International Journal of Sustainability and Advanced Integrated Research
Volume 2, Issue 2 (April-June 2026) | ISSN: 3107-7854
DOI: https://doi.org/10.65339/ijsair.V2.I2.289

Farmers' Knowledge, Perceptions, and Management Practices Against the Coconut Leaf Beetle (*Brontispa Longissima*) in Selected Municipalities of Nueva Vizcaya

Jaira Joy B. Tumapang
College of Agriculture, Cagayan State University–Piat Campus, Piat, Cagayan, Philippines

Publication history: Received: March 12, 2026; Revised: April 19, 2026; Accepted: April 24, 2026
Email of Corresponding Author: jairajoyb.tumapang2000@gmail.com

Abstract

This study examined the socio-demographic characteristics, knowledge, perceptions, and pest management practices of coconut farmers in Bagabag, Quezon, and Kasibu, Nueva Vizcaya, in relation to Coconut Leaf Beetle (Brontispa longissima) infestation. Anchored on the Integrated Pest Management (IPM) framework and farmer behavior perspectives, the research employed a descriptive survey design using a self-constructed questionnaire administered through face-to-face interviews with 60 purposively selected coconut farmers. Data were analyzed using frequency counts, percentages, and weighted mean. Findings revealed that coconut farming is dominated by smallholder, middle-aged farmers with low income and limited educational attainment, factors that constrain access to technical knowledge and adoption of improved practices. A significant knowledge gap exists, with most farmers unfamiliar with the pest and relying primarily on informal information sources. Despite widespread infestation and observable damage, the majority of farmers do not implement pest management practices, while those who do often apply ineffective or non-specific methods. No respondents reported receiving formal training or consulting agricultural experts. However, farmers demonstrated strong awareness of the pest's importance and expressed high willingness to adopt improved and sustainable management strategies, particularly when provided with training, financial assistance, and technical support. The study concludes that limited access to extension services, training, and resources—rather than lack of motivation—hinders effective pest management. It recommends strengthening agricultural extension programs, promoting IPM and biological control, and providing accessible information and financial support to farmers. This study aligns with Sustainable Development Goals (SDG) 2 (Zero Hunger), SDG 8 (Decent Work and Economic Growth), and SDG 12 (Responsible Consumption and Production) by addressing agricultural productivity, farmer livelihoods, and sustainable pest management practices. Its sustainability impact lies in supporting smallholder resilience, promoting environmentally sound farming practices, and informing institutional and community-level interventions for sustainable agricultural.

Keywords: Coconut Farming, Coconut Leaf Beetle, Farmer Knowledge, Integrated Pest Management, Nueva Vizcaya, Pest Management Practices, Smallholder Farmers

1. Introduction

The Philippine coconut industry is a major contributor to the national economy and rural livelihoods but faces persistent challenges such as low productivity, pest infestations, and limited farmer capacity. Among the most significant threats is the Coconut Leaf Beetle (Brontispa longissima), which severely affects coconut yield and farmer income. Despite the availability of Integrated Pest Management (IPM) strategies, adoption remains limited due to gaps in farmer knowledge, access to extension services, and local research. This study examines the socio-demographic profile, knowledge, perceptions, and pest management practices of coconut farmers in selected municipalities of Nueva Vizcaya to inform targeted and sustainable pest management interventions.

1.1 Background of Coconut Farming and Coconut Leaf Beetle Infestation among Smallholder Farmers in Nueva Vizcaya

The Philippines is the second largest producer of coconut products globally, with over 3.6 million hectares of coconut farms supporting more than 2.5 million farmers and generating approximately ₱91.4 billion in export earnings annually (Philippine Coconut Authority, 2026). Despite its importance, the industry suffers from low productivity due to aging trees, poor agronomic practices, and yield gaps ranging from 31–87% (Crisostomo et al., 2023). Natural disasters such as Typhoon Pablo (2012) and Typhoon Yolanda (2013) have further reduced production and increased plantation vulnerability to pests (DOST-PCAARRD, 2025). The Coconut Leaf Beetle (Brontispa longissima) is a destructive pest introduced in the Philippines in 2005, damaging young coconut fronds and reducing photosynthetic capacity, growth, and yield, and in severe cases causing tree mortality (Cabelin and Ceniza, 2021). In areas like Nueva Vizcaya, limited documented information and reliance on experiential knowledge hinder effective pest management. While Integrated Pest Management (IPM) offers

sustainable control through biological, cultural, and chemical approaches, its implementation remains constrained due to limited awareness and access to validated strategies (Navasero and De Panis-Javier, 2017; Chen et al., 2020).

1.2 Farmer Knowledge, Perceptions, and Pest Management Practices on Coconut Leaf Beetle: Synthesis of Related Literature

Literature highlights the economic significance of the coconut industry alongside persistent structural challenges such as smallholder farming systems and financial limitations that restrict investment in improved technologies and pest management (Quitoriand, 2021; Santillán Galicia, 2020). The Coconut Leaf Beetle is identified as a major threat, capable of reducing yields by 50–70% in heavily infested areas (Reyes et al., 2023). Effective management requires targeting both larval and adult stages due to their destructive feeding behavior (Navasero et al., 2019; Chen et al., 2020). Farmer knowledge is a critical factor influencing pest management outcomes. Limited awareness leads to delayed detection and improper control practices (Schreinemachers et al., 2020; Achampong et al., 2022). Studies indicate that farmers often rely on traditional knowledge due to limited extension services, resulting in inadequate pest identification and management (Dela Cruz et al., 2022; Bentayao et al., 2025). IPM strategies, including biological control using natural enemies such as parasitoid wasps and earwigs, have proven effective and environmentally sustainable (Navasero and De Panis-Javier, 2017; PNA, 2018). However, adoption remains low due to financial constraints and lack of technical support (Schreinemachers et al., 2020; Degaine et al., 2021). Despite these barriers, farmers generally show willingness to adopt improved practices when provided with adequate resources, training, and institutional support (Bentayao et al., 2025; Grameen Foundation, 2019, 2023; Winotai, 2024).

1.3 Local (Nueva Vizcaya), National (Philippines), and Global Coconut Industry and Pest Context

Globally, the Philippines ranks as a leading coconut producer, underscoring its role in international agricultural markets (Philippine Coconut Authority, 2026). Nationally, the industry supports millions of smallholder farmers but faces declining productivity and increasing pest pressures (Crisostomo et al., 2023; DOST-PCAARRD, 2025). Locally, in Nueva Vizcaya, limited research on Coconut Leaf Beetle management and farmer practices restricts the development of context-specific interventions. The absence of localized data highlights the need for studies that address community-level knowledge and practices to improve pest management outcomes.

1.4 Integrated Pest Management (IPM) and Farmer Behavior Framework for Coconut Leaf Beetle Control

This study is anchored on the concept of Integrated Pest Management (IPM), which promotes the integration of biological, cultural, and chemical control methods to achieve sustainable pest control while minimizing environmental impact (Navasero and De Panis-Javier, 2017; Chen et al., 2020). It also draws on the premise that farmer knowledge, perceptions, and socio-economic conditions influence the adoption of agricultural innovations and pest management practices (Schreinemachers et al., 2020; Achampong et al., 2022). The interaction between knowledge, attitudes, and practices serves as the basis for understanding farmer behavior in managing Coconut Leaf Beetle infestations.

1.5 Research Gaps on Farmer Knowledge, Perceptions, and IPM Practices on Coconut Leaf Beetle in Nueva Vizcaya

Existing studies emphasize the biological and economic impacts of the Coconut Leaf Beetle but reveal limited research on farmer-level knowledge, perceptions, and practices, particularly in specific local contexts such as Nueva Vizcaya. The lack of localized data constrains the design of effective extension programs and community-based pest management strategies. Furthermore, gaps in farmer awareness and limited access to technical support hinder the adoption of IPM practices (PCAARRD, 2021; Bentayao et al., 2025). This study addresses these gaps by documenting farmer profiles and assessing their knowledge, perceptions, and management practices to support targeted interventions.

1.6 Alignment of Coconut Leaf Beetle Management Study with Sustainable Development Goals (SDGs)

This study aligns with SDG 2 – Zero Hunger by addressing threats to agricultural productivity and food security through improved pest management. It also supports SDG 8 – Decent Work and Economic Growth by enhancing the productivity and income potential of smallholder coconut farmers. Additionally, it contributes to SDG 12 – Responsible Consumption and Production through the promotion of sustainable pest management practices such as IPM, which reduce reliance on harmful chemical inputs.

1.7 Importance of Coconut Leaf Beetle Management Study to Multidisciplinary Sustainability

The study contributes to socio-economic sustainability by supporting smallholder farmers' livelihoods through improved pest management strategies. It promotes environmental sustainability by encouraging IPM approaches that minimize ecological damage and chemical use. It also advances agricultural and community sustainability by strengthening local knowledge systems and informing extension services. Furthermore, the study supports institutional sustainability by providing evidence-based insights for policymakers and agricultural agencies to design targeted interventions that enhance resilience and productivity in the coconut sector.

2. Material and methods

2.1 Research Design

The study employed a descriptive survey research design to document the socio-demographic profile of coconut farmers and assess their knowledge, perceptions, and current pest management practices against the Coconut Leaf Beetle in Nueva Vizcaya. This approach was appropriate for systematically gathering, organizing, and interpreting information about a phenomenon as it naturally exists without manipulation of variables (Campbell et al., 2020). The survey method enabled the collection of standardized data from a defined population, allowing objective analysis and comparison across respondents.

2.2 Locale of the Study

The study was conducted in the municipalities of Bagabag, Quezon, and Kasibu in Nueva Vizcaya. These areas were selected due to the presence of coconut as a host crop and their inclusion in the agricultural zones of Cagayan Valley. The municipalities possess suitable agroclimatic conditions for coconut production and potential pest occurrence, and they are accessible for field data collection. Local farmers were available and willing to participate, and beetle samples were collected directly from coconut trees within these areas for laboratory analysis.

2.3 Respondents of the Study

The respondents were coconut farmers from Bagabag, Quezon, and Kasibu, Nueva Vizcaya. A total of 60 farmers participated, with 20 respondents from each municipality. Participants were selected based on their active involvement in coconut farming and their ownership or management of at least ten coconut trees, ensuring sufficient experience in coconut cultivation to provide relevant information (Campbell et al., 2020).

2.4 Sample and Sampling Procedure

Purposive sampling was used to select respondents who met the inclusion criteria of being actively engaged in coconut farming and managing at least ten coconut trees. This sampling approach ensured that participants possessed adequate practical knowledge and experience relevant to pest management practices, allowing for meaningful and reliable responses.

2.5 Research Instrument

A self-constructed questionnaire approved by the thesis panel served as the primary data collection instrument. It gathered information on respondents' socio-demographic and farm characteristics, including gender, age, educational attainment, civil status, family size, income, land tenure, number of coconut trees, farming experience, and tree age. It also assessed farmer knowledge and ability to identify the Coconut Leaf Beetle, including familiarity, information sources, and recognition methods. The instrument further documented current pest management practices, observed damage symptoms, and perceived economic impacts of infestation. Finally, it measured farmers' attitudes and motivations toward pest management using a 3-point Likert scale.

2.6 Data Gathering Procedure

Data were collected through structured face-to-face interviews conducted by the researcher in each municipality. The researcher visited farms and administered the questionnaire, allowing clarification of questions and direct observation of farm conditions. Prior to data collection, permission was obtained from the Municipal Agriculture Offices of Bagabag, Quezon, and Kasibu, and informed consent was secured from all respondents.

2.7 Data Analysis Techniques

Data were analyzed using descriptive statistics, including frequency counts, percentages, and weighted mean. Frequency counts and percentages were used to summarize socio-demographic profiles, knowledge, identification ability, management practices, and observed damage. Percentages were computed using the formula: Percentage = (Frequency ÷ N) × 100. Weighted means were used to assess attitudes and motivations toward pest management, computed using the formula: $WM = \Sigma (f \times w) \div N$. A 3-point Likert scale was used to interpret responses, and all data were processed using Microsoft Excel.

3. Results and Discussion

3.1 Socio-Demographic Profile and Farm Characteristics of Coconut Farmers

3.1.1 Gender, Age, and Household Characteristics

The results show that 78.33% of respondents were female and 21.67% were male. Most farmers were middle-aged, with the largest groups aged 41–50 and 51–60 (25% each), while only 1.67% were aged 20–30. The majority were married (91.67%) and had family sizes of 5–6 members (46.67%). These findings indicate that coconut farming is largely managed by middle-aged and older individuals, with minimal youth participation. The dominance of older farmers suggests potential challenges in sustaining the industry in the long term. This pattern aligns with Bentayao et al. (2025), who reported an

aging farming population in coconut-growing communities, highlighting concerns about generational continuity in agriculture.

3.1.2 Educational Attainment and Income Status

More than half of the respondents (53.33%) had reached high school, while 25% completed only elementary education, 18.33% attended college, and 3.33% had technical training. Most farmers earned between ₱6,000 and ₱10,000 monthly (38.33%), while 16.67% earned ₱3,000–₱5,000, and none earned above ₱30,000. The results suggest that farmers generally have limited formal education and low income, which may restrict their ability to access and understand technical information on pest management. This supports findings by Dela Cruz et al. (2022), which indicate reliance on traditional knowledge due to limited access to formal training. Financial limitations further constrain farmers' ability to invest in pest control measures, consistent with Schreinemachers et al. (2020), who identified economic constraints as major barriers to effective pest management.

3.1.3 Farm Size, Tenure, and Farming Experience

Most respondents (73.33%) managed 1–20 coconut trees, 20% had 21–50 trees, and only 6.67% had 51–100 trees. A large majority (93.33%) were landowners. Nearly half (48.33%) had 5–10 years of farming experience, while 40% had less than 5 years. Most coconut trees were aged 5–20 years (58.33%). These findings confirm that coconut farming in the area is dominated by smallholder farmers with limited resources. This structure limits the adoption of improved practices, as noted by Santillán Galicia (2020). While farmers possess practical experience, it does not necessarily translate to effective pest management without proper guidance (Dela Cruz et al., 2022). The predominance of trees in the productive growth stage also increases vulnerability to pest infestations such as CLB (Navasero et al., 2019).

3.2 Knowledge and Identification of the Coconut Leaf Beetle

3.2.1 Level of Awareness and Sources of Information

The results indicate that 60% of respondents were not familiar with the CLB, while only 36.67% reported familiarity. Nearly all respondents (98.33%) relied on fellow farmers for information, with only 1.67% obtaining information from the Department of Agriculture. This low level of awareness reflects a significant knowledge gap that limits timely pest detection and control. The reliance on informal information sources increases the risk of misinformation. This finding is consistent with PCAARRD (2021), which noted widespread gaps in farmer awareness of CLB due to limited extension reach.

3.2.2 Recognition and Understanding of Pest Characteristics

Among those who recognized the pest, 66.67% identified it by appearance and 33.33% by plant damage. Most respondents (78.33%) identified the adult stage as the most damaging, while 20% did not know. Additionally, 63.33% rated the pest as serious and 5% as very serious. These results show that while some farmers can recognize the pest, knowledge remains incomplete, particularly regarding its life cycle. Although the adult stage is widely perceived as the most damaging, both larval and adult stages contribute to plant damage (CABI, 2022). The recognition of CLB as a serious threat aligns with Reyes et al. (2023), who reported significant yield losses associated with severe infestations.

3.3 Damage, Management Practices, and Perceived Economic Impact

3.3.1 Observed Infestation and Damage Symptoms

The findings reveal that 80% of respondents observed CLB infestation, and 71.67% reported damage to coconut trees. The most common symptoms were browning of leaves (81.67%) and leaf distortion (18.33%). These observations confirm the presence of CLB infestation in the study area, with symptoms consistent with documented feeding damage that results in scorched and ragged leaf appearance (CABI, 2022). The widespread occurrence of these symptoms indicates that the pest is already affecting coconut productivity at the farm level.

3.3.2 Pest Management Practices and Effectiveness

A majority of farmers (61.67%) reported not using any pest management practices. Only 21.67% practiced manual removal, while 16.67% used chemical pesticides, often repurposed from other crops. Among those applying control measures, 41.67% found them somewhat effective, 30% ineffective, and 28.33% were unsure. These results demonstrate limited adoption of effective pest management strategies. The use of non-specific pesticides reflects inadequate knowledge and may lead to environmental risks. Recommended approaches such as Integrated Pest Management (IPM), including biological control using natural enemies, are more effective and sustainable (Reyes et al., 2023). The low effectiveness ratings further support findings by Schreinemachers et al. (2020) that lack of training reduces the success of pest management practices.

3.3.3 Perceived Economic Impact and Access to Support Services

Most respondents (73.33%) agreed that CLB negatively affects income, and 93.33% considered it a serious industry threat. However, all respondents reported no actual economic loss, and none had consulted agricultural experts or received training

on CLB management. This apparent contradiction suggests underrecognition of actual losses due to limited awareness. Farmers may not associate damage with financial impact or may lack records of yield loss. The absence of consultation and training highlights a major gap in extension services, consistent with Schreinemachers et al. (2020), which emphasizes the importance of knowledge and support systems in improving pest management outcomes.

3.4 Attitude and Motivation Toward Coconut Leaf Beetle Management

3.4.1 Farmer Attitudes Toward Pest Management

The results show that all indicators of attitude and motivation toward CLB management were rated "Strongly Agree," with a grand mean of 1.13. Farmers strongly agreed that infestation affects yield, that pest management is essential, and that training, financial assistance, technical advice, and biological control are beneficial. These findings indicate a strong willingness among farmers to adopt improved pest management practices. Despite limited knowledge and lack of training, farmers recognize the importance of managing CLB and are open to adopting new approaches when support is available. This aligns with Bentayao et al. (2025), which found that farmers are willing to adopt improved practices but are constrained by limited resources and institutional support.

3.4.2 Implications for Sustainable Pest Management Adoption

Farmers expressed strong agreement on the importance of training, collaboration, and access to information, as well as the effectiveness of biological control methods. This positive attitude suggests that the main barrier to effective pest management is not willingness but access to resources and support. The acceptance of biological control is particularly promising, as such methods have been effective in reducing CLB populations in areas like Palawan (PNA, 2018). Strengthening extension services, providing training, and promoting community-based pest management could enhance adoption of sustainable practices and improve coconut productivity in the study area.

4. Conclusion & Recommendations

This study found that coconut farming in Bagabag, Quezon, and Kasibu, Nueva Vizcaya is dominated by smallholder farmers with low income, moderate experience, and limited educational attainment, which restricts their ability to access information and adopt effective pest management practices. A significant gap exists in farmers' knowledge and awareness of the Coconut Leaf Beetle, as most rely on informal sources and have minimal exposure to formal extension services. Despite widespread infestation and observable damage, the majority of farmers do not implement pest management practices, and those who do use ineffective or non-targeted methods, with no respondent having received formal training or consultation. However, farmers demonstrated strong willingness to adopt improved pest management strategies, indicating that the primary constraint is limited access to training, technical support, and financial resources rather than lack of motivation.

Agricultural extension services should be strengthened through coordinated efforts of the Department of Agriculture, Philippine Coconut Authority, and Local Government Units to provide community-based training, farm visits, and demonstrations focused on CLB management. Information, Education, and Communication materials should be developed in accessible formats and local language to improve farmer awareness. Biological control programs using natural enemies should be promoted as cost-effective and sustainable solutions, while financial assistance mechanisms should be provided to support adoption of pest management practices. Further research should be conducted across wider geographic areas with larger sample sizes to enhance data reliability and support the development of more targeted interventions.

This study was limited to 60 purposively selected coconut farmers from three municipalities in Nueva Vizcaya and relied on self-reported data gathered through structured interviews, which may reflect subjective perceptions rather than actual conditions. The scope focused only on socio-demographic characteristics, knowledge, perceptions, and practices without including experimental validation or direct measurement of pest impact, thereby limiting the generalizability and precision of the findings.

Compliance with ethical standards

This study adhered to standard ethical research practices in the conduct of data collection and interaction with participants. Permission to conduct the study was obtained from the Municipal Agriculture Offices of Bagabag, Quezon, and Kasibu, and informed consent was secured from all respondents prior to participation. Data were collected through structured face-to-face interviews, ensuring that participants were aware of the purpose of the study and voluntarily provided information.

REFERENCES

Achampong, R., Dwumfour-Asante, D., Achari, S., Egyir, I. S., & Ninsin, K. D. (2022). Farmers' knowledge and farm-level management practices of coconut pests in Ghana: Assessment based on gender differences. Phyto-Frontiers, 2(3), 280–288.

Bentayao, C. M., Verzosa, R. C., Vilela, E. M., & Nemenzo-Calica, P. (2025). Knowledge, attitudes, and agricultural practices of coconut farmers on the impacts of climate change on coconut productivity and sustainability in Barangay Capasnan, Manay, Davao Oriental, Philippines. Journal of Tropical Crop Science, 12(1), 158–171.

Cabelin, G. R., & Ceniza, M. J. C. (2021). Degree of damage and infestation of coconut leaf beetle Brontispa longissima (Gestro) on seedlings of selected coconut varieties. Annals of Tropical Research, 43(2), 25–34.

CABI. (2022). Brontispa longissima (coconut hispine beetle). CABI Compendium. https://doi.org/10.1079/cabicompendium.10059

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., Bywaters, D., & Walker, K. (2020). Purposive sampling: Complex or simple? Research case examples. Journal of Research in Nursing, 25(8), 652–661.

Chen, Z., Tang, B. Z., Huang, B., & Hou, Y. M. (2020). Effects of temperature on the life history traits of Brontispa longissima (Gestro) (Coleoptera: Chrysomelidae) and its biological control agent Asecodes hispinarum. Biological Control, 141, 104140.

Crisostomo, R. S., Palacpac, E. P., & Laguna, E. P. (2023). Yield gap analysis in Philippine coconut production: Challenges and opportunities. Philippine Journal of Crop Science, 48(1), 12–25.

Degaine, J. P., Aubertot, J. N., Flor, R. J., Lescourret, F., Wyckhuys, K. A., & Ratnadass, A. (2021). Integrated pest management: Good intentions, hard realities. Agronomy for Sustainable Development, 41(3), 38.

Dela Cruz, R. T., Santos, M. A., & Reyes, J. P. (2022). Knowledge and practices of coconut farmers in pest management: Implications for extension programs in the Philippines. Philippine Journal of Crop Science, 47(2), 45–58.

DOST-PCAARRD. (2025). Coconut industry recovery and pest management updates. Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development. https://www.pcaarrd.dost.gov.ph

Grameen Foundation. (2019). Building resilience of coconut smallholder farmers in the Philippines: Final evaluation report of the FarmerLink program. https://grameenfoundation.org

Grameen Foundation. (2023). Notes from the field: Financial empowerment for coconut farmers in the Philippines. https://grameenfoundation.org

Navasero, M. V., & De Panis-Javier, R. (2017). Biological control of Brontispa longissima in the Philippines: Status and prospects. Philippine Entomologist, 31(1), 1–15.

Navasero, M. V., Saavedra, F. T., & Zipagan, M. B. (2019). Biology and management of the coconut leaf beetle Brontispa longissima (Gestro) (Coleoptera: Chrysomelidae) in the Philippines. Philippine Entomologist, 33(1), 1–18.

PCAARRD. (2021). Coconut leaf beetle: A threat to the Philippine coconut industry. Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development. https://www.pcaarrd.dost.gov.ph

Philippine Coconut Authority. (2026). Philippine coconut industry: Statistics and production overview. https://www.pca.da.gov.ph

Philippine News Agency. (2018, October 15). Earwig biological control saves Palawan coconut industry from beetle infestation. https://www.pna.gov.ph

Quitoriand, E. L. (2021). Smallholder coconut farming in the Philippines: Structural constraints and pathways for improvement. Asian Journal of Agriculture and Development, 18(1), 23–39.

Reyes, J. D., Palomar, M. K., & Santos, L. B. (2023). Impact of Brontispa longissima infestation on coconut yield and assessment of integrated management strategies in selected provinces in the Philippines. Philippine Agricultural Scientist, 106(2), 112–124.

Santillán Galicia, M. T. (2020). Overview and constraints of the coconut supply chain in the Philippines. International Journal of Fruit Science, 20(Suppl. 2), S624–S640.

Schreinemachers, P., Balasubramaniam, S., Boopathi, N. M., Ha, C. V., Kenyon, L., Praneetvatakul, S., Rasphone, A., Srinivasan, R., Singh, L. J., & Wu, M. H. (2020). Farmers' perceptions and management of plant viruses in vegetables and legumes in tropical and subtropical Asia. Crop Protection, 127, 104968.

Winotai, A. (2024). Integrated pest management of important insect pests of coconut. Frontiers in Agronomy. https://doi.org/10.3389/fagro.2024.1407495