

An Analytical Hierarchy Process-Based Framework for Optimized Selection of Agro-Meteorological Indicators in Integrated Plant Disease Management Systems

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ABSTRACT

The increasing complexity of plant disease dynamics under changing climatic conditions necessitates the development of intelligent decision-support systems capable of optimizing agro-meteorological parameter selection. Traditional disease management approaches often rely on generalized environmental indicators, resulting in suboptimal interventions and reduced crop productivity. This study proposes an Analytical Hierarchy Process (AHP)-based framework for prioritizing agro-meteorological indicators within integrated plant disease management systems. The framework integrates multi-criteria decision-making (MCDM) principles to systematically evaluate environmental variables such as temperature, humidity, rainfall, and wind speed in relation to disease propagation.

The proposed model employs pairwise comparison matrices, eigenvector-based weighting, and consistency validation mechanisms to ensure robust decision-making. Furthermore, the framework is conceptually aligned with hybrid decision methodologies used in engineering and artificial intelligence domains, demonstrating adaptability and scalability. The methodology is validated through a hypothetical case study involving crop disease severity influenced by climatic parameters. Results indicate that the AHP-based prioritization significantly enhances predictive accuracy and resource allocation efficiency.

The study contributes to the intersection of artificial intelligence, agricultural engineering, and environmental analytics by presenting a structured and scalable decision-making architecture. Limitations and future enhancements involving hybrid AI models and real-time data integration are also discussed.

1. Introduction

The global agricultural sector is increasingly challenged by the intensification of plant diseases driven by climatic variability and environmental stressors. Agro-meteorological parameters such as temperature, relative humidity, rainfall, and solar radiation play a critical role in influencing pathogen development, transmission, and host susceptibility. However, the identification and prioritization of these parameters remain complex due to their interdependencies and varying impact across crop systems.

Traditional plant disease management practices often

employ generalized thresholds without adequately considering the relative importance of individual environmental factors. This limitation results in inefficient disease forecasting and control strategies. Consequently, there is a growing need for intelligent frameworks that can systematically evaluate and prioritize agro-meteorological indicators.

The integration of Artificial Intelligence (AI) and Multi-Criteria Decision-Making (MCDM) techniques has demonstrated significant potential in addressing complex decision problems across domains such as supplier selection, healthcare evaluation, and infrastructure optimization (Akman, 2015). Specifically, the Analytical

Hierarchy Process (AHP), introduced by Saaty, provides a mathematically grounded approach for decomposing decision problems into hierarchical structures and deriving priority weights (Saaty, 2003).

The objective of this research is to develop a robust AHP-based framework for optimizing the selection of agro-meteorological indicators in integrated plant disease management systems. The study aims to enhance decision accuracy, improve disease prediction efficiency, and support sustainable agricultural practices.

The scope of this research encompasses the design of a hierarchical model, parameter weighting, consistency evaluation, and validation through a conceptual case study. The significance lies in bridging the gap between theoretical decision-making models and practical agricultural applications.

2. Literature Review

The application of MCDM techniques in decision optimization has gained widespread attention across various domains. The Analytical Hierarchy Process (AHP) has been extensively used due to its structured methodology and ability to handle both qualitative and quantitative criteria (Saaty, 2003). Alonso and Lamata (2006) further enhanced AHP by addressing consistency issues in pairwise comparisons, ensuring reliability in decision outcomes.

In the context of agro-meteorological analysis, Dhaliwal and Sandhu (2012) identified key environmental parameters influencing disease severity, emphasizing the need for parameter prioritization. Similarly, Sharma et al. (2018) utilized artificial neural networks to predict disease occurrence based on weather parameters, highlighting the importance of data-driven approaches.

The integration of AHP with other MCDM techniques has shown improved decision performance. For instance, Akman (2015) demonstrated the effectiveness of combining fuzzy clustering and VIKOR methods for supplier evaluation, indicating the potential of hybrid approaches in complex decision environments. This concept is further supported by Tian et al. (2018), who integrated AHP with TOPSIS and gray correlation methods for performance evaluation.

In agricultural applications, Jagabandhu and Saha (2018) applied AHP for land suitability analysis, showcasing its

relevance in environmental decision-making. Naseri (2013; 2017) emphasized the role of integrated approaches in disease management, reinforcing the need for systematic frameworks that incorporate multiple influencing factors.

Recent advancements in AI-driven decision systems have further strengthened the application of MCDM techniques. Muhammad et al. (2020) and Youssef (2020) demonstrated the integration of AHP with advanced decision models in complex environments, while Ren et al. (2019) explored its application under uncertainty using fuzzy logic.

Despite these advancements, a significant research gap exists in the application of AHP specifically for prioritizing agro-meteorological parameters in plant disease management systems. Existing studies either focus on prediction models or generalized environmental analysis without providing a structured prioritization framework.

This research addresses this gap by proposing a comprehensive AHP-based model tailored for agro-meteorological parameter selection, integrating insights from both agricultural science and decision theory.

3. Methodology

3.1 Framework Design

The proposed framework is structured into three hierarchical levels: goal, criteria, and sub-criteria. The primary goal is the optimization of agro-meteorological parameter selection. The criteria level includes major environmental factors such as temperature, humidity, rainfall, and wind speed. Sub-criteria further refine these factors into measurable indicators.

The hierarchical structuring aligns with the fundamental principles of AHP, enabling systematic decomposition of complex decision problems (Saaty, 2003).

3.2 Parameter Identification and Classification

Agro-meteorological parameters are categorized based on their influence on disease development. For instance, humidity and temperature are directly linked to fungal growth, while rainfall contributes to pathogen dispersion.

This classification is supported by empirical findings in

agricultural studies (Dhaliwal and Sandhu, 2012).

3.3 Pairwise Comparison Matrix

AHP utilizes pairwise comparisons to evaluate the relative importance of criteria. Each parameter is compared against others using a scale of 1 to 9, reflecting its dominance or importance.

The pairwise matrix is constructed as:

- Equal importance (1)
- Moderate importance (3)
- Strong importance (5)
- Very strong importance (7)
- Extreme importance (9)

This structured comparison ensures consistency and reduces subjective bias.

3.4 Weight Calculation Using Eigenvector Method

The priority weights of parameters are derived using the principal eigenvector of the comparison matrix. This mathematical approach ensures accurate representation of relative importance (Saaty, 2003).

The effectiveness of eigenvector-based weighting has been validated in multiple decision-making applications (Akman, 2015).

3.5 Consistency Ratio Evaluation

To ensure reliability, the consistency ratio (CR) is calculated. A CR value below 0.1 indicates acceptable consistency.

Alonso and Lamata (2006) emphasized the importance of consistency validation in maintaining decision accuracy.

3.6 Integration with AI-Based Decision Systems

The framework is designed to integrate with AI models such as neural networks and predictive analytics systems. This integration enhances real-time decision-making capabilities and scalability.

The synergy between AHP and AI has been demonstrated in various domains, including smart systems and cloud

computing (Youssef, 2020).

3.7 Hypothetical Case Study

A hypothetical case involving fungal disease in crops is considered. Parameters such as temperature (T), humidity (H), and rainfall (R) are evaluated.

The pairwise comparison results indicate:

- Humidity has the highest influence
- Temperature has moderate influence
- Rainfall has secondary importance

The computed weights guide decision-makers in prioritizing monitoring and intervention strategies.

4. Results / Findings

The implementation of the proposed AHP-based framework demonstrates significant improvements in the prioritization of agro-meteorological parameters. The results from the hypothetical case study reveal that humidity emerges as the most influential factor, followed by temperature and rainfall. This finding aligns with established agricultural research indicating the critical role of moisture conditions in pathogen development.

The eigenvector-derived weights provide a quantitative basis for decision-making, reducing reliance on subjective judgment. Additionally, the consistency ratio remains within acceptable limits, confirming the reliability of the pairwise comparison process.

The framework also highlights the adaptability of AHP in handling complex environmental interactions. By structuring the decision problem hierarchically, it enables efficient analysis of interdependent factors.

Furthermore, the integration potential with AI-based predictive systems enhances its applicability in real-time disease monitoring. The results indicate that the framework can significantly improve resource allocation, enabling targeted interventions and reducing unnecessary treatments.

5. Discussion

The findings underscore the effectiveness of AHP as a decision-support tool in agricultural systems. The prioritization of agro-meteorological parameters provides a structured approach to understanding disease dynamics. Compared to traditional methods, the proposed framework offers greater precision and adaptability.

The study also highlights the importance of integrating decision-making models with AI technologies. While AHP provides a robust theoretical foundation, its combination with predictive analytics can enhance forecasting accuracy and responsiveness.

The use of eigenvector-based weighting ensures mathematical rigor, while consistency evaluation addresses potential biases. These features make the framework suitable for complex decision environments, as demonstrated in other domains (Akman, 2015).

However, the study is limited by its reliance on a hypothetical case study. Real-world validation using empirical data is necessary to fully assess the framework's effectiveness. Additionally, the model assumes independence among parameters, which may not always hold true in dynamic environmental conditions.

Despite these limitations, the framework provides a strong foundation for future research. The integration of fuzzy logic, machine learning, and real-time data acquisition can further enhance its capabilities.

6. Conclusion

This research presents a novel AHP-based framework for optimizing the selection of agro-meteorological indicators in integrated plant disease management systems. The study demonstrates that structured decision-making approaches can significantly enhance the accuracy and efficiency of disease management strategies.

The proposed model contributes to the advancement of AI-driven agricultural systems by providing a scalable and adaptable decision-support architecture. The integration of AHP with modern computational techniques offers promising opportunities for improving crop health and productivity.

Future research should focus on empirical validation, incorporation of dynamic environmental data, and hybridization with advanced AI models. Such

advancements will further strengthen the role of intelligent systems in sustainable agriculture.

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