Neutrosophic Sets and Systems, {Special Issue: Artificial Intelligence, Neutrosophy, and Latin American Worldviews: Toward a Sustainable Future (Workshop – March 18–21, 2025, Universidad Tecnológica de El Salvador, San Salvador, El Salvador)}, Vol. 84, 2025

University of New Mexico

NAHP: Neutrosophic Hierarchical Analysis for Pest Prioritization in Plantain Cultivation

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Abstract: The following study addresses the impact of pests on plantain cultivation, recognizing them as a critical factor for both sustainability and productivity. Traditionally, decision-making in this context relies heavily on subjective and unstructured criteria, often leading to inaccurate prioritization of pest- and disease-related risks. This issue becomes even more pressing considering the growing global demand for plantains and the need to manage resources effectively, which calls for clear identification of intervention priorities. However, agricultural systems—characterized by ecological and social variability—often present incomplete, ambiguous, or contradictory information, making conventional multicriteria analysis insufficient. To address this challenge, this research introduces the Neutrosophic Analytic Hierarchy Process (NAHP), an extension of the traditional AHP that incorporates uncertainty and indeterminacy in expert evaluations. Through a hierarchical structure, the model assesses pest threats based on criteria such as economic damage, frequency of occurrence, and control difficulty. Results show that NAHP delivers robust and consistent classifications, enabling more effective pest prioritization for enhancing both technical and agricultural efficiency. This research contributes both theoretically and practically, introducing an innovative methodology to agricultural decision-making and offering a valuable tool for farmers, agronomists, and policymakers. Ultimately, the study expands the application of neutrosophic logic to agriculture, fostering the development of more sustainable and efficient crop protection strategies.

Keywords: NAHP, Neutrosophic, Pests, Crop, Plantain, Prioritization, Multicriteria Analysis, Expert Judgment, Integrated Management, Agriculture, Uncertainty, Indeterminacy, Sustainability, Neutrosophic Logic, AHP.

1. Introduction

Plantain cultivation is a key agricultural activity in tropical countries due to its nutritional and economic value. However, its sustainability is seriously threatened by pests, which reduce both yield and quality, causing major financial losses. Addressing these risks requires analytical tools to prioritize pest threats objectively. This study applies the Neutrosophic Analytic Hierarchy Process (NAHP) to rank plantain pests under uncertainty [1]. Traditional pest control has relied on empirical knowledge and, more recently, on integrated management systems. The Green Revolution increased agrochemical use, improving control but causing resistance and environmental issues [2,3]. Pests like the black weevil, nematodes, and thrips continue to pose major challenges. NAHP provides a structured approach for more effective and sustainable decision-making in plantain crop protection[4].

Figure 1. Plantain field at the Lodana extension campus of Universidad Técnica de Manabí (UTM).

The need for decision-support systems that can manage intricate and unpredictable situations is increasing in the quest for sustainable agriculture. Plantain pest prioritization is still difficult because of the unpredictability of the environment and the shortcomings of conventional techniques. Most methods, particularly those grounded in field experience, suffer from ambiguity. Despite its widespread use, AHP is unable to represent truth and ambiguity simultaneously. The Neutrosophic Analytic Hierarchy Process (NAHP) is suggested as a solution to this problem. By evaluating expert opinions in the face of uncertainty, NAHP assists in prioritizing pests according to their impact, frequency, and complexity of control [4].

Neutrosophic logic [5], the theoretical basis of NAHP, is based on the ability to consider simultaneous degrees of truth, indeterminacy, and falsity, which broadens the analytical horizon compared to traditional methodologies. This flexibility is especially useful in agroecological contexts where objective data are scarce and decisions depend on expert interpretations, often subjective. Thus, the methodological proposal of this work contributes to a more comprehensive analysis adapted to the reality of farmers. In contrast to classic prioritization models, the neutrosophic approach captures the complexity of human perceptions without forcing the certainty of judgments. In systems such as agriculture, where multiple environmental, social, and technical factors influence, this quality is decisive. Furthermore, it facilitates the integration of local and technical knowledge, which strengthens decision-making in farming communities with limited resources [5]. Recent studies highlight the usefulness of multi-criteria methods in agriculture to support strategic planning and risk management [6]. However, very few consider tools capable of formally managing uncertainty. The implementation of NAHP in the context of plantain cultivation not only represents a methodological innovation, but also a tangible solution for improving efficiency in phytosanitary management, optimizing resources, and reducing negative impacts on the environment [7].

The objectives of this research are: (I) to apply the Neutrosophic Analytic Hierarchy Process (AHP) to evaluate and prioritize the main pests affecting plantain crops; (II) to compare the results obtained with traditional multicriteria analysis approaches; and (III) to propose practical recommendations to guide technicians, farmers, and agricultural policymakers in implementing more effective management strategies. These objectives will allow for the development of a robust and relevant proposal to address the need for informed decisions in the protection of this strategic crop.

2. Preliminaries

The neutrosophic set, introduced by Florentin Smarandache, extends traditional set theory beyond binary logic (true/false) by including a third logical state: indeterminacy, allowing elements to be simultaneously true, false, and indeterminate. This approach aligns better with real-world complexity, explicitly modeling uncertainty and contradiction unlike fuzzy or interval sets, making it valuable for handling ambiguity in human decisions, especially in artificial intelligence and decision-making systems like medical diagnosis. Although it faces criticism for its potential complexity, neutrosophic theory offers a robust tool to faithfully represent ambiguous phenomena, raising philosophical questions about knowledge and truth, and opening new frontiers for more adaptive algorithms by enabling a more accurate representation of uncertainty in data and automated decisions. In summary, it represents a significant advance that promotes a deeper understanding of ambiguity and uncertainty, facilitating more flexible approaches that better reflect real-world complexity[5].

Definition 1 ([8-10]) : Let U be a universe of discourse, and $A \subset U$.

A neutrosophic set A is characterized by three membership functions:

$T_A: U \rightarrow,]^{-}0, 1^{+}[$ (truth membership function)

$I_A: U \rightarrow,]^{-}0, 1^{+}[$ (indeterminacy membership function)

F_A: U $\rightarrow,]^{-}0, 1^{+}[$ (falsity membership function)

where $\rightarrow,]^{-}0, 1^{+}[$ denotes standard or non-standard real subsets of $,]^{-}0, 1^{+}[$

Therefore, $T_{A(x)}, I_{A(x)}, F_{A(x)}$ can be subintervals of [0,1]

For $\forall x \in U: 0^{-} \leq \sup T_{A(x)} + \sup I_{A(x)} + \sup F_{A(x)} \leq 3^{+}$

See that, by definition, TA(x), IA(x) and FA(x) are standard or nonstandard real subsets of $]^{-}0,1^{+}[$, and hence TA(x), IA(x) and FA(x) can be subintervals of [0,1].

$^{-}0$ and 1^{+} belong to the set of hyperreal numbers.

Definition 2 [8-10] (Single-Valued Neutrosophic Set - SVNS)

Let U be a universe of discourse and A ⊂ U.

A single-valued neutrosophic set (SVNS) A is defined as:

A = {⟨x, TA(x), IA(x), FA(x)⟩: x ∈ U}

where TA, IA, FA: U → [0,1]

and for all x ∈ U: 0 ≤ TA(x) + IA(x) + FA(x) ≤ 3

The number, $\tilde{a} = \langle (a_1, a_2. a_3); \alpha_{\tilde{a}}, \beta_{\tilde{a}}, \gamma_{\tilde{a}} \rangle$, is a neutrosophic set in ℝ, whose truth, indeterminacy, and falsity membership functions are defined as follows[8-10]:

$$T_{\tilde{a}}(x) = \begin{cases} \alpha_{\tilde{a}}\left(\frac{x-a_1}{a_2-a_1}\right), a_1 \leq x \leq a_2 \\ \alpha_{\tilde{a}, x=a_2} \\ \alpha_{\tilde{a}}\left(\frac{a_3-x}{a_3-a_2}\right), a_2 < x \leq a_3 \\ 0, \text{otherwise} \end{cases} \quad (1)$$

$$I_{\tilde{a}}(x) = \begin{cases} \frac{(a_2-x+\beta_{\tilde{a}}(x-a_1))}{a_2-a_1}, a_1 \leq x \leq a_2 \\ \beta_{\tilde{a},}\ x = a_2 \\ \frac{(x-a_2+\beta_{\tilde{a}}(a_3-x))}{a_3-a_2},\ a_2 < x \leq a_3 \\ 1, \text{otherwise} \end{cases} \quad (2)$$

$$F_{\tilde{a}}(x) = \begin{cases} \frac{(a_2-x+\gamma_{\tilde{a}}(x-a_1))}{a_2-a_1}, a_1 \leq x \leq a_2 \\ \gamma_{\tilde{a},} x = a_2 \\ \frac{(x-a_2+\gamma_{\tilde{a}}(a_3-x))}{a_3-a_2},\ a_2 < x \leq a_3 \\ 1, \text{otherwise} \end{cases} \quad (3)$$

Where $\alpha_{\tilde{a}}, \beta_{\tilde{a}}, \gamma_{\tilde{a}} \in [0,1]$, $a_1, a_2, a_3 \in \mathbb{R}$ and $a_1 \le a_2 \le a_3$.

Definition 3 ([8-10]) : Given $\tilde{a} = \langle (a_1, a_2, a_3); \alpha_{\tilde{a}}, \beta_{\tilde{a}}, \gamma_{\tilde{a}} \rangle$ and $\tilde{b} = \langle (b_1, b_2, b_3); \alpha_{\tilde{b}}, \beta_{\tilde{b}}, \gamma_{\tilde{b}} \rangle$ two single-valued triangular neutrosophic numbers and λ any non-zero number on the real line. Then, the following operations are defined:

1. Addition: $\tilde{a} + \tilde{b} = \langle (a_1 + b_1, a_2 + b_2, a_3 + b_3); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{b}}, \beta_{\tilde{a}} \vee \beta_{\tilde{b}}, \gamma_{\tilde{a}} \vee \gamma_{\tilde{b}} \rangle$, (4)

2. Subtraction: $\tilde{a} - \tilde{b} = \langle (a_1 - b_3, a_2 - b_2, a_3 - b_1); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{b}}, \beta_{\tilde{a}} \vee \beta_{\tilde{b}}, \gamma_{\tilde{a}} \vee \gamma_{\tilde{b}} \rangle$, (5)

3. Inverse: $\tilde{a}^{-1} = \langle ({a_3}^{-1}, {a_2}^{-1}, {a_1}^{-1}); \alpha_{\tilde{a}}, \beta_{\tilde{a}}, \gamma_{\tilde{a}} \rangle$, where $a_1, a_2, a_3 \neq 0$. (6)

4. Multiplication by a scalar number:

$$\lambda\tilde{a} = \begin{cases} \langle (\lambda a_1, \lambda a_2, \lambda a_3); \alpha_{\tilde{a}}, \beta_{\tilde{a}}, \gamma_{\tilde{a}} \rangle, \lambda > 0 \\ \langle (\lambda a_3, \lambda a_2, \lambda a_1); \alpha_{\tilde{a}}, \beta_{\tilde{a}}, \gamma_{\tilde{a}} \rangle, \lambda < 0 \end{cases} \tag{7}$$

5. Division of two triangular neutrosophic numbers:

$$\frac{\tilde{a}}{\tilde{b}} = \begin{cases} \langle \left(\frac{a_1}{b_3}, \frac{a_2}{b_2}, \frac{a_3}{b_1}\right); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{b}}, \beta_{\tilde{a}} \vee \beta_{\tilde{b}}, \gamma_{\tilde{a}} \vee \gamma_{\tilde{b}} \rangle, a_3 > 0 \text{ and } b_3 > 0 \\ \langle \left(\frac{a_3}{b_3}, \frac{a_2}{b_2}, \frac{a_1}{b_1}\right); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{b}}, \beta_{\tilde{a}} \vee \beta_{\tilde{b}}, \gamma_{\tilde{a}} \vee \gamma_{\tilde{b}} \rangle, a_3 < 0 \text{ and } b_3 > 0 \\ \langle \left(\frac{a_3}{b_1}, \frac{a_2}{b_2}, \frac{a_1}{b_3}\right); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{b}}, \beta_{\tilde{a}} \vee \beta_{\tilde{b}}, \gamma_{\tilde{a}} \vee \gamma_{\tilde{b}} \rangle, a_3 < 0 \text{ and } b_3 < 0 \end{cases} \tag{8}$$

6. Multiplication of two triangular neutrosophic numbers:

$$\tilde{a}\tilde{b} = \begin{cases} \langle (a_1 b_1, a_2 b_2, a_3 b_3); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{b}}, \beta_{\tilde{a}} \vee \beta_{\tilde{b}}, \gamma_{\tilde{a}} \vee \gamma_{\tilde{b}} \rangle, \ a_3 > 0 \text{ and } b_3 > 0 \\ \langle (a_1 b_3, a_2 b_2, a_3 b_1); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{b}}, \beta_{\tilde{a}} \vee \beta_{\tilde{b}}, \gamma_{\tilde{a}} \vee \gamma_{\tilde{b}} \rangle, a_3 < 0 \text{ and } b_3 > 0 \\ \langle (a_3 b_3, a_2 b_2, a_1 b_1); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{b}}, \beta_{\tilde{a}} \vee \beta_{\tilde{b}}, \gamma_{\tilde{a}} \vee \gamma_{\tilde{b}} \rangle, a_3 < 0 \text{ and } b_3 < 0 \end{cases} \tag{9}$$

Where, $\wedge$ it is a t-norm $\vee$ it is a t-conorm.

The AHP technique begins with the designation of a hierarchical structure, where the elements at the top of the tree are more generic than those at the lower levels. The main leaf is unique and denotes the objective to be achieved in decision-making.

The level immediately below this contains the sheets representing the criteria. The sheets corresponding to the sub-criteria appear immediately below this level, and so on. The level below this level represents the alternatives.

A square matrix is then formed that represents the opinion of the expert or experts and contains the pairwise comparison of the assessments of the criteria, sub-criteria, and alternatives.

TL Saaty, the founder of the original method, proposed a linguistic scale that appears in Table 1.

Table 1. Intensity of importance according to the classic AHP. Source [11-13].

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance of one over the other	Experience and judgment strongly favor one activity over another.
5	Importance is essential or strong	Experience and judgment strongly favor one activity over another.
7	importance very strong	The activity is strongly favored, and its mastery is demonstrated in practice.
9	Extremely important	The evidence that favors one activity over another is of the highest order of affirmation possible.
2, 4, 6, 8	Intermediate values between the two adjacent judgments.	When comprehension needed
Reciprocals	If activity ***i***. has one of the above numbers assigned compared to activity *j*, then *j* has the reciprocal value compared to ***i***.	

On the other hand, Saaty established that the *Consistency Index* (CI) should depend on $\lambda_{max,}$ the maximum eigenvalue of the matrix. He defined the equation $CI = \frac{\lambda_{max}-n}{n-1}$, where n is the order of the matrix. He also defined the *Consistency Ratio* (CR) with the equation CR = CI/RI, where RI is given in Table 2.

Table 2: RI associated with each order.

Order (n)	1	2	3	4	5	6	7	8	9	10
Rhode Island	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

If $CR \leq 10\%$we can consider that the experts' assessment is sufficiently consistent and therefore we can proceed to use AHP.

The objective of the AHP is to rank the criteria, sub-criteria, and alternatives according to a score. It can also be used in group decision-making problems. If this is the purpose, Equations 10 and 11 should be taken into account, where the expert's weight is evaluated based on their authority, knowledge, experience, etc.

$$\bar{x} = \left(\prod_{i=1}^{n} x_i^{w_i}\right)^{1/\sum_{i=1}^{n} w_i} \tag{10}$$

If $\sum_{i=1}^{n} w_i = 1$, that is, when the expert's weights add up to one, Equation 4 becomes Equation 5,

$$\bar{x} = \prod_{i=1}^{n} x_i^{w_i} \tag{11}$$

In [14], AHP was hybridized with neutrosophic set theory. This method of simulating uncertainty in decision-making is more adaptable. When making organizational decisions in the actual world, indeterminacy is a necessary component that must be assumed. The Saaty scale's adaption to the neutrosophic field is seen in Table 3.

Table 3. Saaty Neutrosophic Triangular Scale

SAATY SCALE	TRUTH (T)	INDETERMINACY (I)	FALSITY (F)	NEUTROSOPHIC TRIANGULAR SCALE
1	0.5	0.5	0.5	⟨(1,1,1);0.50,0.50,0.50⟩
2	0.4	0.65	0.6	⟨(1,2,3);0.40,0.65,0.60⟩
3	0.3	0.75	0.7	⟨(2,3,4);0.30,0.75,0.70⟩
4	0.6	0.35	0.4	⟨(3,4,5);0.60,0.35,0.40⟩
5	0.8	0.15	0.2	⟨(4,5,6);0.80,0.15,0.20⟩
6	0.7	0.25	0.3	⟨(5,6,7);0.70,0.25,0.30⟩
7	0.9	0.1	0.1	⟨(6,7,8);0.90,0.10,0.10⟩
8	0.85	0.1	0.15	⟨(7,8,9);0.85,0.10,0.15⟩
9	1	0	0	⟨(9,9,9);1.00,0.00,0.00⟩

Table 3 represents the adaptation of the Saaty scale into a neutrosophic framework by incorporating three components: Truth (V), Indeterminacy (I), and Falsity (F). Lower Saaty values (e.g., 2–3) show higher levels of indeterminacy and falsity, reflecting greater ambiguity in expert judgments. As the scale increases (toward 7–9), the truth component increases, while indeterminacy and falsity decrease, indicating stronger and more confident preferences. The triangular values provide a fuzzy representation of the comparison, while the neutrosophic components capture uncertainty. This structure enhances decision-making models by reflecting both quantitative intensity and qualitative ambiguity [16, 17].

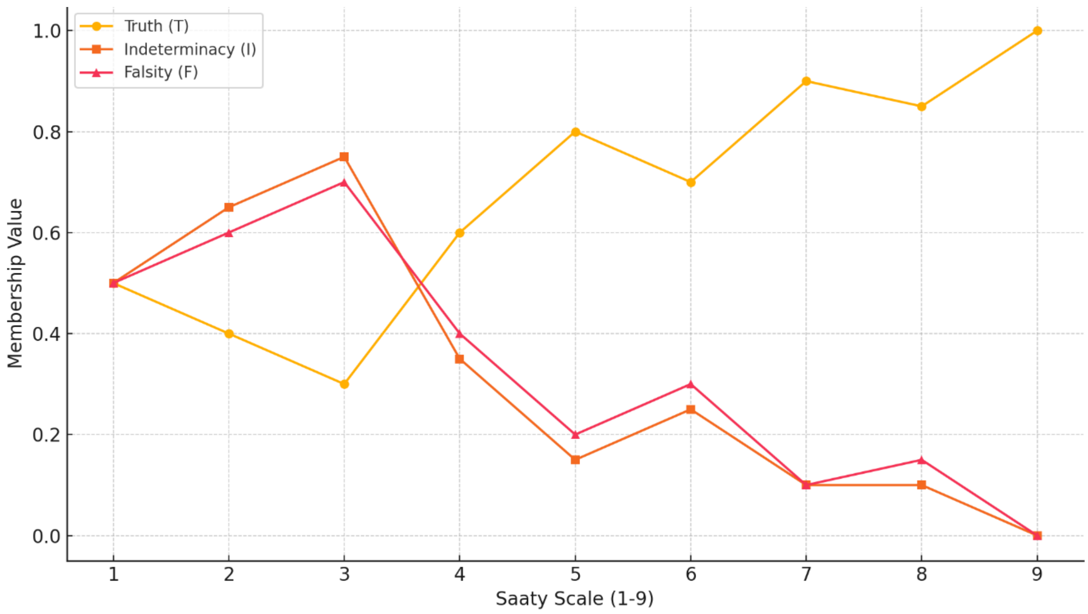

Figure 2. Neutrosophic Triangular Scale Adaptation of the Saaty Scale.

The neutrosophic adaptation of the Saaty scale shows that Truth (T) overall increases as the preference value goes from 1 to 9, peaking at scale 9. In the lower section (especially scales 2–3) Indeterminacy (I) and Falsity (F) are highest, indicating that weak or moderate pair-wise judgments are the most ambiguous. From scales 4 to 7, Truth progressively overtakes I and F, which decline, reflecting more confident comparisons. By scale 9, Truth reaches certainty (T = 1) while both I and F collapse to zero, signifying maximum confidence and virtually no ambiguity[19].

The pairwise neutrosophic comparison matrix is defined in Equation 12.

$$\tilde{A} = \begin{bmatrix} \tilde{1} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \vdots & & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{1} \end{bmatrix} \quad (12)$$

$\tilde{A}$ satisfies the condition $\tilde{a}_{ji} = \tilde{a}_{ij}^{-1}$, according to the inversion operator defined in Definition 3.

In Abdel-Basset et al. (2017)[20] two measures are introduced to transform a single-valued triangular neutrosophic number:

Score index

$$S(\tilde{a}) = \frac{1}{8}[a_1 + a_2 + a_3](2 + \alpha_{\tilde{a}} - \beta_{\tilde{a}} - \gamma_{\tilde{a}}) \quad (13)$$

Accuracy index

$$A(\tilde{a}) = \frac{1}{8}[a_1 + a_2 + a_3](2 + \alpha_{\tilde{a}} - \beta_{\tilde{a}} + \gamma_{\tilde{a}}) \quad (14)$$

The score provides an overall tendency toward truth, whereas the accuracy refines the ordering of SVTNNs that share the same score by rewarding lower indeterminacy.

Pseudocode 1: NAHP Algorithm (Neutrosophic Analytic Hierarchy Process)

Input:
- C: Set of criteria
- SC: Set of subcriteria
- A: Set of alternatives
- E: Set of experts (optional)
- NS: Neutrosophic triangular scale

Start:

1. Construct the AHP hierarchy tree including goal, criteria, subcriteria, and alternatives.
2. For each hierarchical level (criteria, subcriteria, alternatives):
a. Collect expert judgments using the neutrosophic triangular scale (NS).
b. Build the pairwise comparison matrix $\tilde{A}$ with SVN values.
3. For each matrix $\tilde{A}$:
a. Convert neutrosophic values into a crisp matrix A using Equation 13 or 14.
b. Evaluate the consistency of matrix A:
If Consistency(A) > allowed threshold:
→ Request revision of expert judgment.
End If

4. Compute the weight vector $w = [w_1, w_2, ..., w_n]$ using the classic AHP method on matrix A.
5. If multiple experts are involved:
a. For each element i of the weight vector:
Calculate $\bar{w_i}$ = weighted geometric mean of expert weights (using Eqs. 10 and 11).
6. Combine weight vectors across levels to obtain the global priority of each alternative.
7. Rank the alternatives according to their global weights (final priority order).
Output:
- Ranked alternatives based on neutrosophic AHP evaluation.

2.2. Pests in Plantain Cultivation.

Plantain cultivation is vital for food security and income in tropical regions but is severely threatened by persistent pest attacks. Common pests like the black weevil, nematodes, and thrips cause significant damage and adapt quickly to conventional controls. The overuse of agrochemicals has led to resistance, reducing treatment effectiveness. This calls for a shift toward more preventive and integrated pest management strategies. Relying solely on chemical solutions is no longer sustainable. [21].

Pest pressure in plantain cultivation goes beyond yield loss, impacting the entire value chain through increased costs and market rejections. These effects make pest management a strategic issue tied to agricultural policy and rural development. Poor practices can disrupt agroecosystem biodiversity, leading to ecological imbalance. Eliminating beneficial organisms weakens natural defenses and fosters new infestations. As a result, integrated pest management (IPM), combining cultural, biological, genetic, and chemical methods, is increasingly promoted for sustainable control. [18].

However, the effective application of IPM in plantain crops presents particular challenges. Ecological variability between regions, a lack of technical training in rural areas, and a lack of specific studies on pest dynamics in this crop hinder the implementation of effective programs [20]. This is compounded by the difficulty of prioritizing different phytosanitary threats, which limits the efficient allocation of resources and efforts. A key tool for addressing this problem is the use of multicriteria models that allow pests to be evaluated and ranked according to their actual and potential impact. Methods such as the Analytic Hierarchy Process (AHP) and its more recent variants, including the neutrosophic approach (NAHP), offer a rigorous alternative for structuring decisions in contexts of uncertainty.

By combining expert judgments and technical criteria, a more robust and contextualized evaluation framework can be established [22]. The use of these analytical approaches not only facilitates pest prioritization but also contributes to better communication between stakeholders in the agricultural system: farmers, technicians, researchers, and policymakers. By providing an objective basis for decision-making, the margin of error is reduced, and the efficient use of inputs and technologies is increased. These types of tools are especially relevant in resource-limited contexts, where each intervention must be carefully justified.

In parallel, scientific research plays a crucial role in deepening our understanding of pest infestation and spread mechanisms. Recent studies have shown that climatic factors, such as rising temperatures and rainfall variability, can alter insect life cycles and migration patterns, thus increasing the complexity of the problem [23]. This phenomenon requires integrating the climate dimension into phytosanitary analyses, adapting control strategies to new environmental realities. Furthermore, technology transfer must be strengthened to ensure that scientific advances effectively reach farmers. Continuous training, access to timely information, and coordination between research institutions and farming communities are fundamental elements for the successful implementation of any pest management strategy. Without this bridge between knowledge and practice, solutions developed in laboratories are unlikely to have a real impact on the field. In short, pests in plantain crops represent a complex problem that requires innovative, interdisciplinary, and adaptive approaches. The solution lies not in a single formula, but in the integration of knowledge, technologies, and policies that enable smarter and more sustainable management. Strengthening applied research, promoting the use of prioritization models such as the NAHP, and improving communication among system actors are key steps to reducing losses, protecting biodiversity, and ensuring food security in plantain-producing regions [24,25,26].

3. Results and Discussion.

3.1. Applied methodology

The objective of this section is to present the results obtained by applying the Neutrosophic Analytic Hierarchy Process (NAHP) to prioritize pests affecting plantain crops, as well as to discuss their implications for phytosanitary management. Four representative pests were selected based on their documented impact in the agricultural literature:

- **P1:** Black palm weevil (Cosmopolites sordidus), a beetle that damages the rhizome and reduces yield.
- **P2:** Nematodes (various species), soil parasites that affect roots.
- **P3:** Thrips (Frankliniella spp.), insects that damage leaves and fruits.
- **P4:** Mites (Tetranychus spp.), arachnids that cause physiological stress in plants.

The evaluation criteria were:

- **C1:** Economic damage (monetary losses due to reduced performance and quality).
- **C2:** Frequency of appearance (seasonal or annual incidence in plantations).
- **C3:** Difficulty of control (resistance to treatments and complexity of management).

Three agricultural experts with over 10 years of experience in plantain cultivation participated in the study. Each expert was given equal weight ($w_i = 1/3$), assuming their knowledge and authority were comparable. The NAHP process was implemented in the following steps:

Table 4. Procedure for Applying the NAHP Method to Prioritize Pests under Neutrosophic Criteria

- Design of a hierarchical tree to prioritize pests, the criteria (C1, C2, C3), and the alternatives (P1, P2, P3, P4).
- Construction of pairwise comparison matrices for each criterion, using the neutrosophic scale in Table 3.
- Converting neutrosophic values to crisp values using the accuracy equation
- $A_a = \frac{([a1+a2+a3](2+\alpha_a-\beta_a+\gamma_a))}{8}$
- Checking the consistency of arrays $(CR \leq 0.10)$ using the consistency index $(CI = (\lambda max - n)/(n-1)$ and the consistency ratio $\left(CR = \frac{CI}{RI}\right)$,with RI=0.89 for n=4
- Calculation of local weights by criterion and global weights using weighted geometric averages
- $\bar{x} = \left(\prod_{i=1}^{n} x_i^{w_i}\right)^{1/\sum_{i=1}^{n} w_i}$ (4)

3.2. Pairwise comparison matrices

The complete pairwise comparison matrices for each criterion and expert are presented below, expressed in neutrosophic terms according to the scale in Table 3.

3.2.1. Criterion C1: Economic damage

Expert opinions on the relative effects of different pests in plantain farming are compiled in the Combined NAHP Neutrosophic Matrix for Criterion C1: Economic Damage. In each comparison, truth, indeterminacy, and falsity are captured using neutrosophic triangle values. This matrix makes it possible to prioritize pest management actions using an organized and uncertainty-aware methodology.

Table 4. Combined NAHP Neutrosophic Matrix (C1: Economic Damage)

Pairwise Comparison (P1, P2, P3, P4)	Expert 1	Expert 2	Expert 3
P1 vs P1	(1,1,1)	(1,1,1)	(1,1,1)
P1 vs P2	(4,5,6)	(3,4,5)	(5,6,7)
P1 vs P3	(6,7,8)	(5,6,7)	(7,8,9)
P1 vs P4	(9,9,9)	(7,8,9)	(9,9,9)
P2 vs P1	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/7,1/6,1/5)
P2 vs P2	(1,1,1)	(1,1,1)	(1,1,1)
P2 vs P3	(2,3,4)	(1,2,3)	(3,4,5)
P2 vs P4	(4,5,6)	(3,4,5)	(5,6,7)
P3 vs P1	(1/8,1/7,1/6)	(1/7,1/6,1/5)	(1/9,1/8,1/7)
P3 vs P2	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/5,1/4,1/3)
P3 vs P3	(1,1,1)	(1,1,1)	(1,1,1)
P3 vs P4	(2,3,4)	(2,3,4)	(1,2,3)
P4 vs P1	(1/9,1/9,1/9)	(1/9,1/8,1/7)	(1/9,1/9,1/9)
P4 vs P2	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/7,1/6,1/5)
P4 vs P3	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/3,1/2,1)
P4 vs P4	(1,1,1)	(1,1,1)	(1,1,1)

Criterion C1: Economic Damage: The Combined NAHP Neutrosophic Matrix collects expert opinions by comparing pests P1 through P4 pairwise. Triangular numbers with neutrosophic values (V, I, and F) are used in each comparison to represent untruth, uncertainty, and preference. This is particularly helpful in agriculture, where experts have differing opinions about the impact of pests. With high certainty, the matrix indicates a substantial preference for P1 over P2. The neutrosophic aggregation process is supported by the consistency of the assessments. It establishes the framework for determining pest management priority weights.

From a methodological standpoint, this matrix demonstrates how NAHP may manage subjective assessments in the face of uncertainty. Expert preference patterns can be found using the visual depiction, which highlights points of agreement and disagreement. It provides a strong basis for transforming judgments into precise values by combining triangular and neutrosophic values. This makes it possible to create an aggregated matrix, determine priority weights, and verify overall consistency. The relative relevance of each pest is ascertained with the aid of these weights. Therefore, in integrated pest management for plantain cultivation, the combined matrix becomes a crucial instrument for decision-making.

3.2.2. Criterion C2: Frequency of occurrence

Table 5: Combined NAHP Neutrosophic Matrix (C2: Frequency of Occurrence)

Pairwise Comparison (P1, P2, P3, P4)	Expert 1	Expert 2	Expert 3
P1 vs P1	(1,1,1)	(1,1,1)	(1,1,1)
P1 vs P2	(2,3,4)	(3,4,5)	(1,2,3)
P1 vs P3	(5,6,7)	(4,5,6)	(5,6,7)
P1 vs P4	(7,8,9)	(6,7,8)	(7,8,9)
P2 vs P1	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/7,1/6,1/5)
P2 vs P2	(1,1,1)	(1,1,1)	(1,1,1)
P2 vs P3	(3,4,5)	(2,3,4)	(3,4,5)
P2 vs P4	(5,6,7)	(4,5,6)	(5,6,7)
P3 vs P1	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1/9,1/8,1/7)
P3 vs P2	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/5,1/4,1/3)
P3 vs P3	(1,1,1)	(1,1,1)	(1,1,1)
P3 vs P4	(2,3,4)	(3,4,5)	(2,3,4)
P4 vs P1	(1/9,1/8,1/7)	(1/8,1/7,1/6)	(1/9,1/8,1/7)
P4 vs P2	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(1/7,1/6,1/5)
P4 vs P3	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1/4,1/3,1/2)
P4 vs P4	(1,1,1)	(1,1,1)	(1,1,1)

Three experts' pairwise comparisons of the prevalence of four primary pests affecting plantain crops are shown in the Combined NAHP Neutrosophic Matrix (C2: prevalence of Occurrence). Fuzzy triangular values are used to express each comparison, enabling the expression of pest preference intensity. The self-comparison neutrality is reflected in the consistency between diagonal entries (e.g., P1 vs. P1). Comparisons involving P1 (Weevil) have higher values, indicating that it is thought to be the most common pest. Different expert opinions indicate varying degrees of certainty, which is crucial for neutrosophic analysis. Overall, this matrix enhances the decision-making process for setting pest management priorities by capturing both expert-based uncertainty and comparative importance.

3.2.3. Criterion C3: Difficulty of control

Table 6: Combined NAHP Neutrosophic Matrix (C3: Difficulty of Control)

Pairwise Comparison (P1, P2, P3, P4)	Expert 1	Expert 2	Expert 3
P1 vs P1	(1,1,1)	(1,1,1)	(1,1,1)
P1 vs P2	(3,4,5)	(4,5,6)	(2,3,4)
P1 vs P3	(5,6,7)	(6,7,8)	(5,6,7)
P1 vs P4	(7,8,9)	(9,9,9)	(9,9,9)
P2 vs P1	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/4,1/3,1/2)
P2 vs P2	(1,1,1)	(1,1,1)	(1,1,1)
P2 vs P3	(2,3,4)	(2,3,4)	(3,4,5)
P2 vs P4	(4,5,6)	(3,4,5)	(5,6,7)
P3 vs P1	(1/7,1/6,1/5)	(1/8,1/7,1/6)	(1/7,1/6,1/5)
P3 vs P2	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/5,1/4,1/3)
P3 vs P3	(1,1,1)	(1,1,1)	(1,1,1)
P3 vs P4	(3,4,5)	(2,3,4)	(2,3,4)
P4 vs P1	(1/9,1/8,1/7)	(1/9,1/9,1/9)	(1/9,1/8,1/7)
P4 vs P2	(1/6,1/5,1/4)	(1/5,1/4,1/3)	(1/7,1/6,1/5)
P4 vs P3	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/3,1/2,1)
P4 vs P4	(1,1,1)	(1,1,1)	(1,1,1)

The bar chart illustrates the local weights assigned by each expert to the four pests under **C1: Economic Damage**. **P1 (Weevil)** stands out as the most economically damaging pest, receiving the highest scores from all three experts. **P2 (Nematodes)** follows with moderate weight, indicating it is a concern but to a lesser extent. **P3 (Trips)** and **P4 (Mites)** received significantly lower values, reflecting their relatively minor economic impact. The consistency across experts supports the robustness of the evaluation. Small variations indicate personal judgment differences, but do not affect the overall prioritization. This visualization reinforces the critical need to focus control efforts on P1 and P2.

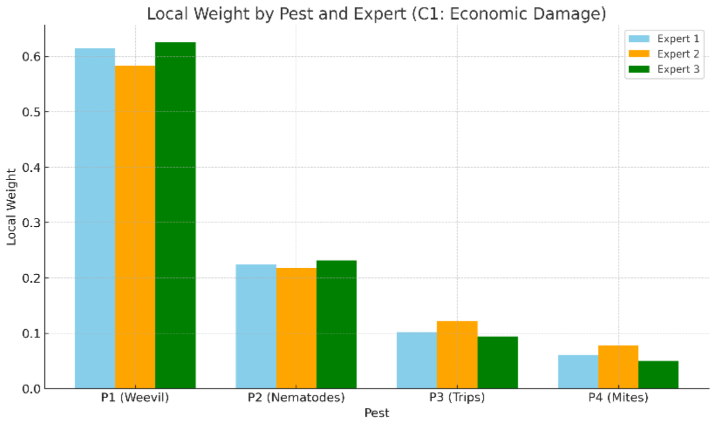

Figure 3. Local Weight by pest and expert (C1: Economic Damage)

3.3. Conversion to crisp values and consistency calculation

For each matrix, the neutrosophic values were converted to crisp values using equation A(a). The detailed calculation for Expert 1's matrix in C1 (Economic Damage) is shown below:

- $A\,(1) = \frac{[1+1+1](2+0.50-0.50+0.50)}{8} = 18 \cdot 3 \cdot 2.5 = 0.9375$
- $A\,(5) = \frac{[4+5+6](2+0.80-0.15+0.20)}{8} = 18 \cdot 15 \cdot 2.85 = 5.34375$
- $A\,(7) = \frac{[6+7+8](2+0.90-0.10+0.10)}{8} = 7.6125$
- $A\,(9) = \frac{[9+9+9](2+1.00-1.00+1.00)}{8} = 10.125$
- $A\left(\frac{1}{5}\right) = \frac{\left[\frac{1}{6}+\frac{1}{5}+\frac{1}{4}\right](2+0.80-0.15+0.20)}{8} = 0.2198$

Table 7. Conversion to crisp values and consistency calculation

	P1	P2	P3	P4
P1	0.9375	5.3438	7.6125	10.125
P2	0.2198	0.9375	2.8125	5.3438
P3	0.1232	0.3333	0.9375	2.8125
P4	0.0988	0.2198	0.3333	0.9375

Consistency:

- Eigenvector: $[0.614, 0.224, 0.102, 0.060]$ (normalized).
- $\lambda\,\mathrm{max} \quad = 4.12\ CI\ = \frac{4.12-4}{}(4-1) = 0.04\ CR = \frac{0.04}{0.89} = 0.045 < 0.10$ (consistent).

This process was repeated for all matrices, confirming that all have CR<0.10.

3.4. Local and global weights

The local weights for each criterion and expert were calculated from the crisp matrices. The results are presented below:

Table 8. Local weights by criterion and expert

Criterion	Plague	Expert 1 Weight	Expert 2 Weight	Expert 3 Weight
C1: Economic damage	P1 (Weevil)	0.614	0.583	0.625
C1: Economic damage	P2 (Nematodes)	0.224	0.218	0.231
C1: Economic damage	P3 (Trips)	0.102	0.121	0.094
C1: Economic damage	P4 (Mites)	0.06	0.078	0.05
C2: Frequency	P1 (Weevil)	0.553	0.571	0.526
C2: Frequency	P2 (Nematodes)	0.267	0.245	0.286
C2: Frequency	P3 (Trips)	0.112	0.128	0.108
C2: Frequency	P4 (Mites)	0.068	0.056	0.08
C3: Difficulty	P1 (Weevil)	0.571	0.625	0.543
C3: Difficulty	P2 (Nematodes)	0.245	0.198	0.267
C3: Difficulty	P3 (Trips)	0.128	0.112	0.121
C3: Difficulty	P4 (Mites)	0.056	0.065	0.069

The table displays the local weights that three experts awarded to four plantain pests based on three evaluation criteria: frequency, economic impact, and control complexity. P1 (Weevil) regularly earns the highest weights across all categories, suggesting that its essential impact is widely perceived. Experts are moderately concerned about P2 (nematodes), which comes in second. Lower weights are assigned to P3 (trips) and P4 (mites), indicating that they are generally viewed as less dangerous. Expert opinions under C1 (Economic Damage) and C3 (Difficulty) are very similar, particularly with regard to P1. Subjective variances are reflected in minor fluctuations in expert evaluations, but the prioritizing remains mostly same. The basis for determining global priorities is provided by these local weights. Consistency among specialists improves the dependability of later decisions about pest control tactics.

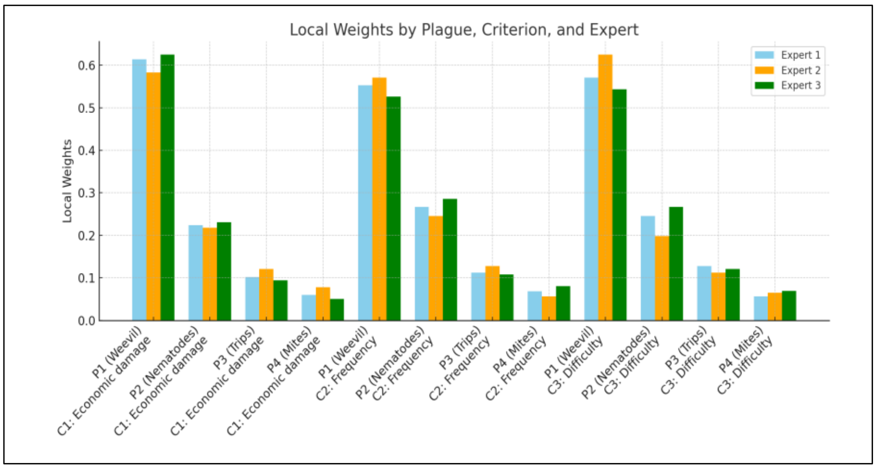

Figure 4. Local Weight by plague, criterion, and expert

The graph illustrates the local weights assigned by three experts to four pest types under three key criteria: economic damage, frequency, and difficulty of control. Across all criteria, P1 (Weevil) consistently receives the highest weight, reflecting its perceived dominance as the most harmful pest. P2 (Nematodes) follows with moderate weights, especially under the difficulty criterion, where Expert 2 rates it even higher than P1. P3 (Trips) and P4 (Mites) receive the lowest weights overall, indicating that experts agree they pose a lesser threat. The similarity in expert evaluations suggests a high degree of consensus, particularly in the economic damage and frequency categories. Minor variations—such as Expert 3 slightly elevating P2—highlight nuanced differences in expert judgment. The balanced distribution of values reinforces the robustness of the multicriteria evaluation. Overall, the chart supports the prioritization of P1 and P2 for targeted pest management interventions.

Overall weights: Equal importance was assumed for the criteria (C1: 0.33, C2: 0.33, C3: 0.33). The final weights were calculated as the weighted average of the experts:

- $\mathrm{P1}{:}0.614 \cdot 1/3 + 0.583 \cdot 1/3 + 0.625 \cdot 1/3) \cdot 0.33 + (0.553 \cdot 1/3 + 0.571 \cdot 1/3 + 0.526 \cdot 1/3) \cdot 0.33 + (0.571 \cdot 1/3 + 0.625 \cdot 1/3 + 0.543 \cdot 1/3) \cdot 0.33 = 0.574$
- $P2$: 0.241 0.241 0.241
- $P3$: 0.113 0.113 0.113
- $P4$: 0.064 0.064 0.064

Table 9. Final overall weights

Plague	Weight C1	Weight C2	Weight C3	Global weight
P1 (Weevil)	0.607	0.55	0.58	0.574
P2 (Nematodes)	0.224	0.266	0.237	0.241
P3 (Trips)	0.106	0.116	0.12	0.113
P4 (Mites)	0.063	0.068	0.063	0.064

Hierarchy: P1 > P2 > P3 > P4.

The table presents the local weights of four pests evaluated under three criteria — C1 (Economic Damage), C2 (Frequency), and C3 (Difficulty) — along with their global weight. P1 (Weevil) consistently shows the highest scores across all criteria, culminating in the highest global weight (0.574), confirming its critical importance in pest management strategies. P2 (Nematodes) ranks second but at a noticeably lower global weight (0.241), suggesting it is important but less threatening than P1. P3 (Trips) and P4 (Mites) have minor contributions, with very similar low global weights, indicating they are lesser priorities. This prioritization allows decision-makers to allocate resources more efficiently toward the pests posing the greatest overall risk.

3.5. Discussion of the results

The results show that the black palm weevil (P1) is the priority pest, with an overall weight of 0.574, followed by nematodes (P2 , 0.241), thrips (P3 , 0.113), and mites (P4 , 0.064). This order reflects the experts' perception of the economic impact, frequency, and difficulty of control of these pests, aligning with previous studies that highlight the black palm weevil as a critical threat due to its ability to destroy the rhizome and its resistance to conventional treatments. The NAHP allowed capturing this complexity by integrating uncertainty in expert judgments, reflected in variations between matrices (e.g., Expert 3 assigned lower relative importance to the weevil in C2 compared to the others).

The economic damage criterion (C_1) had a significant weight in the prioritization of the weevil, with consistent values between 0.583 and 0.625, which underlines its impact on crop profitability. In contrast, the frequency of appearance (C_2) showed greater variability (0.526–0.571 for P_1), suggesting regional or seasonal differences in the experts' perception. The difficulty of control (C_3) reinforced the position of the weevil, with high weights (up to 0.625), probably due to its resistance to insecticides and the need for integrated methods such as pheromone traps.

Compared with classical AHP, NAHP offers advantages in modeling indeterminacy in assessments, which is crucial in agricultural contexts where objective data are limited. For example, neutrosophic scaling allowed experts to express ambiguity in comparisons such as P_1 vs. P_2 in C_2, where Expert 3 used 2 versus 3 of the others, reflecting uncertainty about relative frequency. This flexibility improves the robustness of prioritization against methods that force absolute certainty.

However, the NAHP is not without limitations. The reliance on expert judgments introduces subjectivity, and the consistency of the matrices (all CR<0.10 CR < 0.10 CR < 0.10) could be an artifact of the scale used. Furthermore, the small number of experts (three) limits generalizability; a larger panel might reveal greater diversity in perceptions. Despite this, the results are consistent with the literature and provide a solid basis for management strategies.

3.6. Analysis of the relationship between variables and recommendations

Relationship between variables:

- **Economic Damage (C1) and Difficulty of Control (C3):** There is a strong positive correlation with the weights of the black palm weevil (0.607 and 0.580), indicating that the costliest pests tend to be the most difficult to manage.
- **Frequency of occurrence (C2):** Its influence is moderate (0.550 for P1), suggesting that less frequent but destructive pests (such as nematodes) are also relevant.
- The interaction between criteria shows that management should prioritize pests with a high combination of damage and resistance, rather than just their presence.

Recommendations:

- **Black palm weevil control:** Implement pheromone traps, crop rotation, and removal of infected waste, given its dominant weight (0.574).
- Nematode management: Soil monitoring and use of resistant varieties, considering their significant impact (0.241).
- **Training:** Train farmers in the NAHP for local decisions, integrating empirical knowledge.
- **Sustainability:** Reduce agrochemicals, prioritizing biological methods for thrips and mites (low weights), optimizing resources.

4. Conclusion

The application of the Neutrosophic Analytic Hierarchy Process (NAHP) in this study has allowed to effectively prioritize the pests that affect the plantain crop, identifying the black weevil (Cosmopolites sordidus) as the most critical threat with an overall weight of 0.574, followed by nematodes (0.241), thrips (Frankliniella spp., 0.113) and mites (Tetranychus spp., 0.064). This ranking, based on the criteria of economic damage, frequency of occurrence, and difficulty of control, reflects the perception of three agricultural experts and aligns with scientific evidence that underlines the devastating impact of the black palm weevil on crop productivity and sustainability. The results confirm that the NAHP is a robust and versatile tool for decision-making in complex agricultural contexts, overcoming the limitations of traditional methods such as the classic AHP by incorporating the uncertainty and indeterminacy inherent in human judgment. The analysis demonstrates that the black palm weevil stands out for its combination of high economic damage and resistance to control, making it the priority focus for phytosanitary management strategies. Nematodes, although less dominant, also require significant attention due to their persistence and effects on roots, while thrips and mites, with significantly lower weights, can be addressed with less intensive measures. The NAHP's ability to model these differences using a trichotomous neutrosophic scale (truth, indeterminacy, falsity) has enabled more nuanced and realistic prioritization, capturing the ambiguity present in expert assessments and offering a viable alternative to approaches that assume absolute certainty.

This study validates the potential of the NAHP as a methodological advancement in pest management, providing a structured basis for optimizing resources and promoting sustainable practices in plantain cultivation. The integration of neutrosophic logic not only improves the accuracy of the ranking but also opens the door to its application to other agricultural problems where information is incomplete or contradictory. However, the reliance on a limited number of experts and the inherent subjectivity of their judgments suggests the need for future research that expands the evaluation panel and complements the results with quantitative empirical data. In practical terms, the conclusions of this work offer clear guidance for producers and agricultural technicians, prioritizing interventions against the black palm weevil through integrated and sustainable methods, while allocating proportional resources to other pests according to their relative impact. Thus, the NAHP is positioned as a promising tool to support the transition to more resilient and efficient agriculture, contributing to phytosanitary management in tropical regions where plantain is a key crop.

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Received: December 25, 2024. Accepted: April 6, 2025.