymphs and adults directly damage rice plants by feeding on phloem sap from the tillering to milking stages of rice and by transmitting viral diseases such as rice grassy stunt virus (RGSV) and ragged stunt virus (RRSV). When BPH feeds heavily on the phloem, the plants can die within a few days, a condition known as “hopperburn” before farmers can implement any preventative measures (Islam and Catling, 2012). In addition, the overlapping of rice seasons in Bangladesh is also responsible for insect pest infestation and migration from one season to another season (Islam and Catling, 2012; Roy et al., 2024). The Boro season extends from mid-November to mid-May, whereas the Aus seasons runs from mid-March to August, and the Aman season extends from July to November in Bangladesh. Moreover, the peak abundance of BPH is observed in March–June and September–

November (Islam and Catling, 2012; Roy et al., 2024). Thus, BPH infestation is severe at the early growth stage in some areas of Bangladesh. Chemical management of BPH in rice fields has commonly involved manual foliar applications of organophosphates, nereistoxin, pyrethroids, diamides, and neonicotinoids. However, at the seedling and early growth stages of rice, synthetic insecticides affect not only BPH populations but also the populations of natural enemies. However, using foliar sprays to transfer pesticides from older leaves to newer leaves, or from the mother tiller to new tillers, is challenging (Buchholz and Nauen, 2002). To protect young leaves and new tillers, frequent insecticide sprays are therefore required, which increases management costs, harms natural enemies, and causes environmental pollution. Since insecticides on seeds can be continually absorbed and transported to newer leaves due to the high upward conduction of neonicotinoids, seed treatments offer a good solution to this issue compared with foliar sprays (Alford and Krupke, 2017). Therefore, insect infestation can be avoided during the seedling stage with a single insecticide application to seeds. Because of the potency of neonicotinoids, seed treatments have been shown to be a particularly effective and efficient strategy that requires overall less insecticide (Kundoo et al., 2018). Seed treatment has therefore emerged as a promising new approach to crop protection. Because of their systemic properties, which are expressed throughout the plant, seed coatings, seed dressings and soil treatments are also considered much safer and may be able to replace foliar spraying, providing effective protection against pests from an earlier stage of the growth cycle (Jeschke et al., 2011).

Nowadays, soil and seed treatments account for approximately 60% of all neonicotinoid applications, and most spray applications are specifically designed to combat pests that attack crops such as rice, wheat, maize, vegetables, cotton, potatoes, sugar beet, and others (Jeschke et al., 2011). Young plants can be effectively and safely protected from insect attack by seed dressing, pelleting, multilayer coating and film coating of seeds. Very little literature is available on seed treatments against BPH. Furthermore, a thorough investigation is still needed to determine how registered insecticides differ from other neonicotinoid insecticides used as seed treatments in terms of their safety for rice and natural enemies as well as their effectiveness in managing BPH at the early growth stage of rice. Thus, our present study was undertaken to investigate the efficacy of different synthetic insecticides for the management of BPH and their effects on seed germination, root-shoot development and natural enemies at the early stage of rice.

## Materials and Methods

### Experimental site, design and materials

The experiment was conducted at the greenhouse facilities of the Entomology Division of the Bangladesh Rice Research Institute (BRRI), Gazipur, Bangladesh,

and in the research field of BRRI from August 2024 to March 2025. BRRI dhan89, a modern rice variety for the irrigated (Boro) season, was used for this experiment and was collected from the storage facilities of the Entomology Division, BRRI. After collection, the seeds were fully sun-dried and carefully cleaned. A completely randomised design (CRD) with three replications was used in the greenhouse. An aluminium tray (185 cm length x 100 cm width x 15 cm height) was used under greenhouse conditions.

#### Rearing of brown planthopper (BPH)

Adults of BPH were collected from the research field of the Bangladesh Rice Research Institute (BRRI). After collection, the adults were placed in a rearing cage (160 cm length x 80 cm width x 100 cm height) in the Entomology Division, BRRI greenhouse. The cage was made of a metal frame, with all sides covered by metal netting (mesh number 40) except the bottom. There was an opening at the front of the rearing cage, which could be opened and closed for easy operation. Rice plants of the BR3 variety (susceptible to insects) at the tillering stage were used as the feeding plants for BPH. The feeding plants were grown separately within the greenhouse under insect-free conditions, supplied for BPH feeding, and replaced as required. The rearing procedure was continued until the required number of insects was obtained. The greenhouse was maintained at  $27\pm 2^{\circ}\text{C}$  and  $70\pm 5\%$  relative humidity, with a 14-hour light period and a 10-hour dark period.

#### Experimental treatment and procedure

Seven insecticides and one untreated control were used in this experiment (Table 1). The insecticides were placed in earthen pots according to Table 1 and mixed carefully with 1 L of water on 17 August 2024 for the first trial and on 2 January 2025 for the second trial. Then, 500 g of BRRI dhan89 seeds, which had previously been sun-dried and cleaned, were soaked in each earthen pot for each treatment sequentially and kept for another 24 hours. Only fresh water was used for the untreated control.

After 24 hours of soaking, the water solution was removed from the pots and the seeds were transferred to a germination chamber and kept for another 72 hours for adequate germination. One hundred seeds from each treatment were placed separately in Petri dishes (containing moist filter paper at the bottom) for germination tests and measurement of root and shoot length.

Table 1. Names of different insecticide treatments and their doses for seed treatment.

| Treatment    | Insecticide name       | Dose g/mL L <sup>-1</sup> | Group name            |
|--------------|------------------------|---------------------------|-----------------------|
| T1           | imidacloprid 70 WG     | 1.50 g                    | Neonicotinoid         |
| T2           | cartap 50 SP           | 1.50 g                    | Nereistoxin analogues |
| T3           | isoprocarb 50 WP       | 1.50 g                    | Carbamate             |
| T4 (control) | Water only             | -                         | Untreated control     |
| T5           | tetratanipole 20Sc     | 1.50 mL                   | Diamides              |
| T6           | cyantraniliprole 40 SC | 1.50 mL                   | Diamides              |
| T7           | thiamethoxam 25 WG     | 1.50 g                    | Neonicotinoid         |
| T8           | buprofezin 40 EC       | 1.50 mL                   | Buprofezin            |

Source: Authors' systematisation based on published literature.

Soil preparation, sowing of germinated seeds and BPH infestation under greenhouse conditions

Soil was collected from the research field of BRRI, Gazipur. After collection, the soil was fully sun-dried, then compost and organic fertilisers were thoroughly mixed into it, and the mixed soil was loosened and transferred into the metal aluminium trays (185 cm length x 100 cm width x 15 cm height). The ratio of soil to compost was 2:1. Each aluminium tray was divided into four parts by hand, making bunds of soil. Thus, for one set of replication, two aluminium trays were needed. Then the germinated seeds were sown according to the experimental design. Each replicated treatment was arranged in side by side using two trays, which were covered with a net (mesh number 40) supported by a metal structure. This method is called the choice method. In the choice method, brown planthoppers were given simultaneous access to the insecticide-treated host plant material (e.g., all treated plants) and untreated (control) host plant material. It primarily assessed the BPH preference for or rejection of the treated plants. If the insecticide is repellent or acts as an anti-feedant, the BPH will choose another plant that is less toxic, less repellent, or untreated.

We also used a no-choice technique. In a no-choice method, the BPH were confined to insecticide-treated host plant material only (separate from one treatment to another), with no alternative food source provided. This provides a rigorous measure of the insecticide's absolute toxicity, repellent and anti-feedant activity, or its physiological host range effect. Since the BPH is forced to be in contact with and feed only on the treated plant material, this determines whether the insecticide will kill the pest even if it finds the treated plant undesirable.

In the no-choice method, germinated seeds of one treatment were sowed in a small metal tray (40 cm length x 30 cm width x 15 cm height). A total of eight trays

were required for one replication. The replicated aluminium trays were fully covered with net, each supported by a metal frame. The trays were placed in greenhouse conditions at  $27\pm1^{\circ}\text{C}$  and  $70\pm5\%$  relative humidity.

After 7 days of seed sowing on the trays, when the newly emerged rice seedlings had produced two leaves, second to third instar brown planthopper (BPH) nymphs, previously reared, were introduced at 1000–1100 nymphs tray<sup>-1</sup> in the choice method and at 300–350 nymphs tray<sup>-1</sup> in the no-choice method.

#### Seedbed preparation and sowing of seeds in the seedbed

The seedbed was prepared by ploughing and laddering in the wet research field of BRRI, Gazipur. Previously germinated seeds were then sown (21 August 2024 for the 1<sup>st</sup> trial and 06 January 2025 for the 2<sup>nd</sup> trial) into the moist seedbed (5 m long  $\times$  1 m wide) for one treatment and subsequently for all treatments in a randomised complete block design (RCBD), with three replications.

#### Data collection

The germination percentage of seeds (Eq. 1) was calculated from 100 seeds separately placed in Petri dishes at seven days after soaking. The root and shoot lengths were also measured from 10 seedlings in Petri dishes after seven days of soaking. Seedling damage (%) was calculated by assessing 100 randomly selected seedlings (Eq. 2) and comparing the results with IRRI (2013) on a weekly basis up to 21 days of insect infestation and 28 days after sowing in both choice and no-choice methods. The number of BPHs was counted from 20 randomly selected seedlings on a weekly basis in both choice and no-choice methods. For F<sub>1</sub> progeny emergence, five seedlings were randomly selected, placed in a moist test tube, and covered with a cotton ball at 19 days after insect infestation for one treatment, and regularly observed for BPH nymph emergence. This process was carried out for all treatments and replications. In field conditions, insects were collected weekly from the seedbeds using sweep nets. Sweeping started seven days after seed sowing and continued up to eight weeks after sowing. Sweeping was done using rectangular sweep nets (Kabir et al., 2023), beginning from one side of a single seedbed and then repeated in the same way from the opposite side. After collection, insects were placed in a deep freezer to ensure mortality, then counted and recorded. The entire procedure was repeated twice.

$$\text{Seed germination percentage} = \frac{\text{Number of germinated seeds}}{\text{Total number of tested seeds}} \times 100 \quad \text{Eq. (1)}$$

$$\text{Seedling damage percentage} = \frac{\text{Number of damaged seedlings}}{\text{Total number of counted seedlings}} \times 100 \quad \text{Eq. (2)}$$

### Statistical analysis

We used the “AgroR” package to create graphs and the “doibioresearch” package for analysis of variance (ANOVA) and the mean comparison (least significant difference) test was accomplished by the Shapiro-Wilk test for normality, at the 5% significance level in R studio software (version 2025.05.0).

## Results and Discussion

### Germination percentage of seeds among different treatments

The germination percentage of seeds exhibited a significant difference among the treatments (Table 2). Statistically, the highest percentage of seed germination was observed in the untreated control (91.33%), followed by the other insecticide treatments (imidacloprid, isoprocarb, tetratanipole, cyantraniliprole, thiamethoxam and buprofezin), except T<sub>2</sub> (cartap), where cartap (65.00%) showed the lowest germination percentage. Furthermore, imidacloprid, isoprocarb, tetratanipole, cyantraniliprole, thiamethoxam and buprofezin all resulted in more than 87% seed germination (Table 2). Reduced germination under cartap treatment may be attributed to its phytotoxic effects on seed metabolism, particularly through interference with enzymatic activities involved in seed germination.

Table 2. Germination (%), seedling vigour, damage percentage of seedlings and number of F<sub>1</sub> emergences among different treatments.

| Treatment | Germination (%) | Root length (cm) 7 days after soaking | Shoot length (cm) 7 days after soaking | Damage percentage of rice seedlings |           | Number of F <sub>1</sub> emergences '5 plants <sup>-1</sup> ' |           |
|-----------|-----------------|---------------------------------------|----------------------------------------|-------------------------------------|-----------|---------------------------------------------------------------|-----------|
|           |                 |                                       |                                        | Choice                              | No-choice | Choice                                                        | No-choice |
| T1        | 87.67 b         | 5.57 a                                | 4.11 a                                 | 12.33 f                             | 9.00 e    | 25.33 d                                                       | 21.00 c   |
| T2        | 65.00 c         | 5.06 b                                | 3.41 bc                                | 56.67 b                             | 54.00 b   | 68.33 b                                                       | 69.67 b   |
| T3        | 88.33 b         | 4.83 b                                | 3.58 ab                                | 44.00 cd                            | 42.67 c   | 48.67 c                                                       | 104.00 a  |
| T4        | 91.33 a         | 4.25 c                                | 3.49 bc                                | 81.67 a                             | 90.67 a   | 108.00 a                                                      | 113.67 a  |
| T5        | 87.67 b         | 3.29 e                                | 2.99 cd                                | 53.33 bc                            | 49.33 bc  | 68.67 b                                                       | 72.33 b   |
| T6        | 88.33 b         | 3.10 e                                | 2.80 d                                 | 26.67 e                             | 25.33 d   | 56.33 c                                                       | 66.00 b   |
| T7        | 87.33 b         | 3.54 de                               | 3.24bcd                                | 5.33 f                              | 2.67 e    | 16.33 d                                                       | 6.67 c    |
| T8        | 87.33 b         | 3.85cd                                | 2.94 cd                                | 35.00 de                            | 30.67 d   | 57.67 c                                                       | 66.00 b   |
| Lsd       | 2.54            | 0.48                                  | 0.54                                   | 10.98                               | 9.20      | 10.45                                                         | 16.19     |
| CV (%)    | 1.72            | 6.69                                  | 10.15                                  | 16.11                               | 13.97     | 10.74                                                         | 14.41     |
| P value   | <0.001          | <0.001                                | 0.004                                  | <0.001                              | <0.001    | <0.001                                                        | <0.001    |

Note: Lsd: Least significance difference; CV: Coefficient of variation.

Source: Authors' own data.

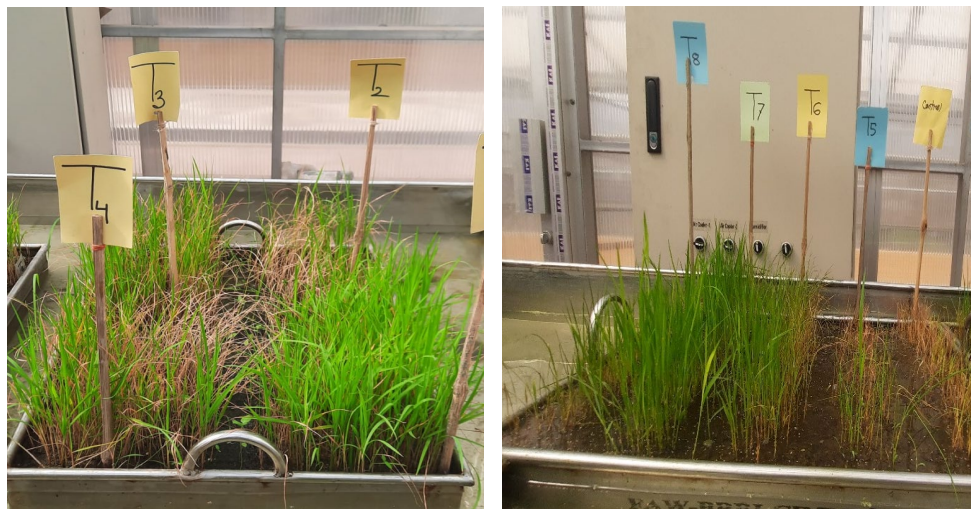
In contrast, imidacloprid, thiamethoxam, and other neonicotinoid treatments maintained relatively high germination (>87%), suggesting lower phytotoxic impact and better seed vigour. Thiamethoxam treatment of maize seeds has been shown to increase gibberellic acid synthesis and decrease abscisic acid synthesis, thus changing germination patterns and increasing germination in the presence of weeds (Afifi et al., 2015). Similar findings were reported by Ding et al., (2018), Lanka et al., (2017), and Xi et al., (2022), who observed that neonicotinoid insecticides such as imidacloprid, thiamethoxam and chlorantraniliprole seed treatments enhanced germination, root and shoot length and vigour index in rice by altering the hormonal network responsible for stress tolerance.

#### Root and shoot length of seedlings among different treatments

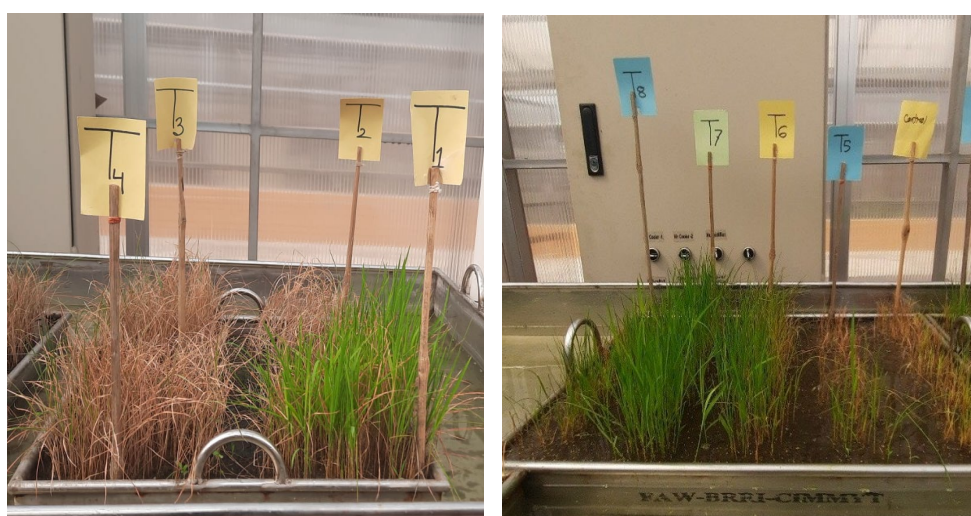
The root length and the shoot length also showed significant differences among treatments (Table 2). The greatest root length was recorded with imidacloprid (5.57 cm), followed by cartap (5.06 cm) and isoprocarb (4.83 cm). The longest shoot length was observed with imidacloprid (4.11 cm) and isoprocarb (3.58 cm), followed by cartap (3.41 cm) and the untreated control (3.49 cm). Seedling vigour, measured in terms of root and shoot length, was significantly affected by the different insecticides tested. Imidacloprid-treated seedlings showed the longest shoots (5.57 cm) and roots (4.11 cm), indicating possible growth-promoting effects. Earlier studies have suggested that neonicotinoids at low concentrations may induce systemic physiological stimulation in plants, including increased height, shoot fresh mass, leaf area, root biomass and photosynthetic efficiency in maize (Ding et al., 2018; House et al., 2021), rice (Roy et al., 2026; Xi et al., 2022) and cotton (Sehrish et al., 2024). Conversely, treatments such as cyantraniliprole and tetrataniliprole resulted in reduced root and shoot elongation, likely due to chemical stress or inhibition of early seedling metabolism.

#### Damage percentage and F<sub>1</sub> emergence among different treatments

The damage percentage of rice seedlings showed a statistically significant difference in both choice and no-choice methods. In the choice method, the maximum damage (%) was observed in the untreated control (81.67%), followed by cartap (56.67), and tetrataniliprole (53.33%). In addition, the minimum damage was recorded with imidacloprid (12.33%) and thiamethoxam (5.33%), which were statistically identical (Table 2, Figure 1). Furthermore, the no-choice method also followed a similar pattern. Here, the maximum damage was recorded in the control (90.67%), followed by cartap (54.00%), and tetrataniliprole (49.33%), while the minimum damage was observed with imidacloprid (9.00%) and thiamethoxam (2.67%), which were statistically identical.



A. Damage pattern at 21 days after sowing.



B. Damage pattern at 28 days after sowing.

Figure 1. Damage pattern of brown planthopper under different treatments.

Note: T<sub>1</sub>=imidacloprid 70 WG; T<sub>2</sub>=cartap 50 SP; T<sub>3</sub>=isoprocarb 50 WP; T<sub>4</sub>=untreated control; T<sub>5</sub>=tetratanipole 20Sc; T<sub>6</sub>=cyantraniliprole 40 SC; T<sub>7</sub>= thiamethoxam 25 WG; T<sub>8</sub>=buprofezin 40 EC.

Source: Authors' own photographs.

The number of F<sub>1</sub> adult emergences also showed a statistically significant difference in both choice and no-choice methods. In the choice method, the

maximum number of  $F_1$  adults emerged in the untreated control (108.00), and the minimum emerged with imidacloprid (25.22) and thiamethoxam (16.33), which were statistically identical (Table 2).

The no-choice method also followed a similar pattern, with the maximum  $F_1$  emergence recorded in the control (113.67) and the minimum damage observed with imidacloprid (21.00) and thiamethoxam (6.67), which were statistically identical. Both the choice and no-choice methods confirmed that untreated control seedlings suffered the highest damage (>80% of seedlings), followed by cartap (>54%) and tetrataniliprole (>49%), whereas imidacloprid and thiamethoxam provided superior protection with minimum damage (<12%), followed by cyantraniliprole and buprofezin (Table 2; Figures 1 and 3).

House et al. (2021) reported that cyantraniliprole effectively controlled *Lissorhoptrus oryzophilus* populations through seed treatment, but was not effective against stem borer. These findings indicate the strong systemic action of neonicotinoids (imidacloprid and thiamethoxam), which protect seedlings from initial hopper attack through ingestion-mediated toxicity, as supported by Ding et al. (2018) and Sehrish et al. (2024). Seed treatment required a very small amount of insecticides, resulting in a significant reduction in the application rate (g of active ingredient per hectare) used per unit area for the early-stage protection.

#### Mean number of brown planthopper per “20 seedlings”

The mean number of brown planthopper (BPH) per “20 seedlings” showed significant difference at 7 days after infestation (DAI), 14 DAI and 21 DAI. At 7 DAI, the maximum number of BPHs was found in the untreated control (37.00) followed by buprofezin (26.00), tetrataniliprole (23.30) and cyantraniliprole (18.30). In contrast, the minimum damage was observed with imidacloprid (10.30) and thiamethoxam (10.00), which were statistically identical (Figure 2A). At 14 DAI, the maximum BPH was again recorded in the untreated control (42.33), followed by tetrataniliprole (28.67), buprofezin (24.33) and cartap (24.00), whereas the minimum was observed with imidacloprid (13.67) and thiamethoxam (9.67), which were statistically identical (Figure 2B). At 21 DAI, the maximum BPH population was observed in the untreated control (43.70), followed by tetrataniliprole (30.00), buprofezin (25.70) and cyantraniliprole (20.00), whereas the minimum was recorded with isoprocarb (12.00), imidacloprid (12.00) and thiamethoxam (9.00), which were statistically identical (Figure 2C). In addition, the average number of BPHs was highest in the untreated control (41.00), followed by tetrataniliprole (27.33) and buprofezin (25.33), whereas the minimum was recorded with isoprocarb (15.67), imidacloprid (12.00) and thiamethoxam (9.56), which were statistically identical (Figure 2D). Moreover, the mean number of BPH per “20 seedlings” also varied significantly across treatments. Control plots consistently

exhibited the highest BPH counts at 7, 14, and 21 DAI, while imidacloprid and thiamethoxam maintained the lowest populations, which remained statistically identical throughout the observation period. These results corroborate earlier findings that neonicotinoids provide long-lasting suppression of sucking pests such as BPH by interfering with nicotinic acetylcholine receptors, thereby reducing feeding and survival (Kundoo et al., 2018; Sehrish et al., 2024; Roy et al., 2026; Uragayala et al., 2015).

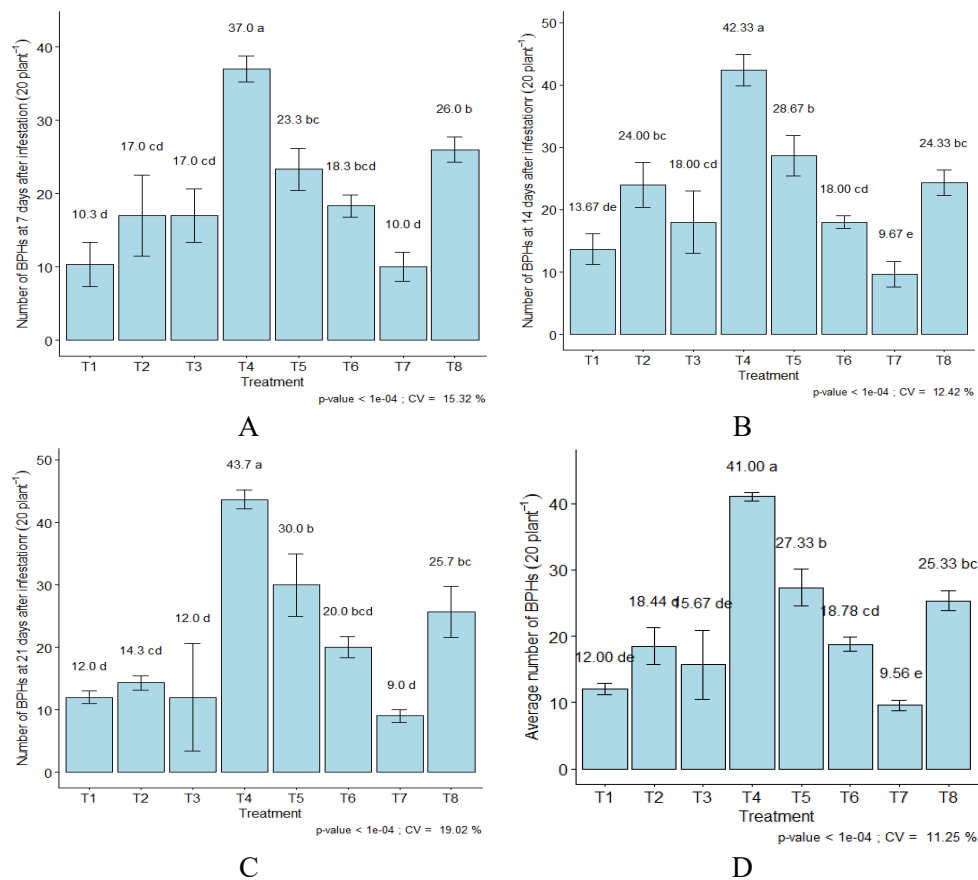


Figure 2. The mean number of BPHs population found per “20 seedlings” at different day.

Source: Authors' own calculation.

Through the induction of secondary metabolites, it has been demonstrated that the plant's defence mechanisms are improved against pests by pesticide seed coating treatment (Ghaffar et al., 2011; Xi et al., 2022). The rice phloem is fed on

by BPH, which alters the chemistry of a number of immune regulators, including phenolic compounds and oxalic acid, and this may lead to resistance to BPH (Xi et al., 2022). In addition, oxalic acid is commonly present in bacteria, fungi, plants, and animals. In plants, it serves vital functions such as protecting against herbivory (Usha and Jyothsna, 2010). Additionally, oxalic acid disrupts the sucking function of the BPH and is an efficient inhibitor of oxalic acids (Ghaffar et al., 2011; Xi et al., 2022). Furthermore, oxalic acid efficiently reduces hopper feeding behaviour by binding to the gustatory receptor Gr23a, which results in adverse responses to seedlings (Kang et al., 2023) and prevents BPH from infesting rice seedlings (Figure 3). Interestingly, isoprocarb, a carbamate insecticide, showed effective suppression of BPH populations at 21 DAI, suggesting its potential in rotation strategies to manage resistance development.

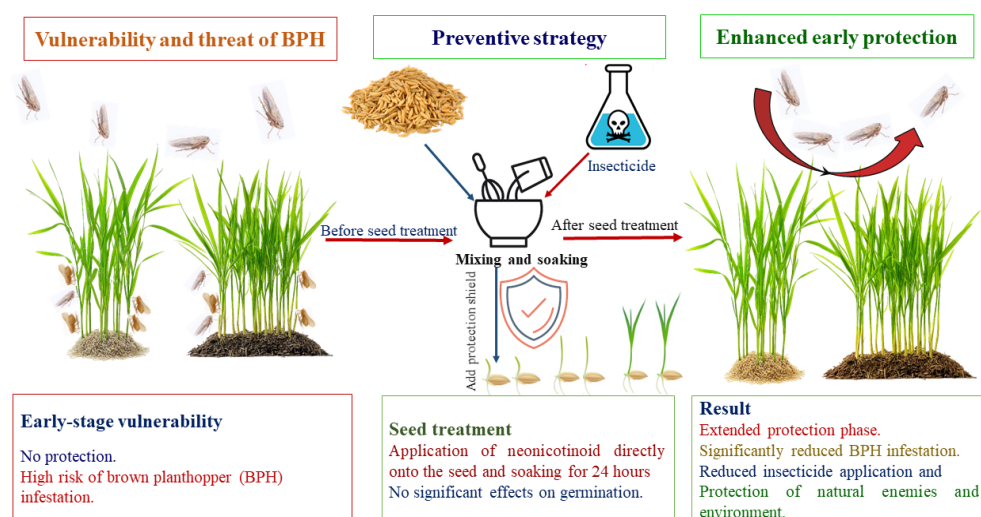


Figure 3. Seed treatment as a preventive strategy against brown planthopper at the early stage of rice cultivation.

Source: Authors' own illustration created using Microsoft PowerPoint.

Number of insect pests and natural enemy catches through sweep net at seedbed

The average number of rice whorl maggots (RWMs) differed significantly among the treatments (Table 3). The highest number of RWMs was found in the cartap-treated plot (144.58), followed by the untreated control plot (109.79) and the isoprocarb-treated plot (98.54). The highest number of brown planthoppers (BPHs) was caught in the untreated control (9.17), which was statistically identical to the cartap-treated plot (7.58), followed by the isoprocarb-treated plot (6.00).

Furthermore, the lowest number of BPHs was observed in the imidacloprid- (1.88) and thiamethoxam-treated plots (1.29) (Table 3). The population of zigzag leafhoppers (ZZLHs) was highest in the untreated control (3.46), cartap- (3.00) and isoprocarb-treated plots (2.79), which were statistically similar. The lowest number of ZZLHs was observed in the imidacloprid- (1.17), cyantraniliprole- (1.50) and thiamethoxam-treated plots (0.79). The population of green leafhoppers (GLHs) was highest in the untreated control (3.17), which differed statistically from the other treatments and was followed by cartap (2.63) and isoprocarb (1.83), respectively. In addition, the lowest number of GLHs was recorded in tetrataniliprole (1.04), cyantraniliprole (1.00), thiamethaxam (0.75) and imidacloprid (0.67). The BPH reduction over the control varied significantly among treatments. Both thiamethoxam (86.08%) and imidacloprid (79.12%) showed the highest reduction in the BPH infestation compared with the untreated control. Moreover, the number of natural enemies recorded in the different treated plots exhibited statistically significant differences except for the parasitic wasps (PW). The population of green mirid bugs (GMBs) was highest in the untreated control (31.67), followed by isoprocarb (23.00) and cartap (13.13), respectively. Furthermore, the lowest number of GMBs was found in tetrataniliprole- (1.71) and buprofezin-treated plots (1.21). The highest number of spiders was recorded in imidacloprid-treated plots (1.79), which differed statistically from the other treatments, and the other treatments showed similar results.

In seedbeds, sweep net catches confirmed that insecticide treatments significantly influenced pest abundance. Among the harmful insects, higher populations of RWMs, BPHs, GLHs, and ZZLHs were recorded in untreated control and cartap plots, indicating ineffective pest suppression. By contrast, imidacloprid and thiamethoxam consistently produced lower pest densities, reaffirming their protective efficacy. Previous studies have reported that seed treatments with imidacloprid and thiamethoxam reduce thrip incidence and suppress early-season insect colonisation in maize (Ding et al., 2018). Neonicotinoids are highly systemic, especially when used as a seed dressing, because of their high water solubility, which allows them to be easily absorbed and translocated by both root systems and leaves. These systemic characteristics allow neonicotinoids to penetrate not only a sapling's roots and leaves but also the soil surrounding the root zone, giving them "excellent activity especially against homopteran (i.e., aphids and leafhoppers), coleopteran (i.e., beetle species), dipteran (i.e., flies), and lepidopteran (i.e., leafworms) pests" (Ding et al., 2018; Kundoo et al., 2018; Sehrish et al., 2024; Uragayala et al., 2015). Because of this characteristic, neonicotinoids are a great complement to seeds and crops. While it takes three to six weeks for emerging seedlings to accumulate enough active ingredients to repel pests, neonicotinoid seed coatings offer instant effectiveness against harmful early-growth-stage pests such as hopper species (Kundoo et al.,

2018; Roy et al., 2026). The imidacloprid reduced BPH infestation by 79.12% and thiamethoxam reduced it by 86.08% compared with the control (Table 3).

Table 3. Average number of insect pests and natural enemies, and weekly catches through using sweep nets from seedbeds.

| Treatment | Harmful insects |          |         |        | Natural enemies |       |        | BPH (%)<br>reduction over<br>control |
|-----------|-----------------|----------|---------|--------|-----------------|-------|--------|--------------------------------------|
|           | RWM             | BPH      | ZZLH    | GLH    | GMB             | PW    | SPD    |                                      |
| T1        | 66.04 c         | 1.88 de  | 1.17 bc | 0.67 d | 6.92 d          | 1.83  | 1.79 a | 79.12 ab                             |
| T2        | 144.58 a        | 7.58 ab  | 3.00 a  | 2.63 b | 13.13 c         | 5.38  | 0.75 b | 15.69 e                              |
| T3        | 98.54 b         | 6.00 b   | 2.79 a  | 1.83 c | 23.00 b         | 4.33  | 0.46 b | 32.68 d                              |
| T4        | 109.79 b        | 9.17 a   | 3.46 a  | 3.17 a | 31.67 a         | 4.63  | 0.88 b | 0.00 f                               |
| T5        | 42.21 cd        | 3.79 c   | 1.92 b  | 1.04 d | 1.71 e          | 3.79  | 0.54 b | 58.49 c                              |
| T6        | 43.25 cd        | 3.50 cd  | 1.50 bc | 1.00 d | 4.96 de         | 4.50  | 0.58 b | 61.08 c                              |
| T7        | 19.63 d         | 1.29 e   | 0.79 c  | 0.75 d | 2.38 de         | 4.08  | 0.83 b | 86.08 a                              |
| T8        | 31.87 d         | 2.96 c-e | 1.17 bc | 1.71 c | 1.21 e          | 3.58  | 0.88 b | 68.68 bc                             |
| Lsd       | 29.87           | 1.71     | 0.86    | 0.49   | 5.18            | -     | 0.45   | 11.16                                |
| CV (%)    | 24.84           | 21.85    | 25.13   | 17.63  | 28.19           | -     | 31.03  | 12.84                                |
| P value   | <0.001          | <0.001   | <0.001  | <0.001 | <0.001          | >0.05 | <0.001 | <0.001                               |

Note: RWM: Rice whorl maggot; BPH: Brown planthopper; ZZLH: Zigzag headed leafhopper; GLH: Green leafhopper; GMB: Green mirid bug; PW: Parasitic wasp; SPD: Spider; Lsd: Least significance difference; CV: Coefficient of variation.

Source: Authors' own calculation.

The abundance of natural enemies, including green mirid bugs and spiders, was also significantly influenced by different seed treatments, while the abundance of parasitic wasps showed no significant difference. The higher populations of green mirid bugs were found in untreated and isoprocarb plots, whereas imidacloprid-treated plots harboured the highest number of spiders. Imidacloprid had little adverse effect and was safe for spiders and ladybird beetles (Chatterjee et al., 2009; Roy et al., 2026; Wilson et al., 2021). However, broad-spectrum insecticides and neonicotinoids reduced the abundance of beneficial insects, which could disrupt natural pest regulation (Wilson et al., 2021; Zhang et al., 2016). This supports earlier findings that insecticide overuse can negatively impact predator-prey balance in rice ecosystems (Roy et al., 2024; Wilson et al., 2021). Compared with foliar insecticide sprays, seed treatments can shield natural enemies from direct insecticide contact. Seed treatment may reduce direct exposure, but systemic insecticides may still influence beneficial organisms through trophic pathways. Furthermore, spiders, parasitic wasps and green mirid bug are well-known beneficial natural enemies that are employed in biological control initiatives all

over the world; because of their high feeding capacity, they were able to switch to a diet that included prey with lower insecticide levels. However, further research is needed to investigate the effects of seed-applied insecticides on natural enemy populations in broader aspects.

### Conclusions

The present investigation highlights that imidacloprid and thiamethoxam are highly effective in reducing the BPH population and are associated with less seedling damage while maintaining good seed germination and seedling vigour compared to other treatments. These insecticides might be used for early-stage protection of rice against the BPH, where early infestation occurred, which helps to reduce insecticide applications at the early stage and may help to protect natural enemies and the environment. Judicious use of selective insecticides, coupled with integration of host plant resistance and conservation of biological control agents, may provide a more sustainable BPH management strategy. However, since the non-selective effects of some insecticides on natural enemies raise concerns about ecological balance and the long-term sustainability of seed treatments, further investigation should focus on this issue in broader terms.

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RANA ZAŠTITA OD SMEĐE PIRINČANE CIKADE (*NILAPARVATA LUGENS*  
STÅL) TRETIRANJEM SEMENA: PREVENTIVNA STRATEGIJA U  
GAJENJU PIRINČA

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R e z i m e

Rana infestacija smeđom priničanom cikadom (engl. *brown planthopper* – BPH) česta je u ekosistemima pirinča. Uobičajena praksa podrazumeva folijarnu primenu insekticida, ali ona ima nepovoljan uticaj na prirodne neprijatelje i životnu sredinu. Cilj ovog istraživanja bio je da se procene uticaji insekticidnih tretmana semena primenom slučajnog eksperimentalnog rasporeda sa tri ponavljanja u Institutu za istraživanje pirinča u Bangladešu u periodu od avgusta 2024. do marta 2025. godine. Procenat klijanja značajno se razlikovao između tretmana, pri čemu je najveća klijavost zabeležena kod netretirane kontrole (91,3%), dok je najniža utvrđena kod tretmana kartapom (65,0%). Tretmani semena neonikotinoidima obezbedili su dobro klijanje (>87%) i podstakli vigor klijanaca. Oštećenje klijanaca bilo je najviše u netretiranoj kontroli (>81%) i kod tretmana kartapom (>54%), dok su imidakloprid (9,00–12,33%) i tiametoksam (2,67–5,33%) pružili jaku zaštitu sa oštećenjem manjim od 12% u testovima bez i sa izborom. Populacija smeđe pirinčane cikade dodatno je suzbijana imidaklopridom i tiametoksamom tokom 28 dana nakon setve, dok su kontrolne parcele imale najveću gustinu štetočina. Prikupljanje uzoraka pomoću kečera pokazalo je veću brojnost štetočina na netretiranim i parcelama tretiranim kartapom, dok su u parcelama tretiranim imidaklopridom i tiametoksamom zabeležene značajno manje populacije. Brojnost prirodnih neprijatelja takođe se razlikovala, pri čemu su netretirane i parcele tretirane isoprokarbom imale više zelenih stenica, dok je najveća brojnost paukova utvrđena kod tretmana imidaklopridom, što ukazuje na relativno manji neciljani uticaj na prirodne neprijatelje kod ovih tretmana. Sveukupno, imidakloprid i tiametoksam su bili najdelotvorniji u poboljšanju vigora i suzbijanju smeđe pirinčane cikade, uz održavanje relativno veće brojnosti paukova u poljskim uslovima u poređenju sa drugim tretmanima. Ovi nalazi ističu potencijal tretmana semena za efikasno tretiranje smeđe pirinčane cikade u ranoj fazi, smanjujući potrebu za folijarnim prskanjem.

**Ključne reči:** pirinač, tretiranje semena, procenat klijanja, imidakloprid, neonikotinoidi, prirodni neprijatelji.

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## STRATEGIC ANALYSIS OF AGRICULTURAL DEVELOPMENT USING SWOT AND QSPM FRAMEWORKS: A CASE STUDY OF HERAT PROVINCE, AFGHANISTAN

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**Abstract:** For development initiatives to be effective and sustainable, an extensive strategic evaluation is essential, especially in sectors as important and complex as agriculture. This study analyses the agricultural sector in Herat Province, Afghanistan, a region with substantial agricultural potential that continues to face numerous challenges, using the SWOT (strengths, weaknesses, opportunities, threats) and quantitative strategic planning matrix (QSPM) frameworks. This research aims to identify and rank the most viable strategic choices for boosting agricultural growth. The Delphi technique and a questionnaire instrument were used to gather insights from experts in the field, with university lecturers representing a large spectrum, which was included in the research. The important findings of this research indicate that, among the four elements of the SWOT model, the most significant strength identified is the strategic position of Herat Province for the export of agricultural products. The most serious weakness is the lack of insurance services in the agricultural sector; the best opportunity is the utilisation of water from the Salma Dam for irrigating agricultural lands, and the most significant threat to agricultural development is the adverse impacts of insecurity. After evaluations, it has been observed that strengths and opportunities in this research are predominant. Therefore, utilising the strategic position and action evaluation (SPACE) matrix, the main strategy aligned with the designated aggressive position has been identified by merging strengths and opportunities. The findings will provide valuable insights for policymakers, development practitioners, and agricultural stakeholders seeking to unlock Herat's agricultural potential and contribute to Afghanistan's broader economic recovery.

**Key words:** strategic analysis, agricultural development, SWOT, QSPM, Herat, Afghanistan.

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## Introduction

Agriculture is not merely a sector of Afghanistan's economy; it is the crucial lifeline that supports the majority of its population, especially in rural areas. It serves as the main source of livelihood for approximately 70% of the population and plays a significant role in the country's gross domestic product (GDP), contributing around 36% (World Bank Group, 2024). Beyond its economic importance, agriculture is deeply interwoven with Afghanistan's social structure, cultural heritage, and rural identity. For generations, Afghan communities have depended on agriculture for sustenance, employment, and social cohesion, shaping traditional practices, social structures, and cultural values. Despite its importance, the agricultural share of GDP from 2003 to 2023 shows a decreasing trend with marked fluctuations corresponding to the annual agricultural growth rate (Figure 1). Thus, understanding the dynamics and potential of Afghanistan's agricultural sector is essential for addressing food security, alleviating poverty, promoting economic growth, and enhancing social stability in the country.

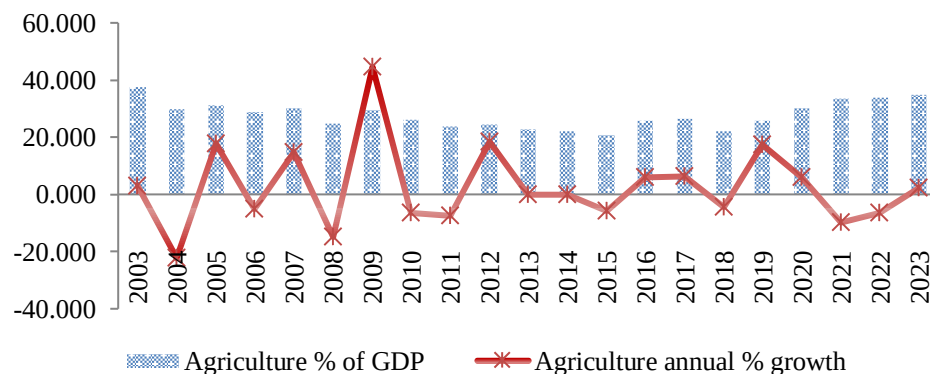


Figure 1. Afghanistan's share of agriculture in GDP (%) and agricultural GDP % growth, 2003-2023.

Source: World Bank's World Development Indicators (WDI), 2024.

Nevertheless, Afghanistan's agricultural sector has been severely hindered by a combination of factors, including decades of armed conflict, persistent droughts, limited access to irrigation and technology, inadequate infrastructure, and fluctuating market conditions. Prolonged conflict and instability have ravaged infrastructure, destroyed irrigation systems, disrupted agricultural production, displaced farming communities, and fostered an atmosphere of uncertainty that discourages investment and innovation (FAO, 2023). Climate change is

exacerbating these challenges, leading to more frequent and intense droughts, erratic rainfall patterns, and increased vulnerability to extreme weather events, which pose a significant threat to agriculture and livestock production. Figure 2 illustrates this issue by depicting the acute fluctuations in rainfall patterns and drastically increased CO<sub>2</sub> emissions (WDI, 2025). Moreover, inadequate access to essential resources, including modern technology, reliable irrigation systems, fertiliser, quality seeds, and access to credit, as well as the volatile market conditions, and limited access to market information, hinders Afghan farmers' ability to enhance their productivity and compete effectively in regional and global markets. These multifaceted challenges stress the immediate need for a strategic and targeted approach to unlock the untapped potential of Afghan agriculture.

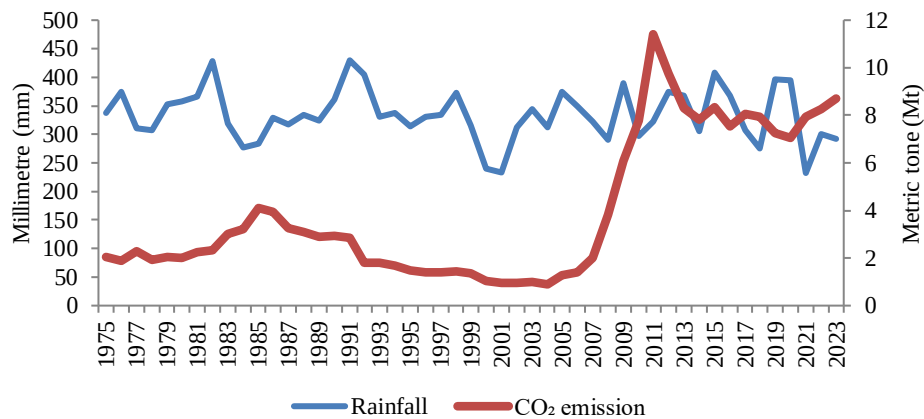


Figure 2. Afghanistan's carbon dioxide (CO<sub>2</sub>) emissions and average rainfall (mm), 1975–2023.

Source: World Bank's Climate Change Knowledge Portal, 2024.

Within this complex and challenging national context, Herat Province stands out as a region of particular strategic importance with considerable agricultural potential. The province plays a vital role in Afghanistan's agricultural economy and has a long history of successful agricultural output, making it a significant contributor to trade and food security. As one of the most developed provinces, it is significant in the overall agricultural landscape. Its economic stability and agricultural viability ensure that it remains a trading point and a significant contributor to Afghanistan's overall GDP (Leslie, 2015). The province's strategic geographical location positions it as a key trading hub, linking Afghanistan with both regional and international markets. However, despite its inherent strengths, the province's agricultural sector still encounters various challenges, including

limited access to modern technology, water scarcity, soil degradation, and susceptibility to disruptions in cross-border trade, which require careful consideration (ADSP, 2019). Unlocking the agricultural potential of Herat requires a strategic approach that leverages its strengths, addresses its weaknesses, capitalises on emerging opportunities, and mitigates potential threats.

Despite the critical role of agriculture in Afghanistan's economy and the unique potential of Herat Province, there is a significant gap in the current literature concerning thorough strategic analyses of agricultural development in the area. Although numerous studies have addressed specific aspects of Afghan agriculture, including irrigation, crop production, or market access, very few have adopted a comprehensive strategic approach that examines the interaction of both internal and external factors influencing agricultural development. Furthermore, there is a scarcity of applications of established strategic planning frameworks, such as SWOT and QSPM, in analysing agricultural development in Afghanistan, resulting in a lack of evidence-based recommendations for policymakers and practitioners seeking to promote sustainable and inclusive agricultural growth.

To address this gap, the present study thoroughly examines agricultural development in Herat Province using the SWOT (strengths, weaknesses, opportunities, and threats) framework alongside the quantitative strategic planning matrix (QSPM). The selection of the SWOT and QSPM frameworks is based on their suitability for a structured and systematic analysis of complex strategic issues (Fan et al., 2023; Ramaloo et al., 2018). According to Ramaloo et al. (2018), SWOT analysis provides a simple yet effective tool for systematically evaluating the internal and external factors essential to the success of an organisation or sector. This encourages a comprehensive approach that considers both positive and negative impacts that could influence strategic choices.

Attributed to Albert Humphrey and his colleagues at the Stanford Research Institute, SWOT analysis is designed to examine the internal resources and capabilities (strengths and weaknesses) as well as the external environment (opportunities and threats) that affect the entity under consideration (Benzaghta et al., 2021). By identifying internal and external factors that affect an organisation or sector, this analysis provides a qualitative foundation for strategic planning (Curry, 1996; Hill and Westbrook, 1997). According to Uztürk and Büyüközkan (2023), SWOT analysis, a key component of strategic management, offers a systematic and structured approach to assess the overall strategic position of the organisation or, in this case, the agricultural sector. In the context of agricultural development, this includes evaluating strengths such as fertile land and skilled labour; weaknesses including poor infrastructure, lack of modern agricultural mechanisation, and limited access to credit; opportunities such as natural resources and growing demand for food; and threats such as market instability, inflation, and climate change. Nevertheless, relying solely on SWOT analysis often results in insufficient

analytical rigour to prioritise these factors and assess alternative strategic options (Houben et al., 1999).

This limitation is addressed by the QSPM framework, which offers a quantitative method to assess and prioritise alternative strategies (Alizadeh et al., 2021). The QSPM is built on the SWOT analysis by assigning weights to identified factors according to their relative importance and then evaluating each strategy's attractiveness in light of these factors (Pazouki et al., 2017). The combined application of SWOT and QSPM provides a powerful and versatile approach to strategic planning in agricultural development. It uses SWOT's breadth and comprehensiveness to identify a wide range of relevant factors and then applies QSPM's rigour and objectivity to assess and prioritise alternative strategies. According to David (1986), this integration improves the quality of strategic decision-making and enhances the possibility of achieving desired results. The literature underscores that effective use of both frameworks requires stakeholder participation and a thorough contextual understanding.

SWOT analysis was first used in agriculture by Faesel and Hill (1995), and since then, many studies have employed SWOT analysis to guide the formulation of agricultural development plans at both national and regional levels, particularly in developing countries (Ali et al., 2021; Benzaghta et al., 2021; Brohi et al., 2020; GC and Ghimire, 2018; Kartika et al., 2024; Khan et al., 2022; Kurmanalina et al., 2020; Nosrati Nigjeh et al., 2023; Ommami, 2010; Ramaloo et al., 2018; Uztürk and Büyüközkan, 2023; Wegren et al., 2019). In addition to opportunities such as increasing production and exports, encouraging sustainable agricultural practices, and enhancing rural livelihoods, these analyses frequently highlight key constraints to agricultural development, for instance, inadequate infrastructure, limited access to credit, and lack of market information.

Numerous scholars have highlighted the application of SWOT and QSPM in developing comprehensive agricultural policies (Abbasi et al., 2019; Abdolshah et al., 2018; Feili et al., 2018; Herdiansyah and Majesty, 2024; Mohebbi et al., 2022; Nourbakhsh et al., 2023; Pazouki et al., 2017). These studies have used the SWOT analysis to indicate the strategic situation of the sector, while QSPM has been used to develop and rank sub-strategies. For instance, Abbasi et al. (2019) used the SWOT and QSPM matrices to formulate strategies for farm advisory services in Valencia, Spain. The findings show that the aggressive strategy was the best and that four sub-strategies were developed using QSPM for the farm advisory services.

Many scholars have applied SWOT analysis and QSPM in developing comprehensive agricultural policies (Abbasi et al., 2019; Abdolshah et al., 2018; Feili et al., 2018; Herdiansyah and Majesty, 2024; Mohebbi et al., 2022; Nourbakhsh et al., 2023; Pazouki et al., 2017). Most studies have used SWOT to pinpoint the sector's strategic position, whereas QSPM is applied to generate and rank sub-strategies.

In Afghanistan, few studies have analysed the strategic situation of the agriculture sector. Nikzad et al. (2023) assessed the agriculture sector in Afghanistan using SWOT analysis and identified a conservative strategy as crucial for agricultural development. In another study, Omar Ali et al. (2024) analysed strategies for developing the saffron value chain in Herat Province and found a conservative strategy as appropriate for the saffron value chain in the province.

Prior studies on strategic analysis have predominantly focused on either the national agricultural sector as a whole or on specific commodities, which do not accurately reflect the distinctive conditions prevalent in individual provinces or regions. This is particularly important, given the variations across provinces, such as ecological and climatic factors, marketing practices, infrastructure, and trade dynamics. Therefore, the present study examines the strategic situation of the agricultural sector in Herat Province, a major agricultural hub in Afghanistan. By focusing specifically on Herat, this research aims to provide insights tailored to the local context and to address the distinct challenges and opportunities faced by its agricultural sector.

Consequently, the general objective of this study is to analyse the agricultural development in the Herat Province of Afghanistan, using the SWOT and QSPM frameworks. Specifically, this study aims to: identify and prioritise the key internal strengths and weaknesses of the agricultural sector, identify and evaluate the significant external opportunities and threats impacting agricultural development, develop a comprehensive SWOT matrix for the agricultural sector, and prioritise strategic alternatives for agricultural development using the QSPM matrix, in Herat Province, Afghanistan.

### **Material and Methods**

This study employed a mixed-methods single-case study approach, focusing on the agricultural sector in Herat Province, Afghanistan. The Province was selected due to its significant contribution to the national economy, its diverse range of agricultural practices, distinct challenges with market access and water scarcity, and its relative stability compared to other regions in Afghanistan, which facilitates data collection. Moreover, its historical significance as an agricultural hub, its variety of products such as industrial crops, cereals, fruits, and livestock, its representation of the challenges and opportunities faced by many rural communities in the country, and the existence of research networks that facilitate data access were also considered.

A purposive sampling approach was used to select a group of 70 experts. The selection criteria included proven experience in agriculture, a focus on the situation in Herat province, and representation of stakeholder groups within the sector. Thirty-four university lecturers specialising in the agriculture sector were selected

from Herat University and the Herat Agricultural Institute. The remaining 36 were senior officials, programme managers, and experienced agricultural and extension workers from the Herat Provincial Department of Agriculture, Irrigation, and Livestock (DAIL), operating in diverse districts of Herat Province. Their selection was based on their involvement in agricultural programme implementation and their understanding of local agricultural challenges and opportunities.

In this study, a mixed-methods strategy integrating the Delphi technique and a questionnaire survey was used to gather both qualitative and quantitative data. The Delphi technique was employed to gather and synthesise expert insights (Hsu and Sandford, 2007), whereas the questionnaire survey was used to validate these insights and assess the perceptions of a broader range of stakeholders. Therefore, this technique systematically compiles and integrates expert perspectives on the key SWOT factors impacting agricultural development in Herat Province, and determines consensus-driven weights for these factors that reflect their perceived relative importance. This process ensures that the strategic analysis is based on the knowledge and experience of local experts.

The SWOT analysis will provide a thorough evaluation of the internal strengths and weaknesses of the agricultural sector in Herat, as well as the external opportunities and threats that could impact its growth. This analysis will serve as a vital initial step in understanding the current state of agricultural development in Herat, providing a basis for evidence-based decision-making and targeted interventions. Subsequently, building on the SWOT findings, the QSPM will assess and rank strategic alternatives according to their relative attractiveness and feasibility, offering actionable recommendations for policymakers, development organisations, and stakeholders.

A structured three-round Delphi process was carried out, using face-to-face interviews and/or online surveys administered remotely through Google Form, to facilitate participation and alleviate logistical challenges (Yousuf, 2007). In the initial round, an open-ended questionnaire was distributed to the panel, asking them to identify the most critical internal factors (strengths and weaknesses) and external factors (opportunities and threats) influencing agricultural development in Herat Province. The questionnaire included prompts to consider factors associated with agricultural production, such as innovation systems, infrastructure, market access, sustainability indicators, and the policy environment. In the second round, participants received a consolidated summary of the responses from round one, categorised into distinct SWOT factors, that is, evaluation of external and internal factors (EFE and IFE). Using a four-point Likert scale, with 1 representing “not at all important” and 4 representing “extremely important”, they were asked to rank the significance of each factor. The third phase involved the selection of an appropriate strategy. For this purpose, the SPACE matrix was employed to determine the orientation and select appropriate strategies. The SPACE matrix reveals the contrast

between the final weighted scores of all internal and external factors (Abbasi et al., 2019; Radder and Louw, 1998). Depending on the combination and predominance of factors, there are four main types of possible strategies: conservative (strengths and threats), aggressive (opportunities and strengths), competitive (weaknesses and opportunities), and defensive (threats and weaknesses).

The Delphi data were used to identify and weight the essential SWOT factors (EFE and IFE), whereas the questionnaire data were used to validate these factors and evaluate stakeholder perceptions concerning their significance and the desirability of strategic alternatives. Descriptive statistics such as the mean, median, and interquartile range (IQR) were computed for each SWOT factor in each round of the Delphi process to monitor the convergence of expert opinions. However, content analysis was conducted on the open-ended responses and justifications submitted by the experts to obtain a deeper understanding of the reasoning behind their ratings and to identify any emerging themes or insights.

Based on the final list of SWOT factors identified through the Delphi process and validated by the questionnaire data, a comprehensive SWOT matrix was developed. Then, using SWOT analysis, a literature review, and input from experts, a set of strategic alternatives (in this case, four strategies from the aggressive typology) was generated. These options were designed to build strengths, reduce weaknesses, take advantage of opportunities, and address threats in Herat Province's agriculture sector (Pazouki et al., 2017). However, while producing such strategies is important, prioritising them is equally critical. Therefore, the QSPM matrix was employed to rank the strategic alternatives (David, 1986) using the internal and external feasibility factors (IEF and EFE, respectively) and their corresponding weights, which were derived from stakeholder preferences and expert opinions.

Eventually, in the QSPM matrix, strategies are ranked by multiplying each strategy's attractiveness coefficient by the weights assigned to the relevant factors. Each strategy's attractiveness is evaluated by comparing it with the others using these factors. The assessment scale generally ranges from 1 (not attractive) to 4 (very attractive). The total weighted attractiveness score is then calculated for each strategy. This total reflects the strategy's relative appeal, incorporating the effects of internal and external factors. Strategies with higher weighted attractiveness scores suggest greater strategy attractiveness (David et al., 2017; Feili et al., 2018).

## Results and Discussion

The demographic characteristics of the respondents are presented in Table 1. The results indicate that the majority of participants are male, comprising 62 individuals who account for 86% of the sample. In contrast, females represent a significantly smaller portion with only 8 respondents (11.4%). This highlights a predominantly male sample. The age distribution shows that a significant portion of respondents are within the 18–35 age group, comprising 68.6%. The 35–50 age

group comprises 28.6%, while only 2 participants (2.9%) are over the age of 50. This indicates that the sample is primarily composed of young adults. Additionally, educational attainment among the respondents indicates that the largest educational category is those holding a bachelor's degree (55.7%), while 35.7% have a master's degree, and the smallest group (8.6%) consists of PhD holders. Overall, the majority of respondents possess higher education. Respondents held diverse positions within their respective fields; nearly half of the participants (48.6%) are university educators. The remaining respondents include office workers (18.6%), experts (15.7%), and managers (17.1%).

Table 1. The socio-demographic characteristics of study participants.

| Factors   | Categories         | Frequency | Percentage |
|-----------|--------------------|-----------|------------|
| Gender    | Male               | 62        | 88.6       |
|           | Female             | 8         | 11.4       |
| Age       | 18–35              | 48        | 68.6       |
|           | 35–50              | 20        | 28.6       |
|           | >50                | 2         | 2.9        |
| Education | Bachelor's degree  | 39        | 55.7       |
|           | Master's degree    | 25        | 35.7       |
|           | PhD                | 6         | 8.6        |
| Position  | University teacher | 34        | 48.6       |
|           | Office worker      | 13        | 18.6       |
|           | Expert             | 11        | 15.7       |
|           | Manager            | 12        | 17.1       |

Source: Authors' calculations.

In the SWOT analysis, internal factors, which encompass strengths and weaknesses, constitute elements that can be controlled and influenced. In the internal factor evaluation (IFE) matrix within the framework of the SWOT analysis, seven strengths and twenty weaknesses have been identified for the agricultural sector of Herat (Table 2). Strengths are positive internal attributes that contribute to effective performance. The strategic location of Herat Province was identified as the most significant strength, with a weight score of 0.138, indicating Herat's importance for Afghanistan's agricultural export activities. The availability of adequate and suitable agricultural land and diverse ecological and climatic conditions for the province's agricultural production ranked second and third, respectively, further reinforcing its status as an important agricultural region within Afghanistan.

Table 2. Internal factor evaluation (IFE) of the agriculture sector.

|     | Internal factors                                                                                                                            | Weighted score | Mean AS | Weight | Rank |
|-----|---------------------------------------------------------------------------------------------------------------------------------------------|----------------|---------|--------|------|
|     | Strengths of the agriculture sector                                                                                                         |                |         |        |      |
| S5  | The strategic position of Herat Province for exporting of agricultural production                                                           | 0.040          | 3.443   | 0.138  | 1    |
| S3  | The existence of suitable agricultural land for sustainable agricultural production                                                         | 0.038          | 3.214   | 0.121  | 2    |
| S1  | Suitable ecological and climatic diversity for agricultural activities in Herat Province                                                    | 0.037          | 3.129   | 0.115  | 3    |
| S2  | Access to the agricultural labour for substantial agricultural production in agricultural and rural areas                                   | 0.036          | 3.057   | 0.109  | 4    |
| S6  | The existence of conditions and potential for developing greenhouse crops in order to reduce water consumption                              | 0.035          | 3.000   | 0.105  | 5    |
| S4  | The existence of vast and diverse areas of agricultural and horticultural production in Herat Province                                      | 0.034          | 2.900   | 0.098  | 6    |
| S7  | Availability of agricultural specialists in Herat Province                                                                                  | 0.033          | 2.786   | 0.091  | 7    |
|     | Sum total of strengths                                                                                                                      | 0.252          |         | 0.777  |      |
|     | Weaknesses of the agriculture sector                                                                                                        |                |         |        |      |
| W17 | Absence of insurance services in the agriculture sector                                                                                     | 0.042          | 3.557   | 0.148  | 1    |
| W3  | Waste of water resources due to traditional irrigation                                                                                      | 0.040          | 3.414   | 0.136  | 2    |
| W20 | Lack of farmers’ access to storage facilities, such as cold storage, silos, and warehouses                                                  | 0.040          | 3.400   | 0.135  | 3    |
| W5  | Lack of standard markets and problems with roads connecting villages to cities                                                              | 0.039          | 3.371   | 0.133  | 4    |
| W12 | Traditional methods of packaging, preserving, and storing agricultural products, and weaknesses in the marketing of agricultural products   | 0.039          | 3.371   | 0.133  | 5    |
| W4  | Lack of agriculture mechanisation and low income of farmers                                                                                 | 0.039          | 3.357   | 0.132  | 6    |
| W13 | Lack of proper infrastructure for transporting agricultural products outside Herat Province                                                 | 0.039          | 3.314   | 0.128  | 7    |
| W9  | Inappropriate selection of suitable products for climatic and geographical conditions due to the lack of knowledge among farmers            | 0.038          | 3.271   | 0.125  | 8    |
| W11 | Poor knowledge levels among farmers in the agriculture sector                                                                               | 0.038          | 3.257   | 0.124  | 9    |
| W8  | Traditional agricultural production methods due to the prevalence of a subsistence and conservative economy among households in rural areas | 0.038          | 3.243   | 0.123  | 10   |
| W1  | High agricultural waste due to inappropriate modern agricultural production methods                                                         | 0.037          | 3.200   | 0.120  | 11   |

Table 2. Continuation.

| Internal factors                          |                                                                                                                                    | Weighted score | Mean AS | Weight | Rank |
|-------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|----------------|---------|--------|------|
| Strengths of the agriculture sector       |                                                                                                                                    |                |         |        |      |
| W10                                       | Lack of coherence in the production-to-consumption chain of agricultural products in Herat Province                                | 0.037          | 3.171   | 0.118  | 12   |
| W6                                        | Insufficient suitable job opportunities for the people in the rural areas due to the gradual destruction of the agriculture sector | 0.036          | 3.114   | 0.113  | 13   |
| W14                                       | Weak relationship between the agriculture and industrial sectors in Herat Province                                                 | 0.036          | 3.129   | 0.113  | 14   |
| W15                                       | Lack of directional and agricultural extension mechanisms for the annual planting programme                                        | 0.036          | 3.086   | 0.111  | 15   |
| W2                                        | Inadequate agricultural productivity                                                                                               | 0.036          | 3.085   | 0.111  | 16   |
| W18                                       | Low export value of agricultural products                                                                                          | 0.035          | 2.971   | 0.103  | 17   |
| W16                                       | Insufficient scientific, research, extension, and study facilities for the growth and development of the agrarian sector           | 0.035          | 2.957   | 0.102  | 18   |
| W19                                       | Low agricultural productivity relative to the amount of water consumption in this sector                                           | 0.034          | 2.914   | 0.099  | 19   |
| W7                                        | The tendency of the agriculture sector to produce irrigated and horticultural products                                             | 0.033          | 2.857   | 0.095  | 20   |
| Sum total of weaknesses                   |                                                                                                                                    | 0.748          |         | 2.403  |      |
| The sum total of strengths and weaknesses |                                                                                                                                    | 1.000          |         | 3.181  |      |

Note: S = strength, W = weakness, and Mean AS = mean of attractiveness score.

Source: Authors' calculations.

On the other hand, weaknesses are internal factors or attributes that impede the performance of an organisation or project, thereby placing it at a competitive disadvantage. With the highest weight score of 0.148, the absence of insurance services in Herat's agricultural sector has been identified as the key weakness, highlighting the detrimental impact of inadequate insurance coverage on the growth of agriculture in Herat Province. Moreover, the ineffective management of water resources, stemming from traditional irrigation methods, was assessed as the second most critical weakness. This is a common situation in developing nations and is mostly caused by inadequate infrastructure and the underuse of contemporary agricultural knowledge. The third major weakness was found to be the lack of storage facilities, such as warehouses, silos, and cold storage.

The cumulative weight for strengths was calculated as 0.777, while the total weight for weaknesses was 2.403. The overall IFE score of 3.181 exceeds the neutral benchmark of 2.5, indicating the predominance of strengths over weaknesses. It also indicates that, despite the key internal weaknesses that significantly hinder development, the agriculture sector in Herat has a net favourable internal position, and its high-value strengths offer a strong basis for national economic growth and

export. Thus, addressing these weaknesses will allow the province to leverage its strengths more effectively and improve sector performance.

In the context of the external evaluation factor (EEF) matrix, ten opportunities and eleven threats encompassing 21 external factors, were identified as influencing Herat's agricultural sector (Table 3). Opportunities, understood as favourable external conditions that can be leveraged to achieve positive outcomes, were analysed. With the highest weight score of 0.140, the Salma Dam's significance for irrigating agricultural fields was deemed the most important opportunity for agricultural development in Herat Province. Subsequently, the increasing demand for Herat's agricultural products as a result of population growth, with a weighted score of 0.129, ranked second, indicating a positive relationship between population increase and demand for agricultural outputs. Moreover, with a weight score of 0.105, hiring agriculture graduates from Herat University was ranked as the third most important opportunity, indicating the existence of a readily available pool of qualified experts who can actively contribute to improvements in the sector. Therefore, the examination of external potential for the agricultural sector in Herat Province suggests a path towards self-reliant and sustainable agricultural growth, prioritising internal resources and local skills. Herat Province can strengthen its agricultural sector and ensure long-term development by optimising the benefits of existing resources, investing in local talent, and strategically engaging with external markets.

On the other hand, threats, which represent external factors in SWOT analysis that impede goal achievement, were also evaluated. The analysis shows that, with the highest weight score of 0.207, insecurity poses a significant threat to agricultural development in Herat Province. This result highlights the vital role of security as a key indicator of social welfare and economic growth. Additionally, farmers' susceptibility to persistent inflation was identified as the second major threat (weighted score of 0.190).

However, temporal and spatial climatic adversities, land salinisation and desertification, and the exponential decline in soil fertility were deemed the three least significant threats to Herat's agricultural development. These results imply that government interventions should prioritise societal management, with particular emphasis on security improvement, price stabilization, and efficient market regulation.

According to Table 2, the total weight for the opportunities is calculated as 1.021, whereas the overall weight of the threats is 1.812. The total EFE score of 2.833 ( $> 2.5$ ) indicates a predominance of opportunities over threats in Herat's agriculture sector. Furthermore, it indicates that, although external threats remain critical constraints, a favourable external environment for Herat's agricultural sector exists, with strong opportunities that can be leveraged for growth.

Table 3. External factor evaluation (EFE) of the agriculture sector.

|                                            | External factors                                                                                                     | Weighted score | Mean AS | Weight | Rank |
|--------------------------------------------|----------------------------------------------------------------------------------------------------------------------|----------------|---------|--------|------|
|                                            | Opportunities of the agriculture sector                                                                              |                |         |        |      |
| O10                                        | Importance of the Salma Dam for the irrigation of agricultural land                                                  | 0.049          | 2.857   | 0.140  | 1    |
| O6                                         | Increased demand for Herat agricultural products due to the population growth                                        | 0.047          | 2.743   | 0.129  | 2    |
| O7                                         | Hiring graduate agriculture students from Herat University in the agriculture sector                                 | 0.042          | 2.471   | 0.105  | 3    |
| O2                                         | Capacity to implement new projects and agricultural mechanisation to increase production and productivity            | 0.042          | 2.457   | 0.103  | 4    |
| O9                                         | Cooperation of agricultural organisations in the growth and development of the agriculture sector                    | 0.042          | 2.443   | 0.102  | 5    |
| O4                                         | Ability to attract private sector investment with the participation of specialised companies                         | 0.040          | 2.357   | 0.095  | 6    |
| O3                                         | Ability to accept foreign investment in planning and implementing support programmes for the farmers                 | 0.040          | 2.314   | 0.092  | 7    |
| O5                                         | Access to international and regional agricultural markets                                                            | 0.039          | 2.286   | 0.090  | 8    |
| O1                                         | Foreign investment for the development of processing, production and packaging industries for agricultural products  | 0.038          | 2.214   | 0.084  | 9    |
| O8                                         | Controlling and properly managing agricultural water and groundwater resources in Herat province                     | 0.037          | 2.171   | 0.081  | 10   |
| Sum total of opportunities                 |                                                                                                                      | 0.417          |         | 1.021  |      |
| Threats of the agriculture sector          |                                                                                                                      |                |         |        |      |
| T10                                        | The effects of insecurity on agricultural development                                                                | 0.060          | 3.471   | 0.207  | 1    |
| T7                                         | Farmers' vulnerability to persistent inflation                                                                       | 0.057          | 3.329   | 0.190  | 2    |
| T6                                         | Lack of government attention and insufficient investment in the agricultural sector of Herat Province                | 0.056          | 3.257   | 0.182  | 3    |
| T9                                         | Severe fluctuations in the agricultural input market                                                                 | 0.056          | 3.257   | 0.182  | 4    |
| T5                                         | Drought and lack of precipitation (rain and snow)                                                                    | 0.055          | 3.186   | 0.174  | 5    |
| T11                                        | The effects of internal and external migration on the backwardness and regression of agriculture in Herat Province   | 0.053          | 3.114   | 0.166  | 6    |
| T1                                         | Insufficient water for agricultural irrigation in the Herat Province                                                 | 0.051          | 3.000   | 0.154  | 7    |
| T2                                         | Gradual soil erosion and the destruction of remaining water due to the unprincipled development of agricultural land | 0.051          | 3.000   | 0.154  | 8    |
| T4                                         | Temporal and spatial climatic adversities                                                                            | 0.049          | 2.829   | 0.137  | 9    |
| T8                                         | Land salinisation and desertification in Herat Province                                                              | 0.048          | 2.814   | 0.136  | 10   |
| T3                                         | Exponential decline in soil fertility                                                                                | 0.047          | 2.743   | 0.129  | 11   |
| Sum total of threats                       |                                                                                                                      | 0.583          |         | 1.812  |      |
| The sum total of opportunities and threats |                                                                                                                      | 1.000          |         | 2.833  |      |

Note: O = opportunity, T = threat, and Mean AS = mean of attractiveness score.

Source: Authors' calculations.

The combined IFE (3.181) and EFE (2.833) scores, presented in Figure 3, indicate a favourable strategic position for Herat's agricultural sector. The strengths dominate the internal space, and opportunities have a higher share in the external space. This supports pursuing growth-oriented strategies to capitalise on opportunities, while simultaneously addressing priority weaknesses and threats to sustain long-term development. Therefore, prioritising security, and market stabilisation, followed by medium-term investments in infrastructure, insurance mechanisms, and human capital, will enable the province to capitalise on its strengths and opportunities for sustainable agricultural development.

In order to determine the strategic position of Herat's agricultural sector, the SPACE matrix, which shows the state of the internal and external factors (IEFs) in the SWOT matrix, is presented in Figure 3. The final weight of the internal-external matrix for Herat's agricultural sector shows the aggressive (developmental) strategy. Thus, this strategy demonstrates how to leverage the current strengths of the system to maximise the exploitation of environmental opportunities.

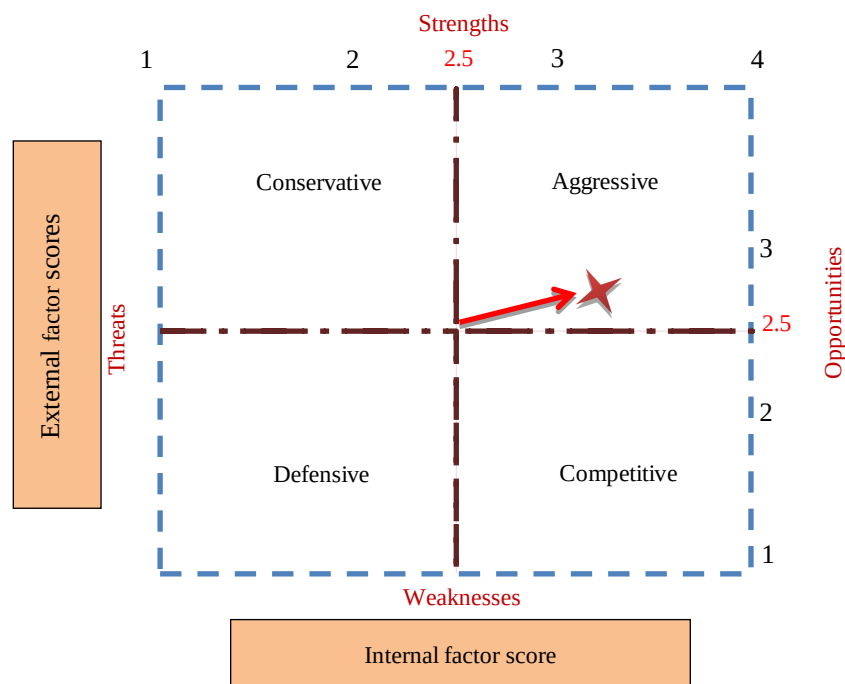


Figure 3. Strategic position and action evaluation (SPACE) matrix.

Source: Authors' compilation.

Following the SWOT analysis and the resulting development strategy for Herat's agricultural sector, Table 4 outlines specific sub-strategies developed by comparing key internal strengths with salient external opportunities.

Table 4. Aggressive strategies in the development of Herat's agricultural sector.

| Symbol | SO Strategy                                                                                                                                                                                                                                                                                             | Time schedule         |
|--------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| SO1    | Develop and invest in transmission and water supply infrastructure by attracting international support in order to increase productivity and exports of agricultural products to potential export target markets.                                                                                       | Long-term             |
| SO2    | Mobilise local talent to facilitate the transfer of agricultural technical knowledge by deploying agricultural institution graduates into extension services, agribusiness start-ups, and applied research and development (R&D) for high-value crops and business skills.                              | Medium- and long-term |
| SO3    | Establish blended finance windows, concessional finance, and targeted incentives to attract private investment into processing, storage infrastructure, and agricultural mechanisation.                                                                                                                 | Long-term             |
| SO4    | Develop the production of diverse organic products with natural quality by utilising all agricultural, livestock, and horticultural production capacities, in accordance with the climatic and ecological conditions of the region, to align crop selection and production with rising regional demand. | Medium-term           |

Note: SO = strength and opportunity (aggressive strategy).

Source: Authors' compilation.

In the final section of this study, the quantitative strategic planning matrix (QSPM) method, as detailed in the research methodology, is applied to prioritise the strategies identified for the aggressive strategy in the development of Herat's agricultural sector (Table 5). The results indicate that the third strategy, which is the establishment of blended finance windows and incentives to attract private investment into processing, storage infrastructure, and agricultural mechanisation, with a total weight score of 6.119, offers the greatest advantage for the province and has been given priority. This could be due to the lack of adequate processing facilities and modern storage, which prevents the province from adding value to its agricultural output and preserving perishable goods. Similarly, limited access to advanced mechanisation restricts overall productivity and efficiency. The proposed strategy of blended finance and incentives is designed to address these critical gaps by leveraging private sector expertise and capital. This approach is particularly relevant in Herat, given the potential for increased private sector engagement when suitable financial mechanisms and risk mitigation tools are in place.

Table 5. Quantitative strategic planning matrix (QSPM) of the Herat's agricultural development.

| Factors          | Weights | Strategy 1 |       | Strategy 2 |       | Strategy 3 |       | Strategy 4 |       |
|------------------|---------|------------|-------|------------|-------|------------|-------|------------|-------|
|                  |         | AS         | TW    | AS         | TW    | AS         | TW    | AS         | TW    |
| S1               | 0.037   | 1          | 0.037 | 1          | 0.037 | 2          | 0.073 | 3          | 0.110 |
| S2               | 0.036   | 3          | 0.107 | 3          | 0.107 | 1          | 0.036 | 4          | 0.143 |
| S3               | 0.038   | 2          | 0.075 | 2          | 0.075 | 2          | 0.075 | 2          | 0.075 |
| S4               | 0.034   | 3          | 0.102 | 3          | 0.102 | 3          | 0.102 | 3          | 0.102 |
| S5               | 0.040   | 4          | 0.161 | 4          | 0.161 | 4          | 0.161 | 4          | 0.161 |
| S6               | 0.035   | 4          | 0.140 | 1          | 0.035 | 4          | 0.140 | 2          | 0.070 |
| S7               | 0.033   | 3          | 0.098 | 4          | 0.130 | 4          | 0.130 | 2          | 0.065 |
| Total strengths  | 0.252   | 20         | 0.720 | 18         | 0.647 | 20         | 0.717 | 20         | 0.726 |
| W1               | 0.037   | 3          | 0.112 | 4          | 0.150 | 4          | 0.150 | 2          | 0.075 |
| W2               | 0.036   | 4          | 0.144 | 4          | 0.144 | 4          | 0.144 | 4          | 0.144 |
| W3               | 0.040   | 4          | 0.160 | 3          | 0.120 | 4          | 0.120 | 1          | 0.040 |
| W4               | 0.039   | 2          | 0.078 | 3          | 0.118 | 4          | 0.118 | 3          | 0.118 |
| W5               | 0.039   | 1          | 0.039 | 3          | 0.118 | 2          | 0.118 | 3          | 0.118 |
| W6               | 0.036   | 2          | 0.073 | 3          | 0.109 | 4          | 0.109 | 3          | 0.109 |
| W7               | 0.033   | 4          | 0.134 | 3          | 0.100 | 3          | 0.100 | 1          | 0.033 |
| W8               | 0.038   | 1          | 0.038 | 3          | 0.114 | 4          | 0.114 | 3          | 0.114 |
| W9               | 0.038   | 1          | 0.038 | 4          | 0.153 | 3          | 0.153 | 1          | 0.038 |
| W10              | 0.037   | 1          | 0.037 | 3          | 0.111 | 3          | 0.111 | 2          | 0.074 |
| W11              | 0.038   | 2          | 0.076 | 4          | 0.152 | 2          | 0.152 | 3          | 0.114 |
| W12              | 0.039   | 1          | 0.039 | 3          | 0.118 | 4          | 0.118 | 2          | 0.079 |
| W13              | 0.039   | 1          | 0.039 | 2          | 0.074 | 1          | 0.077 | 2          | 0.077 |
| W14              | 0.036   | 1          | 0.037 | 4          | 0.146 | 3          | 0.146 | 2          | 0.073 |
| W15              | 0.036   | 1          | 0.036 | 3          | 0.108 | 2          | 0.108 | 1          | 0.036 |
| W16              | 0.035   | 3          | 0.104 | 4          | 0.138 | 3          | 0.138 | 2          | 0.069 |
| W17              | 0.042   | 1          | 0.042 | 2          | 0.083 | 1          | 0.083 | 4          | 0.166 |
| W18              | 0.035   | 3          | 0.104 | 3          | 0.104 | 4          | 0.104 | 4          | 0.139 |
| W19              | 0.034   | 4          | 0.136 | 2          | 0.068 | 3          | 0.068 | 3          | 0.102 |
| W20              | 0.040   | 1          | 0.040 | 2          | 0.079 | 4          | 0.079 | 2          | 0.079 |
| Total weaknesses | 0.748   | 41         | 1.811 | 62         | 2.310 | 62         | 2.312 | 48         | 1.800 |
| O1               | 0.038   | 1          | 0.038 | 3          | 0.114 | 4          | 0.152 | 2          | 0.076 |
| O2               | 0.042   | 4          | 0.168 | 3          | 0.126 | 4          | 0.168 | 1          | 0.042 |
| O3               | 0.040   | 3          | 0.119 | 2          | 0.079 | 2          | 0.079 | 4          | 0.158 |
| O4               | 0.040   | 2          | 0.081 | 1          | 0.040 | 4          | 0.162 | 3          | 0.121 |
| O5               | 0.039   | 3          | 0.118 | 4          | 0.157 | 4          | 0.157 | 2          | 0.078 |
| O6               | 0.047   | 4          | 0.188 | 3          | 0.141 | 4          | 0.188 | 2          | 0.094 |
| O7               | 0.042   | 2          | 0.085 | 4          | 0.170 | 4          | 0.170 | 1          | 0.042 |
| O8               | 0.037   | 4          | 0.149 | 3          | 0.112 | 4          | 0.149 | 2          | 0.074 |
| O9               | 0.042   | 3          | 0.126 | 3          | 0.126 | 2          | 0.084 | 3          | 0.126 |
| O10              | 0.049   | 4          | 0.196 | 2          | 0.098 | 2          | 0.098 | 1          | 0.049 |

Table 5. Continuation.

|                         |       |    |       |    |       |    |       |    |       |
|-------------------------|-------|----|-------|----|-------|----|-------|----|-------|
| Total opportunities     | 0.417 | 30 | 1.267 | 28 | 1.163 | 34 | 1.406 | 21 | 0.858 |
| T1                      | 0.051 | 4  | 0.206 | 2  | 0.103 | 3  | 0.154 | 3  | 0.154 |
| T2                      | 0.051 | 4  | 0.206 | 3  | 0.154 | 4  | 0.206 | 4  | 0.206 |
| T3                      | 0.047 | 4  | 0.188 | 3  | 0.141 | 4  | 0.188 | 1  | 0.047 |
| T4                      | 0.049 | 4  | 0.194 | 2  | 0.097 | 3  | 0.146 | 4  | 0.194 |
| T5                      | 0.055 | 4  | 0.218 | 3  | 0.164 | 3  | 0.164 | 4  | 0.218 |
| T6                      | 0.056 | 2  | 0.112 | 3  | 0.168 | 3  | 0.168 | 4  | 0.224 |
| T7                      | 0.057 | 3  | 0.171 | 2  | 0.114 | 3  | 0.171 | 4  | 0.228 |
| T8                      | 0.048 | 4  | 0.193 | 3  | 0.145 | 2  | 0.097 | 4  | 0.193 |
| T9                      | 0.056 | 1  | 0.056 | 3  | 0.168 | 4  | 0.224 | 4  | 0.224 |
| T10                     | 0.060 | 1  | 0.060 | 3  | 0.179 | 1  | 0.060 | 3  | 0.179 |
| T11                     | 0.053 | 4  | 0.214 | 3  | 0.160 | 2  | 0.107 | 4  | 0.214 |
| Total threats           | 0.583 | 35 | 1.817 | 30 | 1.592 | 32 | 1.683 | 39 | 2.080 |
| Sum total               |       |    | 5.615 |    | 5.714 |    | 6.119 |    | 5.464 |
| Strategy prioritisation |       |    | 3     |    | 2     |    | 1     |    | 4     |

Note: S = strength, W = weakness, O = opportunity, T = threat, AS = attractiveness score, and TW = total weight.

Source: Authors' calculations.

By focusing on these foundational elements of the agricultural value chain, this strategy is poised to have a cascading positive effect on productivity, export capacity and, ultimately, the economic development of the province's agricultural sector. The second strategy, which is the mobilisation of local talent to transfer the agricultural technical knowledge for high-value crops and business skills, with a total weight score of 5.714, has been identified as the second most important advantage. This strategy stands out because it directly addresses the unique socio-economic fabric of the study area, leveraging the existing community trust and cultural familiarity of local farmers to ensure that agricultural techniques are adapted to the specific soil, climate, and cultural practices of the area. Moreover, this strategy is highly feasible because it relies on human capital that is already present and motivated. Thus, by embedding business skills and technical knowledge within the local population, the strategy fosters long-term sustainability. Following that, the first strategy, investment attraction to increase productivity and export of agricultural products to potential export target markets, with a total weight score of 5.615, has gained the third priority. This strategy directly addresses that bottleneck by attracting capital not just for expansion, but specifically for upgrading processing facilities and logistics to meet international export certifications. Unlike generic investment models, this approach targets the region's unique high-value crops that are currently under-utilised. By aligning investor interests with local agricultural strengths, the strategy ensures that foreign capital translates into tangible productivity gains rather than speculative ventures. Finally,

the last strategy with the total weighted score of 5.464 has obtained the lowest priority, indicating that increasing the productivity of diverse organic products by utilising all production capacities in accordance with the region's climatic and ecological conditions to fully meet demand offers fewer advantages for the development of Herat's agricultural sector.

### Conclusion

This study provides a comprehensive strategic evaluation of the agricultural sector in Herat Province, Afghanistan, to delineate viable pathways for sustainable development. To achieve this, the Delphi technique and a questionnaire were used to identify the key strengths, weaknesses, opportunities, and threats that shape the agricultural landscape in the region. Using SWOT analysis, the key internal and external factors were ranked, and suitable strategies were identified. Subsequently, the SPACE matrix was applied to determine the strategic position of the sector. Finally, employing the QSPM framework, the research systematically identified and ranked viable strategic options aimed at enhancing agricultural growth in the region. The findings highlight that Herat's strategic geographical position for exporting agricultural products stands out as its paramount strength, while the lack of insurance services emerges as a critical weakness. Furthermore, leveraging the Salma Dam for irrigation is highlighted as a key opportunity, juxtaposed with the threats posed by insecurity.

With strengths and opportunities demonstrably dominant, this research advocates an aggressive (SO) strategy that capitalises on the identified strengths and opportunities, thereby positioning Herat's agricultural sector for transformative growth. The prioritised sub-strategies, namely, utilising production capacities, enhancing agricultural literacy, effective water management, and investing in agricultural infrastructure are crucial steps towards sustainable development in the sector and provide valuable insights for policymakers, development practitioners, and agricultural stakeholders.

In conclusion, the findings of this study indicate that strategically targeted investment in agro-processing facilities, logistics infrastructure, and high-value agricultural commodities can advance the agricultural sector. By addressing major structural challenges, including inadequate processing capacity, weak supply-chain networks, and limited market access, such investments can significantly improve agricultural productivity and value addition. Moreover, strengthening agro-processing and logistics systems strengthens producers' capacity to meet domestic and international market requirements, thereby creating greater opportunities for export expansion and increased agricultural revenues.

The findings also underscore the importance of aligning investment initiatives with the region's inherent comparative advantages in high-value agricultural

production. This approach promotes the efficient use of financial resources while supporting the development of integrated and competitive agricultural value chains. As productivity and export performance improve, the agricultural sector can generate broader socio-economic benefits, including employment creation, income growth and better livelihoods for rural communities.

Overall, the research underscores that investment-led agricultural development represents a viable approach toward achieving sustainable sectoral growth. By modernising agricultural systems, strengthening value-chain linkages, and enhancing market competitiveness, this strategy can contribute substantially to long-term agricultural sustainability and broader economic development. Therefore, policymakers, development practitioners, and private-sector stakeholders should prioritise investment frameworks that support infrastructure development, technological advancement, and market integration to fully realise the potential of the agricultural sector.

A notable limitation of this study was its reliance on expert opinions gathered through the Delphi technique and questionnaires. While valuable, this method can be susceptible to participant biases and may not fully capture the diverse, on-the-ground realities of the agricultural sector. For future research, it would be beneficial to incorporate a wider range of data collection methods, such as field surveys with farmers and local communities, to triangulate findings and gain a more comprehensive understanding. Expanding the scope to include other Afghan provinces could also provide a broader national perspective.

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STRATEŠKA ANALIZA RAZVOJA POLJOPRIVREDE PRIMENOM  
SWOT ANALIZE I QSPM MATRICE: STUDIJA SLUČAJA  
PROVINCIJE HERAT, AVGANISTAN

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R e z i m e

Da bi razvojne inicijative bile efikasne i održive, neophodna je sveobuhvatna strateška analiza, naročito u sektorima od posebnog značaja i složenosti, kao što je poljoprivreda. U ovom radu analiziran je sektor poljoprivrede u provinciji Herat u Avganistanu, koji predstavlja područje sa značajnim poljoprivrednim potencijalom, ali i brojnim izazovima, primenom SWOT analize (engl. *Strengths, Weaknesses, Opportunities, Threats*) i QSPM matrice (engl. *Quantitative Strategic Planning Matrix*). Cilj istraživanja bio je da se identifikuju i rangiraju najperspektivnije strateške opcije za razvoj poljoprivrede. Za prikupljanje mišljenja stručnjaka korišćeni su anketni upitnik i Delfi tehnika, pri čemu su značajan deo ispitanika činili univerzitetski nastavnici. Rezultati istraživanja pokazali su da je najznačajnija identifikovana snaga, među elementima SWOT analize, strateški položaj provincije Herat za izvoz poljoprivrednih proizvoda. Kao najizraženija slabost izdvojen je nedostatak usluga osiguranja u poljoprivredi, najznačajnija prilika je korišćenje vode iz brane Salma za navodnjavanje poljoprivrednog zemljišta, dok najveću pretnju razvoju poljoprivrede predstavljaju posledice nesigurnosti. Nakon sprovedene evaluacije utvrđeno je da snage i prilike imaju dominantan uticaj. Stoga je primenom SPACE matrice (engl. *Strategic Position and Action Evaluation*) identifikovana agresivna strategija razvoja zasnovana na povezivanju snaga i prilika. Dobijeni rezultati pružaju korisne smernice kreatorima politika, stručnjacima za razvoj i drugim akterima u poljoprivredi koji nastoje da iskoriste poljoprivredni potencijal provincije Herat i doprinesu širem ekonomskom oporavku Avganistana.

**Ključne reči:** strateška analiza, razvoj poljoprivrede, SWOT, QSPM, Herat, Avganistan.

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## EFFECT OF ZINC FERTILISER MANAGEMENT ON THE PERFORMANCE OF PUDDLED TRANSPLANTED RICE

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**Abstract:** A field experiment was conducted at the Agronomy Field Laboratory of Bangladesh Agricultural University, Mymensingh, during the aman season (June–November 2019) to evaluate the effects of different zinc (Zn) fertiliser management practices on the growth, yield-contributing characters, and yield of puddled transplanted rice. The experiment was arranged in a randomised complete block design with four replications. Seven Zn management treatments were evaluated: no Zn application ( $T_0$ ), basal application of the recommended dose (22 kg  $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$   $\text{ha}^{-1}$ ) ( $T_1$ ), foliar application of 0.5%  $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$  at tillering ( $T_2$ ), soil application of the recommended dose at tillering ( $T_3$ ), foliar application at panicle initiation ( $T_4$ ), soil application of 50% of the recommended dose at tillering plus foliar application at panicle initiation ( $T_5$ ), and split foliar application at both tillering and panicle initiation stages ( $T_6$ ). Zinc fertilisation significantly influenced most growth and yield attributes of rice. Basal Zn application produced the tallest plants (104.91 cm), the highest number of total tillers (17.52  $\text{hill}^{-1}$ ), and effective tillers (16.32  $\text{hill}^{-1}$ ). In contrast, split foliar application ( $T_6$ ) resulted in the longest panicles (23.32 cm), the highest number of grains panicle $^{-1}$  (118.40), filled grains panicle $^{-1}$  (109.82), grain yield (5.98 t  $\text{ha}^{-1}$ ), and straw yield (8.51 t  $\text{ha}^{-1}$ ). Thousand-grain weight and harvest index were not significantly affected by Zn management. The superior performance of  $T_6$  indicates that synchronising Zn supply with critical growth stages improved Zn utilisation and enhanced reproductive

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development, leading to greater yield formation. Therefore, split foliar application of 0.5%  $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$  at tillering and panicle initiation stages may be recommended as an effective Zn management strategy for improving the productivity of puddled transplanted rice.

**Key words:** plant nutrition, Zn fertilisation, rice, fertiliser management.

## Introduction

Rice (*Oryza sativa* L.) is a dominant cereal crop and is the staple food for over half of the global population (Jamal et al., 2023). A marked improvement in rice production has been observed since the start of the Green Revolution (Muthayya et al., 2014). Every year around 800 million tonnes of rice (Shrestha et al., 2022) are produced on about 150–160 million hectares across more than 100 countries (Fukagawa and Ziska, 2019; Jamal et al., 2023). Asia leads the industry, producing nearly 90% of the global supply (Bandumula, 2018), with China and India together providing more than half of total production. However, rice production around the world is frequently challenged by climate change, water scarcity and soil degradation; moreover, over-fertilisation is constantly causing economic and environmental losses that constrain rice production (Stuart et al., 2016; Hussain et al., 2020).

Rice production has markedly improved by adopting high-yielding rice varieties in recent decades, but soil fertility constraint limits their performance (Haefele et al., 2014; Liu et al., 2014). Continuous monocropping, intensive cultivation and imbalanced fertilisation have been degrading soil quality and reducing nutrient availability in the soil (Reynolds et al., 2015; Nawaz et al., 2022). For growth and development, rice needs both macronutrients and micronutrients (Nadeem and Farooq, 2019). Among all the micronutrients, Zn is the most commonly deficient in soils worldwide, affecting 30–50% of arable soils, particularly in the calcareous soils of South Asia (Cakmak and Kutman, 2018). Ensuring the optimum application of micronutrients is still a long way off, even though fertilisers are applied frequently (Nadeem and Farooq, 2019).

Zinc deficiency is a particularly widespread problem in rice-growing areas (Mori et al., 2016). As an essential micronutrient, zinc is involved in numerous physiological and biochemical processes in plants, including enzyme activation, protein synthesis, carbohydrate metabolism and auxin production (Khongchui et al., 2025). Adequate zinc nutrition is pivotal for tiller formation, panicle development, grain filling and overall crop productivity. Evidence from multiple studies has demonstrated that zinc fertilisation significantly enhances growth, yield-contributing characters and grain yield in rice (Farooq et al., 2018; Amanullah et al., 2020). In contrast, zinc deficiency disrupts these processes, leading to stunted growth, reduced leaf expansion, impaired photosynthesis and weakened antioxidant defence systems, which collectively reduce plant vigour and

yield potential (Mattiello et al., 2015; Zhao and Wu, 2017). Several studies have highlighted that zinc deficiency not only reduces plant growth but also exacerbates plant susceptibility to abiotic stresses, leading to severe yield losses under unfavourable environmental conditions. The deficiency is particularly acute in submerged and puddled soil conditions in rice, where reduced redox potential, elevated bicarbonate levels and fixation limit Zn availability and uptake by plant roots (Rehman et al., 2018; Singh and Shivay, 2019). Due to zinc deficiency, yield losses ranging from 15% to over 50% have been recorded, depending on soil properties, severity of deficiency, varietal tolerance and agronomic management (Saha et al., 2017; Coffin and Slaton, 2020).

Zinc fertilisers are known to enhance rice growth and yield performance. The effectiveness of zinc largely depends on how, when and at what rate it is applied as zinc availability in flooded paddy fields is often limited due to chemical fixation and restricted mobility (Adisa et al., 2019). Soil Zn becomes unavailable when it binds with soil constituents, especially in alkaline and calcareous soils. Different zinc application methods – basal, foliar, and split at critical growth stages – have produced variable outcomes under different agro-ecological conditions (González-Caballo et al., 2022; Tuiwong et al., 2022). Among these, zinc sulphate foliar application has increased grain and straw yield of rice (Tuiwong et al., 2022; Yogi et al., 2023), and maize (Liu et al., 2016; Wasaya et al., 2017). In puddled transplanted rice, evidence on the comparative effectiveness of different zinc fertiliser management strategies is still limited, particularly for recently released varieties such as Binadhan-7. Therefore, the present study was undertaken to determine the effect of different zinc fertiliser management practices on the growth, yield-contributing characters and yield of puddled transplanted rice, with the aim of improving zinc use efficiency and crop productivity under *aman* (monsoon) season conditions.

## Materials and Methods

### Study location

The experiment was conducted at the Agronomy Field Laboratory of Bangladesh Agricultural University (BAU), Mymensingh, during the *aman* season from June to November 2019. The experimental site falls within the Old Brahmaputra Floodplain agro-ecological zone (AEZ-9). The climate of the area is subtropical monsoon, with high rainfall, warm temperatures, and high relative humidity during the cropping season. The experimental soil is a non-calcareous dark grey floodplain soil with a silt loam texture and a pH of approximately 6.92. The available zinc content of the soil is  $0.63 \mu\text{g g}^{-1}$  (Begum et al., 2015), which is below the critical limit ( $0.8 \mu\text{g g}^{-1}$ ) for rice cultivation in Bangladesh (Islam et al., 2007).

### Experimental design and treatments

Seven zinc fertiliser management treatments, as described in Table 1, were evaluated in this experiment. The experiment was laid out in a randomised complete block design with four replications. Each replication represented a block in the experiment. Each block was divided into seven unit plots, where the seven treatments were allocated at random. In total, there were 28 unit plots in the experiment. The net size of each unit plot was 10 m<sup>2</sup> (4 m × 2.5 m). The spaces between replications and between plots were 1 m and 0.5 m, respectively.

Table 1. Description of the experimental treatments.

| Treatment      | Description of the treatment                                                                                                                                                                      |
|----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| T <sub>0</sub> | No zinc application (control)                                                                                                                                                                     |
| T <sub>1</sub> | Recommended dose <sup>†</sup> as basal application                                                                                                                                                |
| T <sub>2</sub> | Foliar application <sup>‡</sup> of 0.5% ZnSO <sub>4</sub> ·7H <sub>2</sub> O during the tillering stage                                                                                           |
| T <sub>3</sub> | Top-dressing of 100% RD of ZnSO <sub>4</sub> ·7H <sub>2</sub> O during the tillering stage                                                                                                        |
| T <sub>4</sub> | Foliar application of 0.5% ZnSO <sub>4</sub> ·7H <sub>2</sub> O during the panicle initiation stage                                                                                               |
| T <sub>5</sub> | Top-dressing of ZnSO <sub>4</sub> ·7H <sub>2</sub> O (50% of RD) during the tillering stage + foliar application of 0.5% ZnSO <sub>4</sub> ·7H <sub>2</sub> O during the panicle initiation stage |
| T <sub>6</sub> | Foliar application of 0.5% ZnSO <sub>4</sub> ·7H <sub>2</sub> O during both the tillering and panicle initiation stages                                                                           |

<sup>†</sup>Recommended dose (RD): 22 kg ZnSO<sub>4</sub>·7H<sub>2</sub>O ha<sup>-1</sup> (BARC, 2018). <sup>‡</sup>The application rate of 0.5% ZnSO<sub>4</sub>·7H<sub>2</sub>O foliar spray was 1000 L ha<sup>-1</sup> (≡ 5 kg ZnSO<sub>4</sub>·7H<sub>2</sub>O).

Source: Authors' own experimental data.

### Agronomic management

The rice variety Binadhan-7, developed by the Bangladesh Institute of Nuclear Agriculture (BINA) in 2007, was used as the test crop. The seed-to-seed duration of the crop is 110–120 days. Seeds of rice (cv. Binadhan-7) were obtained from the Agronomy Field Laboratory of Bangladesh Agricultural University, Mymensingh. Seedlings were raised in a nursery prepared through puddling, cleaning and levelling of the soil using traditional methods. Seeds were sown on 1 July, and the nursery was maintained with regular irrigation and manual weed control as required, without the application of fertilisers or manure. The experimental field was prepared by repeated tillage using a power tiller, followed by removal of weeds and residues and final levelling. The land was divided into unit plots, and basal fertilisers were incorporated during final land preparation. Fertilisers were applied at rates of 150, 100, 70, and 60 kg ha<sup>-1</sup> of urea, triple superphosphate, muriate of potash, and gypsum, respectively, following BARC (2018) recommendations. The full doses of triple super phosphate, muriate of potash, and

gypsum were applied basally, while urea was top-dressed in three equal splits at 15, 30, and 45 days after transplanting (DAT). Twenty-eight-day-old seedlings of Binadhan-7 were transplanted on 29 July 2019 into well-puddled plots at a spacing of 20 cm × 25 cm, with three seedlings hill<sup>-1</sup>. Missing hills were replanted one week after transplanting. Intercultural operations included manual weeding at 30 and 45 DAT, irrigation immediately after transplanting and timely drainage of excess water after heavy rainfall. Bunds were maintained to prevent water movement between plots. No major insect pest or disease infestation was observed and therefore no plant protection measures were applied. Zinc fertiliser (ZnSO<sub>4</sub>·7H<sub>2</sub>O) was used in the plots as per the treatment. Foliar application of a 0.5% ZnSO<sub>4</sub>·7H<sub>2</sub>O solution was carried out using a hand sprayer at the respective growth stages as per the treatment requirement (Table 1). Foliar application was done early in the morning of non-rainy days.

#### Sampling, harvesting and recording of data

Harvesting was carried out at physiological maturity, defined by approximately 90% grain discolouration to golden yellow, on 30 October 2019. Prior to harvest, five hills plot<sup>-1</sup> were randomly selected, excluding border rows, for recording yield and yield-attributing traits. Plant height was measured from the plant base to the tip of the panicle and averaged across sampled hills. The number of total tillers hill<sup>-1</sup> was counted, including both effective and non-effective tillers; effective tillers were defined as panicle-bearing tillers with at least one filled grain, while non-effective tillers lacked grain-bearing panicles. Panicle length was measured from the basal node to the tip of the panicle. The number of total spikelets panicle<sup>-1</sup> was counted, comprising both filled grains and sterile spikelets. The number of filled grains panicle<sup>-1</sup> was identified by the presence of endosperm, whereas sterile spikelets lacked food material. Thousand-grain weight was determined using oven-dried grains, while grain yield was obtained from a 5 m<sup>2</sup> central harvest area of each plot after sun drying, weighing and converting to t ha<sup>-1</sup>. Both parameters were standardised to 14% moisture content. Straw yield was recorded from the same harvested area after sun drying and expressed in t ha<sup>-1</sup>. Harvest index (%) was calculated as the ratio of economic yield (grain) to biological yield (grain + straw).

#### Statistical analysis

The recorded data were statistically analysed using the open-source statistical environment 'R' (R Core Team, 2025). The analysis of variance (ANOVA) was conducted using the 'agricolae' package in 'R'. The differences among treatment means were adjudged using the Tukey's *post hoc* test.

## Results and Discussion

The present study revealed that the management of zinc fertiliser had a significant effect on growth, yield-contributing characters and yield of puddled transplanted rice. The response magnitude varied with the timing and method of Zn application. Basal application of Zn was found to be more effective in promoting vegetative growth, while foliar application at critical growth stages was more effective in enhancing reproductive development and yield formation.

Plant height of puddled transplanted rice was significantly affected by zinc (Zn) fertilisation. The tallest plant ( $104.91 \pm 0.39$  cm) was recorded in T<sub>1</sub>. The shortest plants were observed in T<sub>4</sub> and T<sub>6</sub> ( $95.02$  cm), which were statistically similar to T<sub>5</sub> (Table 2). The superior plant height in T<sub>1</sub> may be due to the continuous availability of Zn in the root zone during early crop growth, which favours cell division, auxin synthesis and nutrient uptake. Zinc has been reported to enhance auxin signalling and Zn-use efficiency in rice (Begum et al., 2016).

Zn application had a pronounced effect on the number of total tillers hill<sup>-1</sup>. The maximum number of tillers hill<sup>-1</sup> ( $17.52 \pm 0.20$ ) was recorded in T<sub>1</sub>, followed by T<sub>4</sub>, T<sub>3</sub>, and T<sub>2</sub>. The minimum number ( $12.9 \pm 0.33$ ) was observed in plots receiving treatment T<sub>6</sub> which was statistically similar with T<sub>0</sub>, T<sub>2</sub> and T<sub>5</sub> (Table 2). Correspondingly, the maximum number of effective tillers hill<sup>-1</sup> ( $16.32 \pm 0.18$ ) was obtained from T<sub>1</sub>, and the lowest number of effective tillers hill<sup>-1</sup> ( $10.97 \pm 0.30$ ) was found in T<sub>0</sub>, which was statistically identical to T<sub>2</sub>, T<sub>5</sub> and T<sub>6</sub> (Table 2). The higher tiller production under basal Zn application indicates that Zn availability during the vegetative phase stimulated tiller initiation, tiller survival and vegetative vigour. Additionally, Zn application improves nutrient uptake, regulates phytohormonal balance, and stimulates tiller regrowth and survival, consequently increasing tiller output and vegetative vigour (Liu et al., 2022a; Liu et al., 2022b).

However, panicle length of puddled transplanted rice varied significantly in response to zinc application, and a different trend was observed in the results. The longest panicle ( $23.32 \pm 0.20$  cm) was recorded in T<sub>6</sub>, whereas the shortest ( $19.79 \pm 0.20$  cm) was observed in T<sub>0</sub> (Table 2). The longer panicles under T<sub>6</sub> may be due to the increased availability of Zn during both the vegetative and reproductive phases. Foliar application at critical growth stages can bypass soil-related constraints and deliver Zn directly to metabolically active tissues, thereby supporting reproductive development (González-Caballo et al., 2022; Tuiwong et al., 2022).

Zn fertilisation had a significant effect on the number of grains panicle<sup>-1</sup>. The maximum number of grains panicle<sup>-1</sup> ( $118.4 \pm 0.72$ ) was obtained from T<sub>6</sub>, whereas the minimum number ( $96.45 \pm 0.94$ ) was recorded in T<sub>0</sub>, and was statistically similar to T<sub>2</sub> (Table 2). The higher number of grains panicle<sup>-1</sup> under T<sub>6</sub> suggests that Zn supply at tillering and panicle initiation improved panicle development and spikelet formation. The foliar application of Zn at critical growth stages has been

reported to improve photosynthetic activity, nutrient accumulation and yield formation in rice (Tuiwong et al., 2022; Tuiwong et al., 2024).

Table 2. Effect of Zn fertiliser management on plant and yield-contributing characters of puddled transplanted rice

| Treat-<br>ment | Plant height<br>(cm) | Total tillers<br>hill <sup>-1</sup> | Effective<br>tillers hill <sup>-1</sup> | Panicle<br>length (cm) | Grains<br>panicle <sup>-1</sup> | Filled grains<br>panicle <sup>-1</sup> | WTS<br>(g)        |
|----------------|----------------------|-------------------------------------|-----------------------------------------|------------------------|---------------------------------|----------------------------------------|-------------------|
| T <sub>0</sub> | 99.20 ±<br>0.10c     | 12.15 ±<br>0.25d                    | 10.97 ±<br>0.30d                        | 19.79 ±<br>0.20c       | 96.45 ±<br>0.94e                | 87.72 ±<br>1.17e                       | 22.215 ±<br>0.34a |
| T <sub>1</sub> | 104.91 ±<br>0.39a    | 17.52 ±<br>0.20a                    | 16.32 ±<br>0.18a                        | 21.16 ±<br>0.22b       | 106.72 ±<br>1.20bc              | 97.70 ±<br>0.99bc                      | 22.67 ±<br>0.35a  |
| T <sub>2</sub> | 102.69 ±<br>0.77ab   | 12.97 ±<br>0.19cd                   | 11.95 ±<br>0.17cd                       | 21.31 ±<br>0.15b       | 101.55 ±<br>0.80de              | 91.77 ±<br>0.88de                      | 23.35 ±<br>0.25a  |
| T <sub>3</sub> | 100.67 ±<br>0.53bc   | 14.05 ±<br>0.18c                    | 13.00 ±<br>0.14c                        | 21.82 ±<br>0.31b       | 110.22 ±<br>1.92b               | 101.65 ±<br>1.70b                      | 23.29 ±<br>0.48a  |
| T <sub>4</sub> | 95.02 ±<br>0.49d     | 15.75 ±<br>0.11b                    | 14.67 ±<br>0.13b                        | 21.39 ±<br>0.22b       | 103.02 ±<br>0.65cd              | 94.00 ±<br>0.79cd                      | 22.75 ±<br>0.54a  |
| T <sub>5</sub> | 95.87 ±<br>0.89d     | 12.72 ±<br>0.28d                    | 11.60 ±<br>0.24d                        | 21.81 ±<br>0.13b       | 109.02 ±<br>1.01b               | 100.25 ±<br>1.06b                      | 22.517 ±<br>0.38a |
| T <sub>6</sub> | 95.02 ±<br>0.42d     | 12.90 ±<br>0.33d                    | 11.72 ±<br>0.42d                        | 23.32 ±<br>0.20a       | 118.40 ±<br>0.72a               | 109.82 ±<br>0.75a                      | 23.97 ±<br>0.32a  |
| P value        | <0.001               | <0.001                              | <0.001                                  | <0.001                 | <0.001                          | <0.001                                 | 0.071             |
| CV (%)         | 11.15                | 5.20                                | 6.26                                    | 4.24                   | 9.29                            | 14.51                                  | 3.44              |

Values in a column with the same letter are not statistically different at P = 0.05.

Source: Authors' own data.

It was found that the number of filled grains panicle<sup>-1</sup> was significantly affected by Zn application. The highest number of filled grains panicle<sup>-1</sup> (109.82 ± 0.75) was obtained from T<sub>6</sub>, and the lowest number (87.72 ± 1.17) was observed in T<sub>0</sub>, which was statistically similar to T<sub>2</sub> (Table 2). The increase in filled grains panicle<sup>-1</sup> under T<sub>6</sub> may be associated with better pollen viability, grain setting and grain filling due to Zn availability during reproductive development. Application of zinc during reproductive development has been reported to improve pollen viability, grain setting and grain filling, ultimately leading to higher grain yield (Kandil et al., 2022; Chattha et al., 2023). El-Sobky et al. (2022) and Kunlanit et al. (2025) also reported that Zn application increased the translocation of photosynthates from source leaves to developing grains.

On the other hand, thousand-grain weight was not significantly affected by zinc application. However, T<sub>6</sub> showed the highest value (23.97 ± 0.32), whereas T<sub>0</sub> produced the lowest (22.215 ± 0.34). There were no statistical differences among the values (Table 2). This indicates that Zn management primarily affected grain number and grain filling rather than individual grain size. Therefore, the yield advantage under T<sub>6</sub> was mainly associated with improved panicle length, grains panicle<sup>-1</sup> and filled grains panicle<sup>-1</sup> rather than heavier grains.

Grain yield of puddled transplanted rice was significantly influenced by zinc application, with the highest yield ( $5.98 \text{ t ha}^{-1}$ ) recorded in treatment  $T_6$ , which was statistically similar to  $T_1$ ,  $T_4$  and  $T_5$ . The lowest grain yield was observed in  $T_0$ , which did not differ significantly from several intermediate treatments (Figure 1A). Although  $T_6$  produced fewer effective tillers than  $T_1$ , the substantial increases in panicle length, grains panicle $^{-1}$ , and filled grains panicle $^{-1}$  compensated for the lower tiller number, resulting in the highest grain yield. Zinc is a structural and catalytic component of several enzymes, including carbonic anhydrase, which is involved in photosynthetic carbon assimilation (Tuiwong et al., 2024; Zhao et al., 2024). Recent studies have also shown that foliar application of Zn improves photochemical performance and assimilative capacity, resulting in increased dry matter production and translocation of assimilates to reproductive organs (Zhao et al., 2024).

Significant variation in straw yield was observed in puddled transplanted rice due to Zn application. The highest straw yield ( $8.505 \text{ t ha}^{-1}$ ) was obtained from  $T_6$ , and was statistically similar to  $T_1$ . On the other hand, the lowest straw yield ( $6.965 \text{ t ha}^{-1}$ ) was observed in  $T_0$ , and was statistically similar to  $T_2$ ,  $T_3$ ,  $T_4$  and  $T_5$  (Figure 1B). The significant increase in straw yield under  $T_6$  further indicates enhanced biomass accumulation and overall crop growth. Similar improvements in biomass production and straw yield following Zn fertilisation in rice have been reported by Amanullah et al. (2020) and Yogi et al. (2023).

Harvest index was not significantly affected by Zn fertilisation ( $p = 0.067$ ), although a slight increasing trend was observed in some treatments (Figure 1C). The unchanged harvest index suggests that Zn application increased grain and straw production proportionally rather than altering the partitioning of biomass towards grain yield.

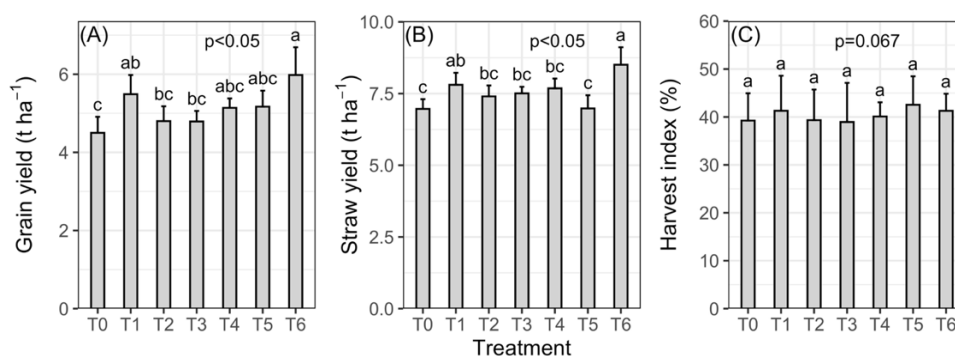


Figure 1. Effect of Zn fertiliser management on (A) grain yield, (B) straw yield, and (C) harvest index of puddled transplanted rice. Values in a column with the same letter are not statistically different at  $P = 0.05$ .

Source: Authors' own data.

An important observation is that T<sub>1</sub>, T<sub>5</sub>, and T<sub>6</sub> received approximately similar total amounts of ZnSO<sub>4</sub>·7H<sub>2</sub>O (22 kg ha<sup>-1</sup>), yet T<sub>6</sub> consistently outperformed the other treatments for major yield attributes. This suggests that the timing and method of Zn application were more important than the total quantity applied. In flooded rice soils, Zn availability is often restricted because of fixation and reduced mobility (Rehman et al., 2018; Singh and Shivay, 2019). Foliar application bypasses soil-related constraints and supplies Zn directly to metabolically active tissues, thereby improving Zn-use efficiency (González-Caballo et al., 2022; Tuiwong et al., 2022). The results of the study clearly indicate that Zn application significantly enhances rice productivity, but the magnitude of its effect is strongly determined by the application strategy adopted. The application of 0.5% ZnSO<sub>4</sub>·7H<sub>2</sub>O as split foliar sprays at the tillering and panicle initiation stages was most effective in maximising the yield and improving the yield-contributing characters under puddled transplanted rice conditions.

### Conclusion

The growth and productivity of puddled transplanted rice were significantly affected by zinc fertiliser management. The basal application of ZnSO<sub>4</sub>·7H<sub>2</sub>O at the recommended rate (22 kg ha<sup>-1</sup>) was found to be better for vegetative growth as it increased plant height and tiller production. However, split foliar application of 0.5% ZnSO<sub>4</sub>·7H<sub>2</sub>O at tillering and panicle initiation stages resulted in the highest grain and straw yields through improvements in panicle length, grains panicle<sup>-1</sup> and filled grains panicle<sup>-1</sup>. The results suggest that the timing and mode of Zn application are more important than the total amount of Zn applied. Thus, split foliar application of 0.5% ZnSO<sub>4</sub>·7H<sub>2</sub>O at tillering and panicle initiation stages may be recommended as an effective Zn management strategy for puddled transplanted rice grown in Zn-deficient soils. Future research should evaluate this practice across different agro-ecological zones, rice varieties and growing seasons, and its impact on Zn uptake, grain Zn enrichment and Zn-use efficiency.

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UTICAJ UPRAVLJANJA ĐUBRENJEM CINKOM NA PERFORMANSE  
PIRINČA PRESAĐENOG NA ZEMLJIŠTU OBRAĐENOM U  
VLAŽNOM STANJU

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R e z i m e

Poljski ogled izveden je u Agronomskoj oglednoj stanici Poljoprivrednog univerziteta u Bangladešu u Mymensingu tokom sezone aman (jun–novembar 2019. godine), sa ciljem ispitivanja uticaja različitih načina đubrenjem cinkom (Zn) na rast, komponente prinosa i prinos presađenog pirinča na zemljištu obrađenom u vlažnom stanju. Ogled je postavljen po slučajnom blok-sistemu sa četiri ponavljanja. Ispitivano je sedam tretmana primene đubrenja cinkom: bez primene cinka ( $T_0$ ), osnovna primena preporučene doze ( $22 \text{ kg ZnSO}_4 \cdot 7\text{H}_2\text{O ha}^{-1}$ ) ( $T_1$ ), folijarna primena  $0,5\% \text{ ZnSO}_4 \cdot 7\text{H}_2\text{O}$  u fazi bokorenja ( $T_2$ ), primena preporučene doze preko zemljišta u fazi bokorenja ( $T_3$ ), folijarna primena u fazi početka formiranja metlice ( $T_4$ ), primena  $50\%$  preporučene doze preko zemljišta u fazi bokorenja, uz folijarnu primenu u fazi početka formiranja metlice ( $T_5$ ), i podeljena folijarna primena u fazama bokorenja i početka formiranja metlice ( $T_6$ ). Đubrenje cinkom značajno je uticalo na većinu karakteristika rasta i prinosa pirinča. Osnovnom primenom cinka postignute su najveća visina biljke ( $104,91 \text{ cm}$ ), najveći ukupan broj izdanaka ( $17,52$  po biljci) i najveći broj produktivnih izdanaka ( $16,32$  po biljci). Nasuprot tome, kod podeljene folijarne primene ( $T_6$ ) zabeležene su najduže metlice ( $23,32 \text{ cm}$ ), najveći broj zrna po metlici ( $118,40$ ), najveći broj ispunjenih zrna po metlici ( $109,82$ ), kao i najveći prinos zrna ( $5,98 \text{ t ha}^{-1}$ ) i prinos slame ( $8,51 \text{ t ha}^{-1}$ ). Masa  $1.000$  zrna i žetveni indeks nisu bili značajno pod uticajem upravljanja đubrenjem cinkom. Bolji rezultati tretmana  $T_6$  ukazuje na to da je usklađivanje primene cinka sa kritičnim fazama rasta poboljšalo iskorišćavanje cinka i pospešilo reproduktivni razvoj biljaka, što je doprinelo povećanju prinosa. Stoga se podeljena folijarna primena  $0,5\% \text{ ZnSO}_4 \cdot 7\text{H}_2\text{O}$  u fazama bokorenja i početka formiranja metlice može preporučiti kao efikasan način primene đubrenja cinkom na povećanje produktivnosti pirinča presađenog na zemljištu obrađenom u vlažnom stanju.

**Ključne reči:** ishrana biljaka, đubrenje cinkom, pirinač, upravljanje đubrenjem.

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## INSTRUCTIONS FOR AUTHORS

### GENERAL INFORMATION

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The entire text of the manuscript should be written in Times New Roman, font size 11, with single line spacing and justified alignment. Paragraphs should be indented (first-line indentation of 0.75 cm), and no additional spacing should be inserted before or after paragraphs. Page numbering should not be used.

Authors are advised to ensure consistency throughout the manuscript in terms of formatting, terminology, and style.

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The material and methods should be clearly outlined, explaining all procedures applied in the paper. Standard methods should be described briefly; detailed explanations are required only for modifications or new procedures. Papers with an experimental design should include a clear description of the statistical methods used for data analysis. This section, as well as the *Results and Discussion* section, if needed, may comprise subparts.

### **Results and Discussion**

In the part Results and Discussion data obtained on the basis of observation and conducted experiments should be interpreted. In the comment of the results, references should be quoted at the end of the paper, providing the comparison between the obtained results and previous knowledge of the certain area.

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The Conclusion should summarise the key findings and their significance, focusing on the main outcomes rather than repeating numerical results already presented in the *Results and Discussion* section. Potential future directions or applications may also be briefly indicated. References should not be included.

### **Acknowledgements**

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### **References**

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The References should be formatted in Times New Roman, font size 9, not bold, justified, with paragraph spacing: before/after 0 pt, line spacing: single, indentation: hanging 0.75 cm.

### **Examples**

#### **Periodicals**

Bekić Šarić, B., Paraušić, V., & Nastić, L. (2025). E-Agrar platform: assessment of benefits and usage challenges from the perspective of beekeepers in Serbia. *Journal of Agricultural Sciences*, 70(2), 205–218. <https://doi.org/10.2298/JAS2502205B>

#### **Books**

Lang, T., & Heasman, M. (2015). *The Global Battle for Mouths, Minds and Markets* (2nd ed.). London: Routledge. <https://doi.org/10.4324/9781315754116>

### **Book chapter**

Fajardo-García, G., & Soler-Tormo, F. (2016). The credit cooperative system in Spain. In S. Karafolas (Ed.), *Credit cooperative institutions in European countries* (pp. 213–232). Springer.  
[https://doi.org/10.1007/978-3-319-28784-3\\_11](https://doi.org/10.1007/978-3-319-28784-3_11)

### **Proceedings**

Iakovlev, D., Kolesnikov, A., & Jugović, M. (2025). Forecasting of the tractors fuel consumption with machine learning methods based on remote monitoring data. In A. Dragičević, & M. Milanović (Eds.), *Proceedings of the 7th International Symposium on Agricultural Engineering - ISAE 2025* (pp. 19–24). University of Belgrade – Faculty of Agriculture.  
<https://doi.org/10.5937/ISAE25019I>

### **Thesis**

Singh, N. K. (1985). *The structure and genetic control of endosperm proteins in wheat and rye*. University of Adelaide.

### **Report**

Ballard, J. (1998). *Some significant apple breeding stations around the world*. Selah, Washington.

### **Website**

Platnick, N. I. (2010). The world spider catalog, version 10.5.  
<http://research.amnh.org/entomology/spiders/catalog/index.html> *American Museum of Natural History*. Retrieved February 12, 2016, from  
<http://research.amnh.org/entomology/spiders/catalog/index.html>

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Tables should be created within the text of the article and numbered with Arabic numerals in order of appearance. Tables should be clear, simple, and unambiguous. The vertical sections should be avoided, and the number of columns should be limited so that the table does not exceed a maximum width of 13 cm (Right-click on the table: Table Properties – preferred width – 13 cm – Measure in: Centimetres).

The title of the table should be placed above the table, single-spaced, justified, ending with a full stop. Complete text within the table cells should be in Times New Roman, font size 9, with paragraph spacing before/after 0 pt, line spacing: single. A source and a detailed explanation of abbreviations, symbols, and signs used in the table should be provided below the table. Each table must be referenced in the text.

### Example

Table 1. Volume and dynamics of Serbia's foreign trade in meat and meat preparations, 2020–2024.

|                         | Average (t) | Min (t) | Max (t)  | CV (%) |
|-------------------------|-------------|---------|----------|--------|
| Export (000 USD)        | 105,693     | 97,583  | 114,098  | 5.74   |
| Import (000 USD)        | 260,256     | 180,337 | 343,095  | 27.52  |
| Trade balance (000 USD) | -154,563    | -76,815 | -245,513 | -47.95 |
| Coverage rate (%)       | 43.4        | 57.4    | 28.4     | -      |

Source: Authors' calculations

### Illustrations

All illustrations, including diagrams, photographs and charts, are referred to as figures and should be placed in the text. Graphs and diagrams should be computer-drawn using Times New Roman, font size 9, with a maximum width of 13 cm to ensure legibility and clarity after size reduction. Excessive colours should be avoided. The detailed legend without abbreviations for each graph and diagram should be provided. The photographs must be of high quality, submitted in TIF or JPG format, and will be printed in black and white.

The title of each illustration should be centred, single-spaced, placed one line below the illustration, ending with a full stop. Each illustration should be mentioned in the text. Source for each figure should be provided below the title.

### Example

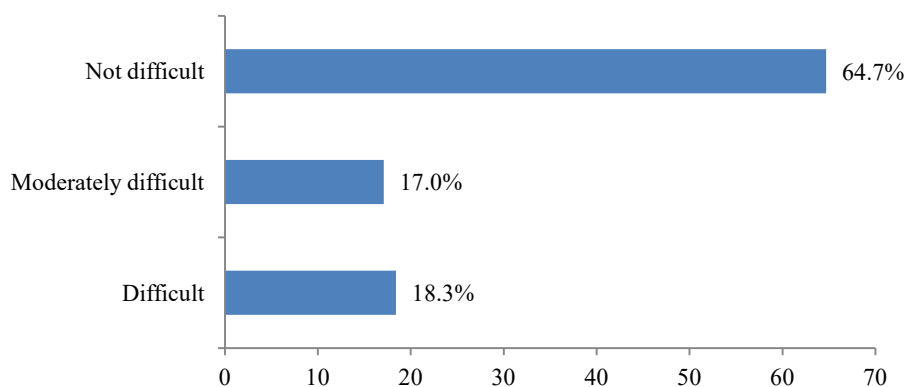


Figure 1. The difficulty of using the eAgrar platform, answer structure, 2023.

Source: Survey results. Authors' calculations

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At the end of the manuscript, a Serbian version of the title, authors' names, affiliations, abstract, and keywords should be provided. For foreign authors, the translation into Serbian will be provided by the Editorial Office.

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Zahvalnica treba da sadrži naziv i broj projekta, odnosno naziv programa u okviru koga je rad nastao, kao i naziv institucije koja je finansirala projekat ili program. Navodi se između *Zaključka* i *Literature*.

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Spisak literature treba da bude formatiran fontom Times New Roman, veličine 9, bez bolda, obostrano poravnat, bez razmaka pre i posle pasusa, sa jednostrukim proredom i uvučenim drugim redom (indentation 0,75 cm).

### **Primeri navođenja referenci**

#### **Rad u časopisu**

Bekić Šarić, B., Paraušić, V., & Nastić, L. (2025). E-Agrar platform: assessment of benefits and usage challenges from the perspective of beekeepers in Serbia. *Journal of Agricultural Sciences*, 70(2), 205–218. <https://doi.org/10.2298/JAS2502205B>

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Ballard, J. (1998). *Some significant apple breeding stations around the world*. Selah, Washington.

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## Tabele

Tabele treba da se nalaze na odgovarajućem mestu u tekstu i numerišu se arapskim brojevima po redosledu pojavljivanja. Tabele treba da budu jasne, jednostavne i pregledne. Treba izbegavati vertikalne linije, a broj kolona ograničiti tako da širina tabele ne prelazi 13 cm.

Naslov tabele navodi se sa jednim redom razmaka iznad tabele, poravnat obostrano i sa tačkom na kraju. Tekst unutar tabele piše se fontom Times New Roman, veličine 9, sa jednostrukim proredom. Ispod tabele treba dati izvor, kao i detaljno objašnjenje skraćenica, simbola i oznaka korišćenih u tabeli. Svaka tabela mora biti pomenuta u tekstu.

## Primer

Tabela 1. Obim i dinamika spoljne trgovine mesom i prerađevinama od mesa u Srbiji, 2020–2024.

|                                         | Prosek (t) | Minimum (t) | Maksimum (t) | CV (%) |
|-----------------------------------------|------------|-------------|--------------|--------|
| Izvoz (000 USD)                         | 105.693    | 97.583      | 114.098      | 5,74   |
| Uvoz (000 USD)                          | 260.256    | 180.337     | 343.095      | 27,52  |
| Bilans (000 USD)                        | -154.563   | -76.815     | -245.513     | -47,95 |
| Stopa pokrivenosti<br>uvoza izvozom (%) | 43,4       | 57,4        | 28,4         | -      |

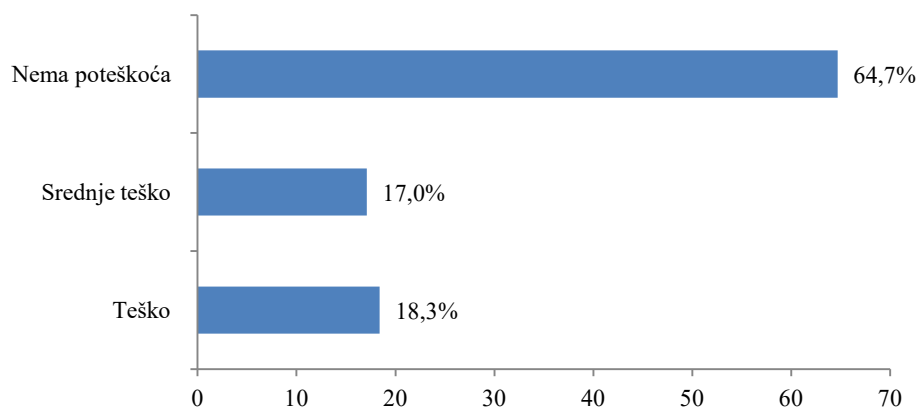
Izvor: Obračun autora

## Ilustracije

Sve ilustracije, uključujući dijagrame, fotografije i grafikone, označavaju se kao slike i treba da budu postavljene u tekstu. Grafikoni i dijagrami treba da budu pripremljeni na računaru, koristeći font Times New Roman, veličina 9, sa maksimalnom širinom od 13 cm, kako bi ostali čitki i jasni i nakon redukcije veličine. Treba izbegavati prekomernu upotrebu boja. Za svaki grafikon i dijagram treba dati detaljnu legendu bez skraćenica. Fotografije moraju biti visokog kvaliteta, dostavljene u TIF ili JPG formatu i biće štampane u crno-beloj tehnici.

Naslov svake slike treba da bude centriran, sa jednostrukim proredom, postavljen sa jednim redom razmaka ispod slike, sa tačkom na kraju. Svaka slika mora biti pomenuta u tekstu. Izvor za svaku sliku navodi se ispod naslova.

### Primer



Slika 1. Teškoće u korišćenju platforme eAgrar, struktura odgovora, 2023.

Izvor: Obrada autora na osnovu sprovedenog istraživanja.

### Skraćenice i jedinice

U radu treba koristiti samo standardne skraćenice. Merne jedinice treba izražavati u internacionalnom sistemu jedinica (SI). Skraćenice se mogu koristiti i za druge izraze pod uslovom da se ti izrazi navedu u punom obliku prilikom prvog pominjanja u tekstu, sa skraćenim oblikom u zagradi. Vrednosti od jedan do devet se izražavaju slovima, a ostali brojevi isključivo numerički. U naslovu rada ne treba koristiti skraćenice.

### Nomenklatura

Međunarodni standardi (IUPAC, IUB, ICN itd.) treba da se primenjuju za hemijske, biohemijske, taksonomske i genetičke termine.

### Formule

Sve formule i jednačine u radu moraju biti urađene pomoću programa *Microsoft Word Equation Editor* ili *MathType*. Prilikom pisanja jednačina treba dati značenje svih simbola odmah posle formule u kojoj se simbol prvi put koristi. Formule treba da budu numerisane arapskim brojevima, serijski u zagradama, na desnoj strani. Svaka jednačina mora biti pomenuta u tekstu kao Eq. (1), Eq. (2), itd.

Na kraju rukopisa navode se naslov rada, imena autora, afiliacije, sažetak i ključne reči na srpskom jeziku. Za strane autore, prevod na srpski jezik obezbeđuje redakcija.

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