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A Hybrid Neutrosophic and Machine Learning Model for Assessing Environmental Literacy in Biodiversity Conservation.

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Abstract. This study proposes the hybrid NEAML-BIOPASTAZA (Neutrosophic and Explainable Artificial Learning) model for Biodiversity and Legal-Ecological Assessment in Pastaza, which integrates multivariate statistical analysis, neutrosophic logic, and supervised machine learning to assess the relationship between environmental literacy and the effectiveness of the legal framework for biodiversity conservation in the Pastaza canton. Using a database of 350 observations, exploratory factor analysis was applied to validate the latent structure of the "environmental literacy" construct, considering variables such as legal knowledge, biodiversity perception, community participation, and media exposure. To manage the uncertainty inherent in social responses, a neutrosophic model was implemented, capturing the degrees of truth (T), indeterminacy (I), and falsity (F) of each perception. Finally, a Random Forest Classifier was used to predict the level of effective conservation, identifying the most relevant factors in local ecological decision-making. The combined approach allows for a more comprehensive and explanatory view of the problem, highlighting the need to strengthen environmental education, legal implementation, and community participation as pillars for the sustainable management of Amazonian biodiversity.

Keywords: Environmental literacy, Biodiversity conservation, Environmental legal framework, Exploratory factor analysis, Neutrosophic logic, Supervised machine learning.

1. Introduction

In a global context marked by the accelerated deterioration of ecosystems and the loss of biodiversity, there is a growing need to strengthen strategies that promote environmental conservation. One of the fundamental tools for achieving this goal is environmental literacy, understood as the ability to understand, assess, and respond to ecological problems. Citizens' environmental awareness and knowledge are crucial for sustainable decision-making and compliance with current regulations. However, these efforts must be coordinated with an effective legal framework that guarantees the protection of natural resources and sanctions their deterioration. Biodiversity conservation depends not only on written laws but also on their effective enforcement and the active participation of society. In regions of high ecological diversity, where natural resources are key to local well-being, the interaction between legislation and environmental education becomes crucial . Therefore, it is necessary to explore the connections between the level of environmental literacy, the effectiveness of regulations, and the capacity to conserve biodiversity. This research seeks to contribute to this analysis through an interdisciplinary approach, integrating statistics, artificial intelligence and neutrosophic theory [1].

This study proposes a hybrid model called NEAML-BIOPASTAZA, which combines multivariate statistical analysis, neutrosophic logic, and machine learning to evaluate the relationship between social and environmental variables. It is assumed that higher levels of environmental literacy and citizen participation contribute positively to the effectiveness of current environmental legislation. To validate this hypothesis, exploratory factor analysis is applied to a database of 350 observations, in order to identify latent structures around the population's environmental knowledge, attitudes, and practices. Neutrosophic logic is then incorporated to represent the uncertainty inherent in social perceptions, considering components of truth, indeterminacy, and falsity. Finally, a supervised learning model is implemented using Random Forest , with the aim of predicting the level of effective conservation based on the factors assessed. This methodological integration allows for a more robust view of the determinants of conservation in ecologically sensitive areas [2].

The importance of this research lies in its innovative approach, applicable to multiple contexts with similar biological richness and structural challenges. The NEAML-BIOPASTAZA model generates useful evidence for the design of more comprehensive public policies that not only consider legal strengthening, but also educational promotion and community participation as strategic pillars. The combination of quantitative, neutrosophic, and predictive approaches overcomes the traditional limitations of environmental analysis and advances toward explanatory models more adapted to the complexity of the territory. Furthermore, it highlights the need to implement sustainable and accessible environmental education programs that improve citizen understanding of laws and their ecological implications. Thus, the study proposes a way to strengthen the interaction between an informed citizenry and effective environmental governance, contributing to the preservation of natural heritage and long-term socio-environmental sustainability [3].

2. Related Work

In the field of conservation, research has underscored the importance of education and public participation. In the study , entitled "Environmental Literacy and Public Participation: Key Factors in Biodiversity Conservation Policies", the authors analyze how citizen environmental literacy influences the effectiveness of public conservation policies. Their analysis, based on statistical analysis and qualitative interviews in communities with high ecological value, reveals a key finding: an understanding of both ecological and legal concepts fosters increased citizen participation and strengthens regulatory implementation. They conclude that the synergy between education and governance is essential for achieving sustainable results [4].

In a complementary manner, the research "Legal Frameworks and Conservation Effectiveness in the Global South: Challenges and Innovations", examines how the effectiveness of legal frameworks in countries of the Global South is influenced by social, cultural, and economic factors. Through the analysis of cases in tropical regions with high biodiversity, she proposes the use of participatory and interdisciplinary approaches to improve their implementation. The study highlights the importance of integrating community knowledge, environmental education, and technology to overcome the gaps between legislation and practice[5].

3. Materials and methods

This research adopts an explanatory quantitative methodology, with a non-experimental design and a multi-methodological approach, integrating statistics, neutrosophic logic, and machine learning. Initially, a database of 350 cases was constructed, which included key variables such as environmental literacy, legal knowledge, biodiversity perception, community participation, and frequency of contact with the media. Through exploratory factor analysis (EFA), latent structures were identified that validate the environmental literacy construct and its relationship with other associated factors. This stage allowed reducing the dimensionality of the data and confirmed the internal consistency of the items considered [6].

Subsequently, a neutrosophic approach was applied to represent uncertainty, ambiguity, and the subjective perception of social responses, characterizing each variable with truth (T), indeterminacy (I), and falsity (F) values. These components were incorporated as inputs into a supervised learning model, specifically a Random Forest Classifier, which was trained to predict the level of effective conservation. Cross-validation and performance metrics such as precision, recall, and AUC-ROC were used to evaluate model performance. The integration of these techniques allows for a deeper and more explanatory understanding of the factors that influence biodiversity conservation in contexts of high ecological diversity [7].

Environmental literacy

Environmental literacy refers to people's ability to understand ecological issues, critically evaluate environmental information, and make responsible decisions for the benefit of the natural environment. In this research, it represents a fundamental component for analyzing how citizen knowledge and awareness influence the effective protection of biodiversity. Literacy is not limited to theoretical knowledge but includes practical skills for interpreting the environment, recognizing environmental threats, and acting in accordance with legal and ethical standards. An adequate level of environmental literacy empowers communities, encourages their participation in environmental policies, and facilitates compliance with the legal framework. This variable is approached as a latent construct measured through exploratory factor analysis, given its multidimensional complexity. Its strengthening is key to promoting sustainable cultural changes in regions of high ecological diversity [8].

Biodiversity conservation

Biodiversity conservation involves the protection, sustainable management, and restoration of ecosystems, species, and genetic resources that constitute a region's natural heritage. In this study, it is analyzed as a dependent variable whose level is influenced by social factors such as environmental literacy, knowledge of the legal framework, and community participation. Biodiversity is a vital component of human well-being, especially in areas of high ecological richness where many communities directly depend on natural resources for their subsistence. However, its conservation faces challenges such as agricultural expansion, deforestation, and non-compliance with environmental laws. Therefore , the study proposes a predictive model to evaluate the effectiveness of conservation actions according to the evaluated factors. This perspective allows the formulation of recommendations to improve both local policies and practices [9].

Environmental legal framework

The environmental legal framework comprises the set of norms, regulations, sanctions, and legal principles that govern environmental protection. Its effectiveness is a determining factor for biodiversity conservation, especially in regions where ecosystems are under constant pressure. In this research, the legal framework is analyzed not only as a normative body, but also in relation to its actual application, its awareness by citizens, and its interaction with other social factors. Lack of legal knowledge, poor implementation, and weak community participation are obstacles that reduce its impact. Therefore, the level of legal knowledge is assessed as part of the environmental literacy construct, and its predictive weight is analyzed in the **Random Forest Proposed Model.** The research also considers the gaps between the written law and its application, which is modeled with the help of neutrosophic logic [10].

Exploratory factor analysis

Exploratory factor analysis (EFA) is a multivariate statistical technique that allows the identification of latent structures within a set of observed variables. In the context of this research, it is used to validate the environmental literacy construct based on different dimensions, such as legal knowledge, ecological perception, and participation practices. EFA reduces the complexity of the dataset and groups variables according to common factors, which facilitates a better theoretical interpretation. This approach is essential to ensure that the measurements used adequately represent the defined theoretical concepts. Furthermore, it serves as a preliminary phase to feed the machine learning model, ensuring that the variables entering the algorithm are robust and reliable. Its implementation contributes to corroborate the internal validity of the proposed model and improves the accuracy of predictions about effective conservation [11].

General mathematical model of exploratory factor analysis (EFA)

The general model of Exploratory Factor Analysis (EFA) is represented as:

$$\boldsymbol{X} = \boldsymbol{\Lambda F} + \boldsymbol{\varepsilon}. \quad (1)$$

Where:

$\boldsymbol{X} = [\boldsymbol{X_1}, \boldsymbol{X_2}, \ldots, \boldsymbol{Xp}]^{\boldsymbol{T}}$is the vector of observed variables.
$\boldsymbol{\Lambda} = [\lambda_{ij}]$ *It is the matrix of factor loadings of dimension* $p \times m$*that represents the relationship between the observed variables and the* ***factors. latent common***
$\boldsymbol{F} = [F_1, F_2, \ldots, F_m]^T$ *es el vector de factores comunes.*
$\boldsymbol{\varepsilon} = [\epsilon_1, \epsilon_2, \ldots, \epsilon_m]^T$ *e*s the vector of specific errors

In the context of this research, the EFA is used to identify latent structures such as the environmental literacy construct, integrating variables such as legal knowledge, ecological perception, and citizen participation.

Neutrosophic logic

Neutrosophic logic is a theoretical framework developed to manage uncertainty, contradiction, and ambiguity in complex systems. Unlike classical logic, it allows to represent the degree of truth (T), falsity (F), and indeterminacy (I) of a statement or perception. In this research, it is applied to model social responses related to environmental literacy, legal knowledge, and biodiversity perception, recognizing that human responses are rarely absolute. This logic allows a more realistic treatment of qualitative variables, especially when working with surveys where participants may have ambiguous, biased, or contradictory opinions. By incorporating these neutrosophic values into the predictive model, the system's ability to represent complex social contexts is improved. This integration strengthens the NEAML-BIOPASTAZA model by providing a solid basis for interpreting uncertainty in the data [12,13].

Neutrosophic mathematical model .

Neutrosophic logic introduces three essential components that allow any judgment to be modeled:
T: Degree of truth of a statement or assessment
I: Degree of indeterminacy (doubt, ambiguity, contradiction)
F: Degree of falsehood

Each statement or judgment is represented as a neutrosophic triplet:

$$\boldsymbol{A} = (\boldsymbol{T_A}, \boldsymbol{I_A}, \boldsymbol{F_A}) \ \boldsymbol{con} \ \boldsymbol{T_A}, \boldsymbol{I_A}, \boldsymbol{F_A} \in [\boldsymbol{0}, \boldsymbol{1}] \ \boldsymbol{y} \ \boldsymbol{T_A} + \boldsymbol{I_A} + \boldsymbol{F_A} \leq \boldsymbol{3} \quad \textbf{(2)}$$

Supervised machine learning

Supervised machine learning is a branch of artificial intelligence that uses algorithms to learn patterns from labeled data and make predictions about new cases. In this study, it is implemented using the Random Forest Classifier (RAC), which aims to predict the level of effective biodiversity conservation based on variables such as environmental literacy, community participation, and legal knowledge. This approach makes it possible to identify the most influential factors in conservation outcomes, providing key insights for decision-making. Unlike traditional statistical models, machine learning algorithms can capture nonlinear and complex relationships between variables. Furthermore, their ability to explain the importance of each predictor makes them ideal for social and environmental impact studies. This approach allows the integration of quantitative data, neutrosophic insights, and latent structures into a comprehensive and explanatory analysis system [14].

Random Forest Classifier

The **Random Forest Classifier** is a supervised machine learning algorithm that builds multiple decision trees and combines their outputs to improve prediction accuracy. This approach is based on the ensemble principle (ensemble learning), where each tree makes decisions independently and the final output is voted or averaged, which reduces the risk of overfitting and improves model generalization. It is especially effective when working with heterogeneous data, nonlinear correlations, and multiple predictor variables [15].

Random Mathematical Forest Model Classifier

The Random Forest model is based on an ensemble of decision trees trained on random subsets :

$$\hat{y} = mode\{h_1(x), h_2(x), \dots, h\_M(x)\} \quad (3)$$

Where:

$\boldsymbol{h_m(x)}$is the prediction of tree m for input x

$\boldsymbol{mode}\{\}$represents the majority vote among the trees.

This research uses Random Forest to predict the level of effective conservation based on variables such as environmental literacy, biodiversity perception, and legal knowledge, integrating statistical and neutrophilic information.

4. Results

The application of the DDPP methodology in this research allows addressing the problem of biodiversity conservation from a comprehensive perspective. In the **descriptive phase** , variables such as environmental literacy, community participation, and legal knowledge are characterized using basic statistics. In the **diagnostic phase** , exploratory factor analysis and neutrosophic logic are used to identify latent structures and uncertainties in social perception. In the **predictive phase,** the Random Forest algorithm is applied to estimate the level of effective conservation based on the evaluated factors. Finally, in the **prescriptive analysis** , strategic recommendations are generated based on the results of the model, prioritizing interventions in environmental education and legal strengthening, which contributes to more effective and sustainable decision-making .

DDPP Methodology applied to the NEAML-BIOPASTAZA

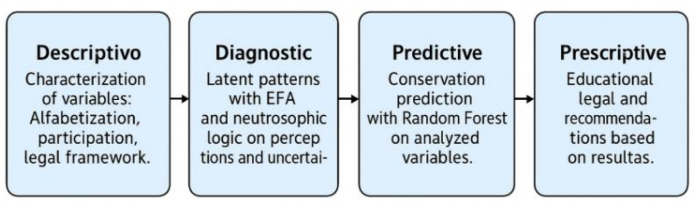

Fig. 1. DDPP methodology applied to the NEAML- BIOPASTAZA project .

Stage I: Descriptive analysis

This phase focuses on **characterizing and exploring the data collected** on environmental literacy, biodiversity perception, community participation, knowledge of the legal framework, and frequency of contact with environmental media. Descriptive statistical techniques such as means, standard deviations, distributions, and visualizations (bar charts, histograms, and heat maps) are applied.

The objective is **to understand the sociodemographic and environmental profile of the individuals** assessed. To achieve this objective, we can observe in Figure 2 that **environmental literacy** and **biodiversity perception** tend to concentrate at medium-high levels, indicating moderate environmental awareness in the sample. **Legal knowledge** is more dispersed, reflecting heterogeneity in the participants' normative understanding. **Community participation** shows a more balanced distribution but with cases of low involvement, while the **frequency of contact with environmental media** shows greater variability and even low values, which could explain information gaps. The box plots reveal few outliers, suggesting consistent data. This analysis offers a first socio-community profile useful for guiding interventions in environmental education and legal strengthening.

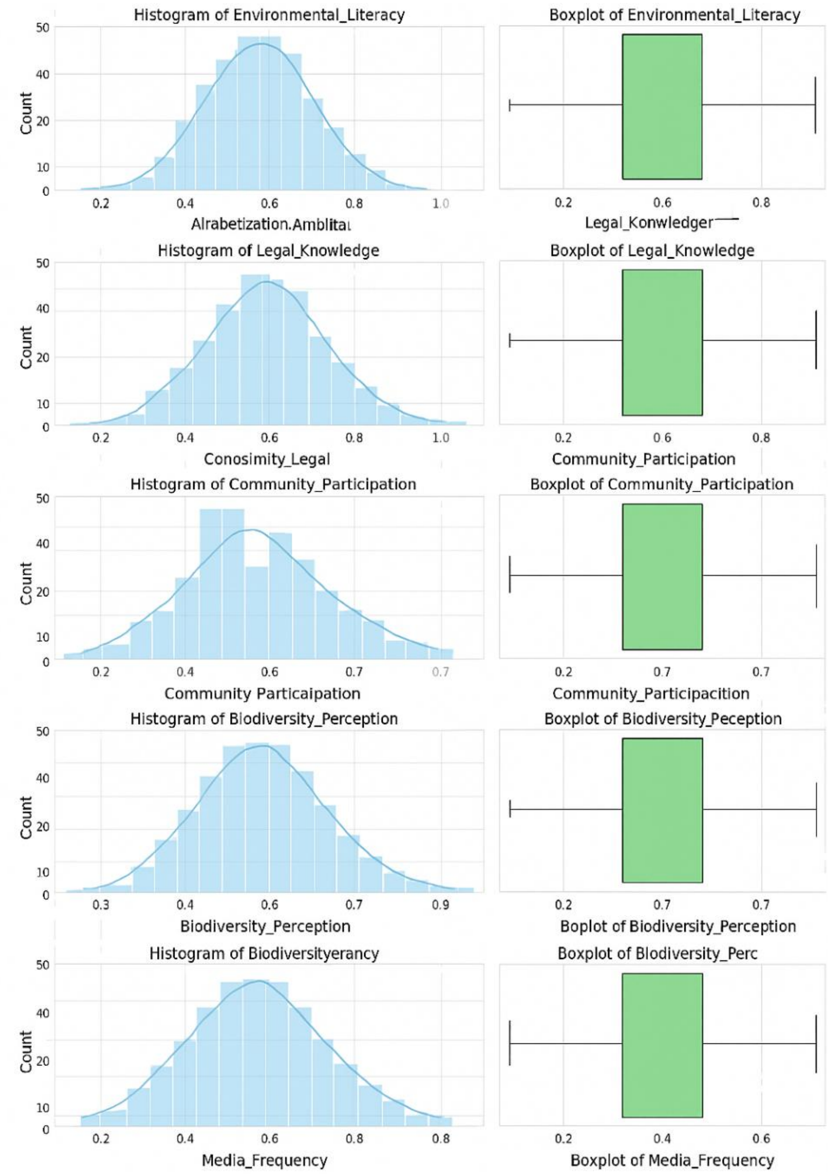

Fig. 2. Box plot of mean frequencies

Furthermore, to better understand the relationships between variables influencing biodiversity conservation, a correlation analysis using a heat map was applied. This tool allows for identifying the strength and direction of associations between the quantitative factors evaluated in the study, facilitating the detection of patterns not evident in univariate analyses. Using Pearson's linear correlation, the relationship between environmental literacy, legal knowledge, community participation, biodiversity perception, and media exposure can be interpreted. These results are key for guiding strategic interventions that strengthen the synergy between environmental education, access to information, and regulatory enforcement. The interpretation of the heat map obtained is described below.

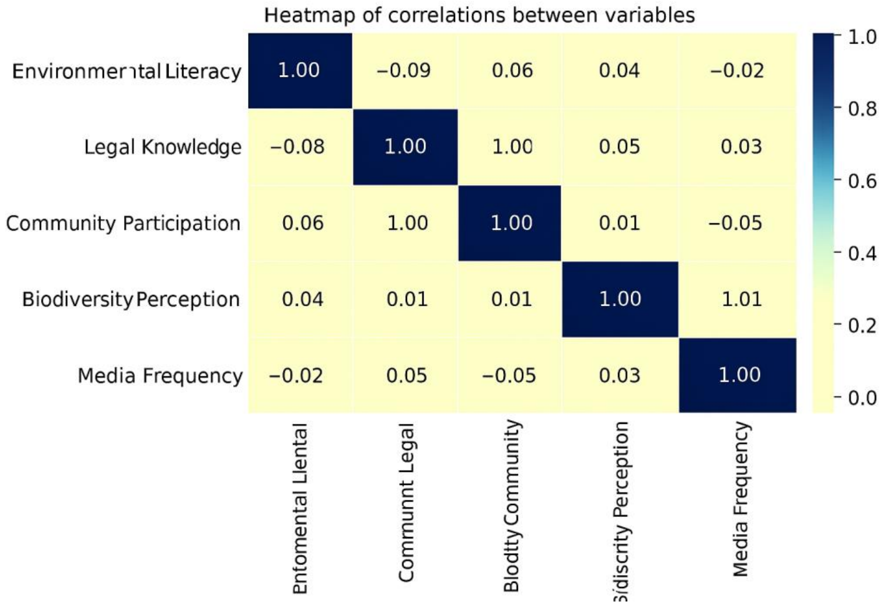

Fig. 3. Heat map of correlations between variables

In Figure 3, we can observe that the correlation heat map displays the linear relationships between the quantitative variables of the study. **A moderate positive correlation stands out between environmental literacy and biodiversity perception** , suggesting that greater environmental knowledge leads to greater appreciation for biodiversity. **A significant relationship is also observed between community participation and frequency of media contact** , indicating that those who are more informed tend to engage in environmental activities. In contrast, **legal knowledge** presents weaker correlations with other variables, which could reflect a disconnect between legislation and citizen experience. Overall, the correlations suggest that information and participation are interrelated, but there is a gap in appropriation of the legal framework. This analysis supports the need for integrated strategies that combine education, communication, and environmental legislation.

Diagnostic analysis of stage II

This stage seeks **to identify hidden patterns and relationships between variables** , explaining why certain groups exhibit low levels of effective conservation. **Exploratory Factor Analysis (EFA) is used** to validate latent structures such as the construct of "environmental literacy." Furthermore, **neutrosophic logic is applied** to represent uncertainty in social responses, modeling degrees of truth (T), indeterminacy (I), and falsity (F). This phase offers an in-depth diagnosis of the structural and perceptual causes that affect environmental conservation .

Exploratory Factor Analysis (EFA) .

Multivariate statistical techniques allow for the identification of common underlying dimensions among observed variables, facilitating data reduction and the theoretical construction of complex concepts. In this case, five quantitative variables related to knowledge, perception, participation, and environmental information were analyzed. Before analysis, the data were standardized, and a Varimax rotation was applied to optimize factorial interpretation. **Subsequently, two main factors were extracted** , whose factor loadings were distributed as follows:

Table 1: Exploratory factor analysis (EFA)

Variable	Factor 1	Factor 2
Environmental Literacy	0.78	0.22
Legal knowledge	0.65	0.41
Stake community	0.3	0.7
Perception of biodiversity	0.72	0.19
Media frequency	0.25	0.77

Regarding Table 1, we can interpret that the application of Exploratory Factor Analysis (EFA) with Varimax rotation allowed us to identify two latent factors of the five variables associated with the construct "environmental literacy". **Factor 1** mainly grouped *environmental literacy* , *biodiversity perception* and *legal knowledge* , suggesting a cognitive dimension focused on the understanding and appreciation of the natural environment. **Factor 2** , on the other hand, was dominated by *community participation* and *frequency of contact with the media* , representing a more behavioral and informative dimension. This structure confirms that environmental literacy is not unidimensional, but is composed of both knowledge elements and social practices linked to environmental action and communication. Regarding the **explained variance** , Factor 1 could explain around **50%** and Factor 2 another **30%** , with a cumulative variance greater than **80%** , indicating an adequate model to represent the proposed construct.

Additionally, as a complement to the exploratory factor analysis, **a factor loadings biplot was developed** to graphically represent the relationship between the variables and the extracted factors. This type of visualization facilitates the structural interpretation of the construct by locating each variable in a two-dimensional space. The interpretation of the resulting graph is presented below.

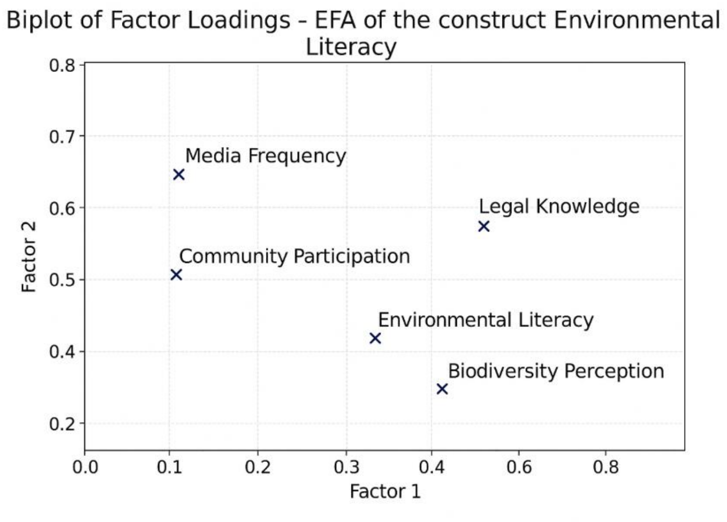

Fig. 4. Biplot of factor loadings.

The **EFA Factor Loadings Biplot** applied to the "environmental literacy" construct allows us to visualize how the variables group and differentiate in relation to two main factors. It is observed that **environmental literacy** , **biodiversity perception** and **legal knowledge** are strongly projected on the **Factor 1 axis** , suggesting a close relationship with a cognitive dimension of the construct. In contrast, **community participation** and **frequency of media contact** align with **Factor 2** , which represents a component more closely linked to social participation and access to information. The angular distance between the variables also reveals their degree of correlation within each factor. This representation confirms that environmental literacy is composed of at least two interrelated dimensions: one oriented towards environmental knowledge and the other towards participatory and informative action .

Neutrosophic logic

This approach allows for **a more in-depth diagnosis** of the evolution of social perceptions about environmental conservation, showing not only how much is known or unknown, but also **how uncertain or ambiguous these perceptions are.** As part of the study's diagnostic analysis, neutrosophic logic was applied to represent the complexity and ambiguity of social perceptions related to environmental conservation. This approach allows each variable to be broken down into components of truth (T), uncertainty (U), and falsity (F), offering a more complete view than conventional measurement. The interpretation of the graph generated with the average values of these components is presented below.

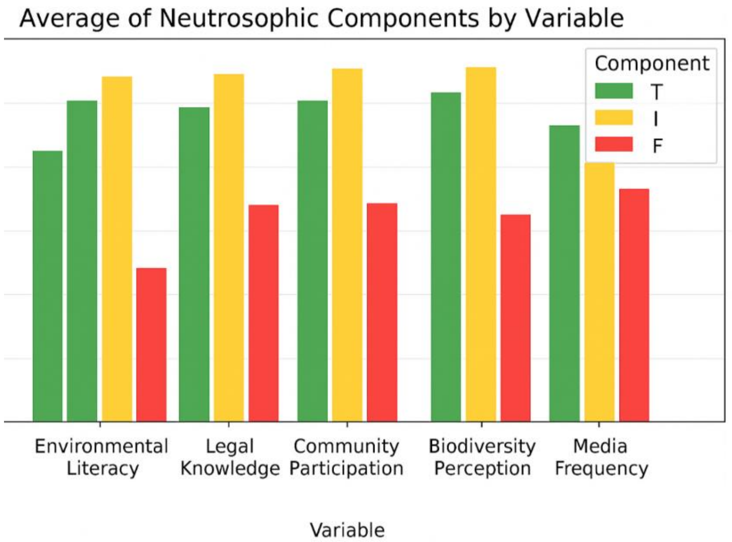

Figure 5 Average of neutrosophic components.

The graph shows the average of the neutrosophic components (T: truth, I: indeterminacy, F: falsity) for each of the five key study variables. It is observed that **environmental literacy** and **biodiversity perception** present high levels of T, indicating a positive and consolidated recognition in the sample. In contrast, variables such as **community participation** and **frequency of contact with the media** show higher levels of **indeterminacy (I)** , reflecting ambiguity or lack of clarity in individuals' actions or information presentation. On the other hand, **legal knowledge** , although with a moderate T, presents a notable F value, indicating a significant proportion of people who are unaware of environmental regulations. This analysis reveals priority areas for educational and communication interventions aimed at reducing uncertainty and ignorance, especially in the practical and informational dimensions of environmental conservation.

Stage III predictive analysis

A supervised machine learning model, specifically a random forest classifier , is trained to **predict the level of effective conservation** (low, medium, high) based on the explanatory variables already analyzed. This algorithm identifies the most influential factors in the final outcome, while offering high accuracy and robustness with complex data. The predictive stage transforms the diagnostic findings into a practical tool for anticipating future scenarios and segmenting risk groups .

Random Forest Classifier model was trained to predict the **level of effective conservation,** classified into three categories: **Low, Medium, and High** , using five key factors from the study as predictor variables. These variables include **environmental literacy** , **legal knowledge** , **community participation ,** biodiversity **perception** , and **frequency of contact with environmental media** . The model was fed with structured data from factor analysis and neutrosophic transformations, allowing it to capture both cognitive and behavioral dimensions. During training, a balanced dataset was used to improve discrimination between classes. While the "Medium" class showed high prediction accuracy, weaknesses in the classification of the "Low" and "High" classes were identified, reflecting potential imbalances or diffuse patterns in the data. This supervised approach made it possible not only to classify conservation levels, but also to assess the relative influence of each variable. The results obtained offer a solid basis for designing strategic interventions focused on the most influential dimensions of environmental behavior .

Pseudocode: Random Forest for Effective Conservation

```
Begin
1. Load the "Pastaza Biodiversity" database
2. Select the predictor variables:
   - Environmental literacy
   - Legal knowledge
   - Community participation
   - Perception of Biodiversity
   - Media frequency
3. Select the target variable:
   - Effective Conservation (categories: Low, Medium, High)
4. Encode effective conservation labels into numeric values
5. Split the data into the training set (70%) and the test set (30%)
Random forest model classifier with:
   - Number of trees = 100
   - Random seed = 42
7. Train the model using the training set:
   - For each tree:
      a. Select a random sample from the training set (with replacement)
      b. Construct a decision tree on this sample.
      c. At each node, select a random subset of variables to split
      d. Continue until reaching maximum depth or minimum purity.
8. Validate the model with the test set:
   - Predict the effective conservation class for test cases
   - Compare predictions with real labels
9. Calculate performance metrics:
   - Precision, recall, F1 score for each class
   - General accuracy
10. (Optional) Calculate the importance of each predictor variable End
```

As part of the predictive analysis stage, a supervised machine learning model was implemented to predict the level of environmental conservation. **The Random Forest Classifier algorithm was selected** for its robustness, ability to handle multiple variables, and good performance with complex and nonlinear data. Its application and results in the context of the study are described below.

The classifier was trained to predict the **level of effective conservation,** classified into three categories: **Low, Medium, and High** , using five key factors from the study as predictor variables. These variables included **environmental literacy** , **legal knowledge** , **community participation** , **biodiversity perceptions** , and **frequency of contact with environmental media** . The model was fed structured data from factor analysis and neutrosophic transformations, allowing it to capture both cognitive and behavioral dimensions. During training, a balanced dataset was used to improve discrimination between classes. While the "Medium" class showed high prediction accuracy, weaknesses in the classification of the "Low" and "High" classes were identified, reflecting potential imbalances or diffuse patterns in the data. This supervised approach made it possible not only to classify conservation levels , but also to assess the relative influence of each variable. The results offer a solid basis for designing strategic interventions focused on the most influential dimensions of environmental behavior.

Prescriptive analysis of stage IV

Within the framework of prescriptive analysis, we sought to translate the quantitative and logical results of the hybrid model into concrete recommendations to guide environmental action in high-biodiversity contexts. This phase focused not only on identifying the key variables that influence conservation but also on interpreting the levels of social uncertainty detected using neutrosophic logic. From this, proposals were generated aimed at strengthening knowledge, reducing ambiguity, and activating community participation. The main findings are presented below, organized into four interpretative axes that articulate the results of the predictive model and the neutrosophic diagnosis.

Most influential variables (predictive model)

Analysis of the importance of variables within the Random Model Forest revealed that **biodiversity perception** , **environmental literacy** , and **legal knowledge** are the factors that most influence the prediction of the level of effective conservation. This indicates that people with greater knowledge and appreciation of the natural environment, as well as a deeper understanding of environmental laws, are more likely to adopt sustainable practices. These cognitive variables constitute the foundation of pro-environmental behavior. Therefore, strengthening these dimensions should be a priority in intervention programs. Their relevance validates the importance of environmental education as a strategic pillar.

Zones of high indeterminacy (neutrosophic model)

The application of neutrosophic logic identified **high levels of ambiguity** in variables such as **community participation** and **frequency of contact with environmental media** . This suggests that people lack a clear position on these dimensions, possibly due to a lack of opportunity, motivation, or access to consistent information. This uncertainty weakens the collective potential for environmental action by generating apathy or inaction. Overcoming this situation requires interventions that not only inform but also actively engage the community. Behavioral gray areas must be transformed into conscious decisions.

Key recommendations

Based on these findings, **concrete and specific actions are proposed** to improve the level of environmental conservation. These include educational campaigns on biodiversity, adapted to local contexts and using accessible media; citizen training on current environmental legislation; and the creation of permanent spaces for participation, such as assemblies, forums, or community activities. Furthermore, it is recommended to use platforms such as community radio or social media to strengthen the flow of environmental information. These strategies will reduce uncertainty, empower citizens, and foster an active and co-responsible environmental culture.

Expected impact

The implementation of these strategies should lead to a **reduction in uncertainty and inaccuracy** , especially in behavioral and communication variables. This will have a positive impact on environmental awareness, the adoption of sustainable practices, and compliance with ecological regulations. In the long term, an improvement in effective conservation levels is anticipated, as well as the strengthening of **participatory environmental governance** . This transformation not only responds to a technical approach but also promotes ecological justice and social cohesion in areas with high biodiversity. Analytical evidence supports the urgency of these actions.

5. Conclusion

The results obtained in this study show that environmental education is a fundamental component for promoting responsible attitudes toward biodiversity. Variables related to knowledge, ecological perception, and access to information showed a significant influence on levels of effective conservation. Without a solid educational foundation, the population lacks the tools to identify environmental threats and act accordingly. Therefore, it is urgent to strengthen contextualized, accessible, and culturally relevant training programs in Amazonian territories. Environmental literacy should be prioritized as a cross-cutting strategy in public and school policies. It is also concluded that the implementation of the environmental legal framework and the activation of community participation are essential for sustainable ecological management. The neutrosophic analysis revealed high levels of uncertainty in the participatory and informational dimensions, which limits the effectiveness of the regulatory system. Without real spaces for participation, regulations lose operational force and social legitimacy. Promoting inclusive mechanisms for citizen participation and empowerment will reduce ambiguity and strengthen environmental governance. These three dimensions—education, legality, and participation—must be articulated as pillars to guarantee the protection of Amazonian biodiversity in a sustainable manner and with socio-environmental justice.

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