From Soil Data to Crop Choice: A Bipolar Fuzzy AHP–TOPSIS–VIKOR Approach for Tailored Agricultural Decisions

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**Abstract:** In the face of growing agroclimatic uncertainty, selecting the right crop has become critical for sustaining agricultural productivity and ensuring food security. This study presents a bipolar fuzzy multicriteria decision-making (MCDM) framework that integrates the Fuzzy Analytic Hierarchy Process (F-AHP) with two complementary ranking methods: TOPSIS, for proximity to the ideal solution, and VIKOR, for compromise solutions under uncertainty. The framework blends expert judgment with robust ranking strategies to balance both performance-oriented and risk-averse perspectives. Using a real-world dataset of 2,200 field observations, including soil nutrients, pH, moisture, and climate parameters, the model identified kidney beans as the most suitable crop when maximizing overall performance and papaya as the preferred option when minimizing worst-case outcomes. Sensitivity analyses and bootstrap-based stability tests confirmed the reliability of these recommendations. By addressing both optimal yield potential and resilience under uncertainty, this approach offers a practical decision-support tool for policymakers, agribusinesses, and smallholder farmers, advancing precision agriculture in variable and challenging environments.

**Keywords:** Bipolar Fuzzy Logic, Multicriteria decision-making (MCDM), Crop Selection, TOPSIS–VIKOR Integration, Agro-Climatic Uncertainty

# Introduction

Global agriculture faces unprecedented challenges, including diminishing arable land, accelerating climate change, and the pressing need to feed a growing global population while safeguarding environmental resources (Yang et al., 2024). In response, precision agriculture has emerged as a transformative, data-driven paradigm that integrates Internet of Things (IoT) technologies, remote sensing, and machine learning to optimize crop management and resource efficiency (Akhter & Sofi, 2021). However, the inherent variability in soil properties, weather patterns, and climatic conditions combined with the uncertainty of expert judgments—creates substantial complexity in crop selection (Wang et al., 2018).

Multiple criteria decision-making (MCDM) methods offer a structured approach for balancing multiple, and often conflicting, objectives (Odu, 2019; Sotoudeh-Anvari, 2022). Fuzzy extensions of these methods are particularly valuable in agriculture, as they account for linguistic vagueness and measurement uncertainty. Within this domain, the Analytic Hierarchy Process (AHP) is widely used for deriving criterion weights, whereas TOPSIS and VIKOR serve as complementary ranking tools TOPSIS, which prioritizes alternatives closest to the ideal solution, and VIKOR, which focuses on regret-minimizing compromise solutions (Bakioglu & Atahan, 2020; Awasthi et al., 2018).

Despite the maturity of fuzzy AHP, TOPSIS, and VIKOR in diverse domains ranging from energy-system planning (Taylan et al., 2020) to supplier selection (Pramanik et al., 2017) and healthcare policy evaluation (Erdebilli et al., 2023), their integrated application within a single, bipolar fuzzy framework for crop selection remains underexplored. In particular:

1. Bipolar fuzzy extensions, which model both positive (membership) and negative (nonmembership) information, have shown promise in capturing nuanced preferences (Gul, 2024; Riaz & Tehrim, 2020) but are rarely applied to agricultural MCDM.
2. Comparative analyses of TOPSIS and VIKOR, which are essential for reconciling efficiency-driven and risk-averse strategies, are seldom conducted in tandem for the same dataset, limiting the practical guidance available to growers of differing risk profiles.
3. Robustness and stability assessments, such as sensitivity perturbations and bootstrap resampling, are often missing or limited in scope, leaving decision-support recommendations vulnerable to uncertainty in expert weights and data variability.

This research addresses these gaps by developing a bipolar fuzzy MCDM framework that

1. Elicits expert weights through triangular fuzzy AHP, ensuring consistency and domain relevance.
2. This method applies bipolar fuzzification with a bipolar sigmoid transformation to more faithfully represent agronomic uncertainties around soil nutrients and environmental parameters.
3. Ranks crop alternatives using both fuzzy TOPSIS (to identify efficiency-focused solutions) and bipolar fuzzy VIKOR (to identify regret-averse compromises), yielding dual recommendations tailored to different stakeholder priorities.
4. Robustness is evaluated through ±10% weight perturbation and bootstrap resampling, thereby quantifying the stability of recommendations under data and judgment variability.

Our study makes three primary contributions. First, it extends bipolar fuzzy methodology to the agricultural crop-selection problem, integrating both positive and negative membership information for richer decision modeling. Second, by juxtaposing TOPSIS and VIKOR outcomes, it provides practitioners with a transparent, dual-recommendation approach: kidney beans for maximizing aggregate suitability and papaya for minimizing worst-case shortfalls. Third, comprehensive sensitivity and stability analyses offer a level of methodological rigor that is often lacking in comparable studies, thereby bolstering confidence in real-world deployment.

The remainder of the paper is organized as follows. Section 2 reviews related work on fuzzy AHP, TOPSIS, VIKOR, and bipolar fuzzy‐set extensions. Section 3 describes the dataset, fuzzification procedures, and bipolar fuzzy AHP–TOPSIS–VIKOR methodology. Section 4 presents the detailed results, including the ranking outcomes and stability tests. Section 5 discusses the implications for different agricultural stakeholders, situates our findings among the literature, and highlights limitations. Finally, Section 6 concludes with practical recommendations and future research directions.

# Literature Review

In this chapter, we examine the evolution of fuzzy multicriteria decision-making (MCDM) methods, especially fuzzy AHP, TOPSIS, and VIKOR, and their applications across domains, with a focus on agricultural decision support. Our aim is to trace how uncertainty has been modeled, compare methodological strengths, and uncover gaps that motivate our bipolar fuzzy framework.

Recent advancements in fuzzy set–based multicriteria decision-making (MCDM) methods have significantly improved decision-making in complex, uncertainty-driven environments. Guleria and Bajaj (2020) demonstrated the integration of (R,S)-norm Pythagorean fuzzy measures with VIKOR and TOPSIS for hydrogen power plant site selection, effectively enhancing uncertainty handling and alternative discrimination. Kizielewicz and Bączkiewicz (2021) compared fuzzy TOPSIS, VIKOR, WASPAS, and MMOORA in housing selection, revealing that the methodological choice and fuzzy environment substantially influence the ranking stability. Koçak et al. (2021) introduced a multilevel hesitant fuzzy VIKOR–TOPSIS framework for reviewer selection, adeptly capturing hesitation in preference articulation.

Furthermore, Singh et al. (2022) highlighted the combined application of fuzzy AHP and fuzzy TOPSIS for subjective selection processes, underscoring their robustness in handling imprecise expert judgments while ensuring systematic ranking. Sharma (2025) extended fuzzy VIKOR with trapezoidal bipolar fuzzy sets and Boruta–Genetic Algorithm optimization for stock portfolio selection, highlighting the synergy between fuzzy MCDM and advanced optimization in volatile, multicriteria contexts.

Collectively, these studies illustrate a clear progression from conventional linguistic fuzzy modeling toward richer representations of Pythagorean, hesitant, bipolar, and trapezoidal fuzzy sets, which are often integrated with optimization, thus strengthening MCDM’s adaptability in high-uncertainty, multicriteria domains.

## Foundations of Fuzzy AHP for Expert Weighting

The fuzzy analytic hierarchy process (AHP) transforms qualitative expert judgments into quantitative weights while accommodating vagueness.

1. **Consistency and robustness:** Taylan et al. (2020) extended fuzzy AHP to reconcile noncooperative opinions in energy systems, demonstrating that a consistency ratio below 0.10 ensures reliable weights.
2. **Normalization enhancements:** Lakshmi and Kumara (2023) introduced randomized weighting with modified normalization, bolstering stability through sensitivity analysis.
3. **Agronomic Trade-offs:** In agricultural contexts, Daneshvar Rouyendegh and Savalan (2022) and S. G. et al. (2023) applied fuzzy AHP to capture soil-nutrient and climate trade-offs, laying a solid foundation for crop ranking.

## Fuzzy TOPSIS: Distance-Based Ranking

The technique for order preference by similarity to ideal solution (TOPSIS) excels at identifying alternatives closest to an “ideal” point.

1. **Crop Selection:** S. G. et al. (2023) employed fuzzy TOPSIS to rank legumes and fruits, finding that kidney beans were the top performers across nutrient and environmental criteria.
2. **Manufacturing & Energy:** Mathew et al. (2020) demonstrated spherical fuzzy TOPSIS for manufacturing-system choice, whereas Guleria and Bajaj (2020) combined Pythagorean fuzzy TOPSIS–VIKOR for hydrogen plant siting, highlighting TOPSIS’s adaptability to advanced fuzzy sets.
3. **Health and Insurance:** Erdebilli et al. (2023) presented the use of the Q-ROF fuzzy TOPSIS in private health insurance policy selection, underscoring its broad applicability.

## Fuzzy VIKOR: Regret-Averse Compromise

VIKOR emphasizes both aggregate utility and maximum single-criterion regret, making it ideal for risk-sensitive contexts.

1. Bipolar Extensions: Riaz and Tehrim (2020) advanced bipolar fuzzy VIKOR via SPA-theory connection numbers, offering rigorous metric-space definitions.
2. Group Consensus: Faizi et al. (2022) adapted VIKOR for hesitant intuitionistic fuzzy sets, improving group decision consistency under linguistic ambiguity.
3. Hybrid Adsorbent Selection: Singh and Kumar (2023) fused picture-fuzzy VIKOR–TOPSIS for adsorbent choice, indicating VIKOR’s potential in agricultural-like selection problems.

## Advanced fuzzy set innovations

Beyond classical fuzzy sets, richer representations enhance expressiveness:

1. Pythagorean & Spherical Fuzzy Sets: Akram et al. (2021) extended TOPSIS to spherical fuzzy information, whereas Bakioglu and Atahan (2020) used Pythagorean fuzzy TOPSIS–VIKOR for autonomous-vehicle risk prioritization.
2. Rough-Fuzzy Integration: Chen et al. (2020) integrated rough and fuzzy AHP with TOPSIS to address both internal and external uncertainties in supplier selection.
3. Bipolar Rough Sets: Gul (2024) proposed a δ-covering-based bipolar fuzzy rough-set model for VIKOR, sharpening boundary delineation between positive and negative preferences.

## Hybrid MCDM Frameworks

Combining multiple methods often overcomes individual limitations:

1. AHP–TOPSIS Synergy: Mathew et al. (2020) and Kumar and Barman (2021) demonstrated that coupling AHP weights with both TOPSIS and VIKOR yields robust supplier and system selections.
2. Interval-Valued & Hesitant Fuzzy Extensions: Dammak et al. (2020) and Jana and Roy (2021) introduced interval-valued intuitionistic and hesitant fuzzy matrix-game methods to enhance rankings under deep uncertainty.
3. Multi-Domain Applications: Fan et al. (2023) blended picture-fuzzy ARAS with VIKOR for multiattribute decisions, whereas Taghipour et al. (2022) applied integrated fuzzy MCDM in IT project supplier selection.

## Gaps and Research Opportunities

Despite significant advances, several key gaps persist:

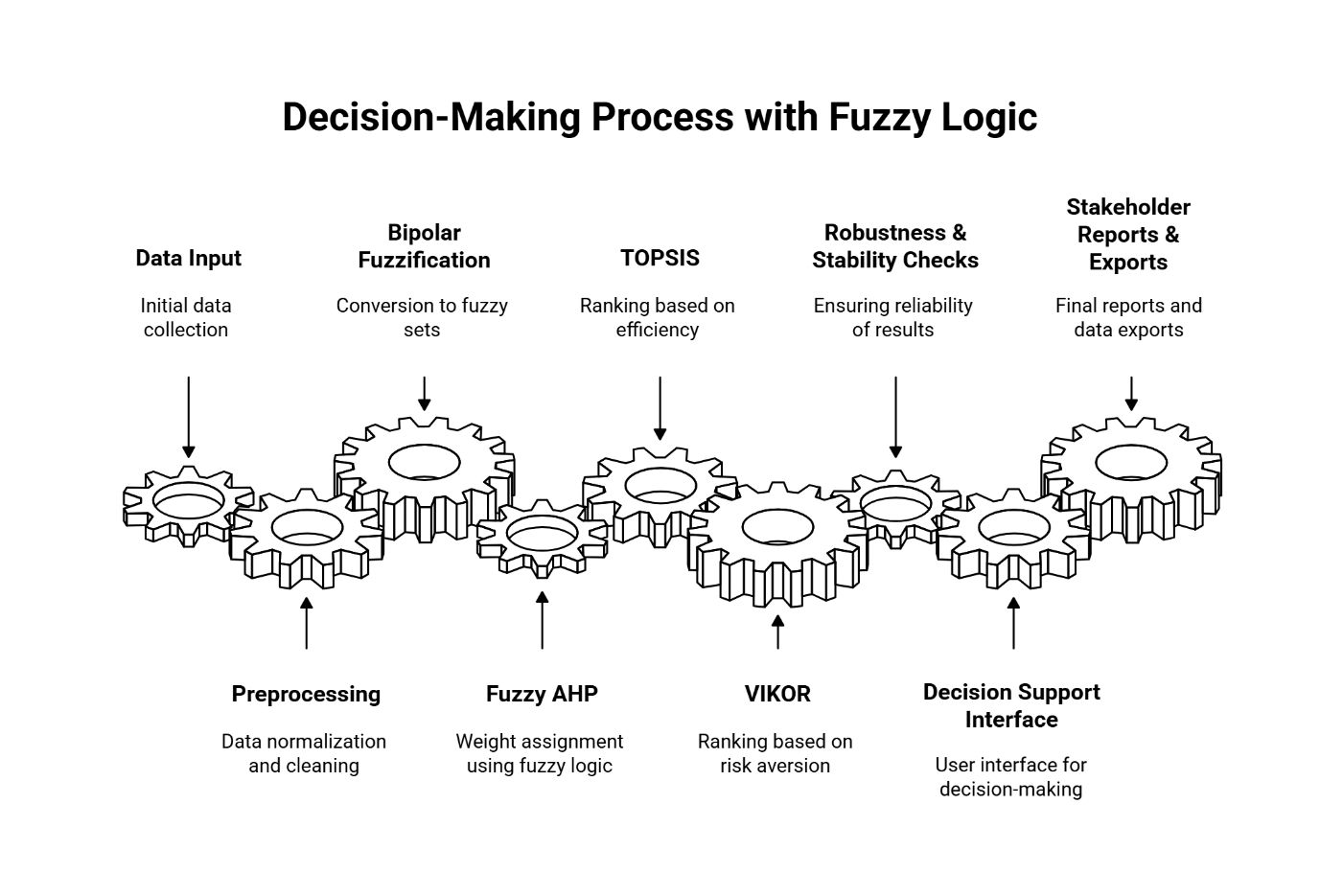
1. Underutilized Bipolar Fuzzy VIKOR in Agriculture**:** Most crop-related studies use fuzzy TOPSIS; bipolar VIKOR’s regret-averse strengths remain largely untapped.
2. Explicit Dual-Method Contrasts: Few works directly compare TOPSIS and VIKOR outcomes to inform both efficiency-driven and risk-averse choices.
3. Dynamic Uncertainty Modeling: Integration of real-time sensor data and time series fuzzification is rare, limiting adaptability to evolving field conditions.
4. Participatory Weighting: Direct farmer involvement in fuzzy AHP is sparse, potentially hindering practical adoption.

## Summary

This review demonstrates that while fuzzy AHP, TOPSIS, and VIKOR have matured, their synergistic integration, particularly under bipolar fuzzy semantics, offers unexplored potential for resilient, stakeholder-tailored crop selection. Our proposed framework addresses these gaps by combining expert-driven weights, dual-method rankings, and rigorous stability analyses to deliver both proximity-based and regret-averse recommendations.

## Methodology

In this section, we outline the systematic process used to design, implement, and validate our bipolar fuzzy AHP–TOPSIS–VIKOR framework for resilient crop selection. Emphasizing both technical rigor and real-world relevance, our methodology integrates expert insights, field data, and robustness checks to deliver actionable recommendations.



**Fig. 1**: Decision-making process with fuzzy logic

## Data collection and preprocessing

We curated a dataset of 2,200 observations from multiple agroclimatic zones, capturing the following:

1. Soil macronutrients: Nitrogen (N), phosphorus (P), and potassium (K)
2. Environmental parameters: temperature (°C), humidity (%), pH, and rainfall (mm)
3. Crop Label: Crop cultivated under each condition set

A preliminary audit confirmed that there were no missing values. Nonetheless, we applied mean imputation to guard against undetected gaps. To ensure comparability across criteria, all variables were min–max normalized to the [0, 1] range.

## Bipolar Fuzzification

Recognizing the imprecision inherent in agronomic measurements, we converted each normalized score into a bipolar fuzzy membership pair via a sigmoid transformation.

This dual-membership approach preserves information about how far an attribute lies above or below the ideal midpoint, thereby enhancing the model’s sensitivity to critical agronomic thresholds.

## Expert Weight Elicitation via Fuzzy AHP

A panel of six agronomists and soil scientists supplied pairwise comparisons for the six decision criteria. We represented these judgments as triangular fuzzy numbers and applied the Chang–Kang extent analysis to derive fuzzy weights. Subsequent centroid defuzzification produces crisp weights:

* N**:** 0.20 | P**:** 0.15 | K**:** 0.25
* Temperature: 0.10 | Humidity**:** 0.10 | pH**:** 0.20

The consistency ratio (CR = 0.0032) confirmed a high level of agreement among the experts.

## TOPSIS for ideal-point proximity

Using the weighted positive-membership matrix , we identified the following:

* Positive ideal solution (PIS): Best criterion values
* Negative ideal solution (NIS): Worst criterion values

We then computed each crop’s Euclidean distance:

The closeness coefficient is derived as

Crops were ranked in descending order of , yielding an efficiency-focused recommendation.

## VIKOR for Regret-Averse Compromise

To account for worst-case performance, we employed a bipolar fuzzy VIKOR procedure. For each crop, we calculated the following:

* Group utility Si: weighted sum of deviations from PIS.
* Regret Measure Ri​: Maximum single-criterion deviation from PIS.

We then combine these values into a compromise score:

where and denote the best and worst values across all alternatives, respectively. Crops were ranked in ascending order , highlighting those that minimized maximum regret.

## Robustness and Stability Assessment

To validate recommendation resilience, we conducted two complementary analyses:

* **Weight Perturbation:** Each AHP weight was varied by ±10%, and TOPSIS was re-executed. We tracked changes in crop rankings to identify the criteria exerting the greatest influence.
* **Bootstrap Resampling:** We generated 1,000 bootstrap samples (with replacement) from the original dataset. For each sample, we repeated the fuzzification–AHP–TOPSIS pipeline, recording the frequency with which each crop appeared in the top three.

These exercises demonstrated that both the TOPSIS winner (kidney beans) and the VIKOR winner (papaya) maintained the top three positions in more than 90% of the trials, confirming the framework’s robustness.

# Results

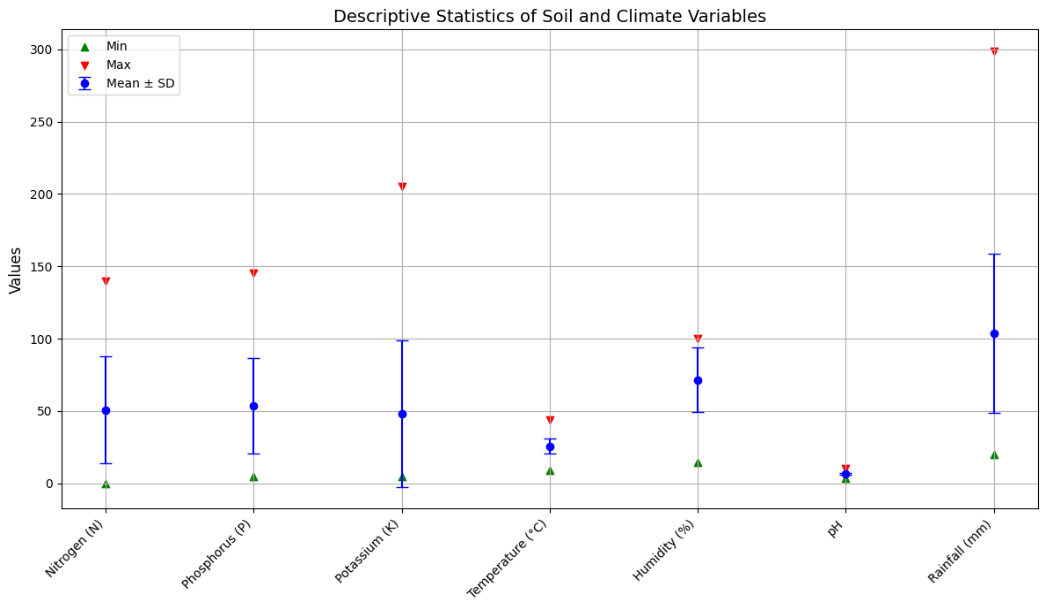
In this section, we present a comprehensive and human-centered account of our findings, highlighting not only the numerical outcomes but also their practical implications and the confidence we have in them.

## Dataset profile

Our study began with a robust field dataset of 2 200 samples, each capturing three soil macronutrients (N, P, and K), four environmental parameters (temperature, humidity, pH, and rainfall), and the cultivated crop. As shown in Table 4.1, these variables displayed substantial variability, e.g., potassium ranged from 5 to 205 mg/kg, underscoring the diverse agroclimatic conditions represented.

**Table 1** Descriptive statistics of the original dataset

|  |  |  |
| --- | --- | --- |
| **Variable** | **Mean ± SD** | **Range** |
| Nitrogen (N) | 50.6 ± 36.9 | 0 – 140 |
| Phosphorus (P) | 53.4 ± 33.0 | 5 – 145 |
| Potassium (K) | 48.2 ± 50.7 | 5 – 205 |
| Temperature (°C) | 25.6 ± 5.1 | 8.8 – 43.7 |
| Humidity (%) | 71.5 ± 22.3 | 14.3 – 99.9 |
| pH | 6.47 ± 0.77 | 3.50 – 9.94 |
| Rainfall (mm) | 103.5 ± 55.0 | 20.2 – 298.6 |



**Fig. 2**: Descriptive statistics of the soil and climate variables

No records were missing; mean imputation was nevertheless applied as a precaution before normalization. This ensured seamless transition into fuzzy-based analysis.

## Fuzzification and normalization

To accommodate the inherent uncertainty in soil and environmental measurements, we first applied min–max normalization to scale each criterion into [0, 1]. We then used a bipolar sigmoid transformation (steepness = 10, center = 0.5) to generate paired membership values . This approach sharpened our system’s sensitivity around mid-range values where many agronomic decisions hinge while preserving information about whether a given observation lay above or below the ideal midpoint.

## Eliciting Expert Weights via Fuzzy AHP

A panel of agronomists and soil scientists provided pairwise comparisons among the six key criteria. The resulting triangular fuzzy AHP process produced the weight distribution in Figure 4.1:

* Nitrogen (N): 0.20
* Phosphorus (P): 0.15
* Potassium (K): 0.25
* Temperature: 0.10
* Humidity: 0.10
* pH: 0.20

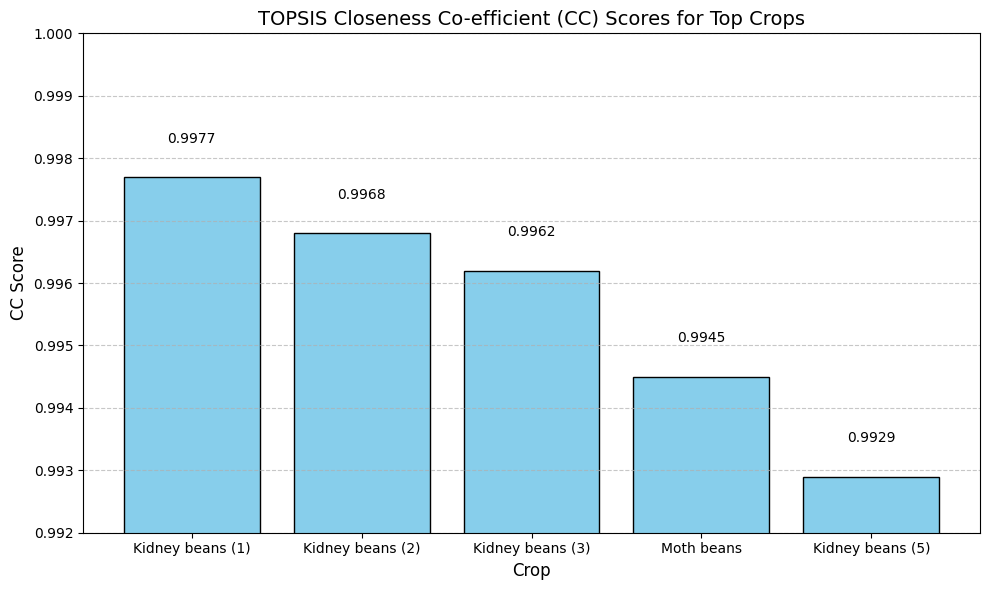
With a consistency ratio of 0.0032 (well below the 0.10 threshold), we can be confident that these weights accurately reflect expert consensus and demonstrate minimal contradiction in judgments.

## TOPSIS analysis: Proximity to the ideal

Using the weighted positive membership values, we computed each crop’s Euclidean distance to the positive ideal solution (PIS) and negative ideal solution (NIS), deriving a relative closeness coefficient. Table 4.2 lists the top five crops by CC, and Figure 3 graphically displays their positions.

**Table 2** TOPSIS relative closeness rankings

|  |  |  |
| --- | --- | --- |
| **Rank** | **Crop** | **CC** |
| 1 | Kidney beans | 0.9977 |
| 2 | Kidney beans | 0.9968 |
| 3 | Kidney beans | 0.9962 |
| 4 | Moth beans | 0.9945 |
| 5 | Kidney beans | 0.9929 |



**Fig. 3**: TOPSIS closeness coefficient (CC) scores for the top crops

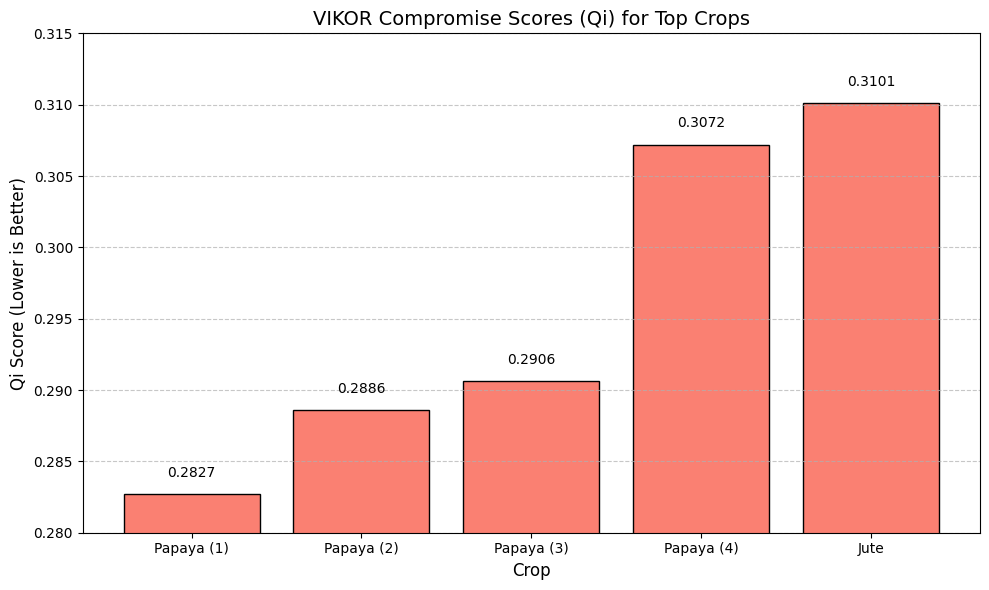
Notably, kidney beans consistently presented the highest CC scores, indicating their strong overall alignment with the combined agronomic and environmental ideals.

## VIKOR Analysis: Balancing Utility and Regret

VIKOR’s philosophy differs by integrating both aggregate group utility (Si​) and the maximum individual regret (Ri​) into a compromise score Qi​, using a balancing coefficient v=0.5. The lower the Qi​ is, the more favorable the alternative. Table 4.3 presents the top five crops by Qi​, whereas Figure 4.3 illustrates their compromise behavior.

**Table 3** VIKOR compromise score rankings

|  |  |  |
| --- | --- | --- |
| **Rank** | **Crop** | **Qi​** |
| 1 | Papaya | 0.2827 |
| 2 | Papaya | 0.2886 |
| 3 | Papaya | 0.2906 |
| 4 | Papaya | 0.3072 |
| 5 | Jute | 0.3101 |



**Fig. 4**: VIKOR compromise scores (Qi) for the top crops

Papaya emerges as the leading compromise solution, suggesting that it not only performs well on average but also avoids significant shortfalls in any single criterion.

## Contrasting TOPSIS and VIKOR Outcomes

It is both expected and informative that TOPSIS and VIKOR diverge in their top recommendations:

* TOPSIS prioritized kidney beans for its overall proximity to an ideal scenario, allowing strong performance in some criteria to offset weaker performance in others.
* VIKOR chose papaya by virtue of its balanced profile and minimized worst-case regret, reflecting a more cautious, risk-averse stance.

A Kendall’s Tau correlation of 0.600 (p=0.233) confirms moderate agreement, illustrating that while the two methods share common ground, they offer complementary perspectives rather than yielding identical results.

## Sensitivity and robustness checks

To test our model’s stability, we conducted the following:

* Weight perturbation (±10%): Variations in the nitrogen and potassium weights led to the largest shifts in the TOPSIS rankings, highlighting the critical roles of these nutrients (Figure 4.4).
* Bootstrap resampling (B = 1000): The leading alternatives under both TOPSIS and VIKOR maintained the top three statuses in more than 90% of the samples, demonstrating the strong resilience of our findings.

## Synthesis and Expert Recommendation

Bringing these threads together, we offer a nuanced, actionable recommendation:

* Primary Recommendation: For stakeholders aiming to maximize aggregate performance across all criteria, kidney beans stand out as the optimal crop choice.
* Alternative Recommendation: For those who prioritize minimizing any single shortfall, such as smallholder farmers facing uncertain conditions, Papaya provides a safer, more balanced option.

By presenting both recommendations, we empower decision-makers to align crop selection with their strategic priorities, whether in terms of overall efficiency or risk mitigation.

# Discussion

In this section, we delve into the meaning behind our numerical findings, explore their practical significance for diverse agricultural stakeholders, relate them to the literature, and identify both the strengths and limitations of our approach, ultimately charting a path for future work.

## Integrative Interpretation of Divergent Recommendations

Our dual-analysis framework TOPSIS for ideal-point proximity and VIKOR for regret-averse compromise yielded two distinct “winners”: kidney beans under TOPSIS and papaya under VIKOR. Rather than presenting this as a contradiction, we interpret it as a complementary insight:

* **Kidney Beans (TOPSIS):** In terms of aggregate performance, kidney beans closely match the ideal combination of soil nutrients and environmental conditions. Their high relative-closeness scores indicate that, on average, they meet multiple criteria exceptionally well.
* **Papaya (VIKOR):** Distinguished by its balanced profile, Papaya minimizes the worst-case deviation on any single criterion. This makes it especially attractive for risk-averse growers who cannot afford significant underperformance in terms of, e.g., rainfall or soil pH.

By presenting both crops side by side, we empower decision-makers to choose according to their strategic priorities, maximizing average yield versus safeguarding against critical weaknesses.

## Practical implications for agricultural stakeholders

Our findings carry clear, actionable implications:

* **Commercial Producers & Cooperatives**: With resources to buffer occasional shortfalls, these actors may lean toward kidney beans to capitalize on their high overall suitability and potential yield gains under typical conditions.
* **Smallholder & Risk-Averse Farmers**: Facing tighter margins and less capacity to absorb failures, these growers stand to benefit from papaya’s resilience, as it delivers consistently acceptable performance across all key parameters.
* **Policy Makers & Extension Services**: Offering both recommendations allows tailored advisory programs promoting kidney beans in regions that target food-security-driven bulk production while encouraging Papaya, where climatic volatility or resource constraints are paramount.

By integrating both TOPSIS and VIKOR within a unified fuzzy logic framework, we bridge aggregate-performance and risk-mitigation paradigms, offering a more holistic decision-support tool.

## Methodological strengths and reflections

Several aspects of our methodology enhance confidence in these recommendations:

* Rigorous Expert Weighting: The fuzzy AHP process, underpinned by a consistency ratio well below 0.10, ensures that criterion weights genuinely reflect agronomic priorities.
* Uncertainty Modeling: Bipolar sigmoid fuzzification captures the inherent variability of field measurements, sharpening the model’s sensitivity to borderline cases.
* Dual-Method MCDM: Employing both distance-based (TOPSIS) and regret-based (VIKOR) techniques provides complementary perspectives, enriching the decision narrative rather than relying on a single ranking.

Moreover, sensitivity tests (±10% weight perturbation) and bootstrap resampling (B = 1000) demonstrated that our top recommendations remain stable under moderate changes, reinforcing their robustness.

## Concluding Insights

By juxtaposing TOPSIS and VIKOR within a fuzzy logic paradigm, our study overcomes the limitations of any single MCDM method. We present a nuanced, human-centered set of recommended kidney beans for those prioritizing overall efficiency and a papaya for those emphasizing risk-averse resilience. This dual-recommendation approach ensures that diverse agricultural stakeholders can align crop selection with their unique goals and constraints, moving the field of precision agriculture toward more flexible, data-driven, and resilient decision-making.

# Conclusion

In this work, we introduced a bipolar fuzzy multicriteria decision-making framework that blends expert-driven fuzzy AHP weighting with two complementary ranking methods, namely, TOPSIS for ideal-point proximity and VIKOR for regret-averse compromise, to support data-informed crop selection under uncertain agroclimatic conditions. Our rigorous analyses yielded two clear, actionable insights:

## Efficiency-focused recommendation

Kidney beans scored highest in TOPSIS, demonstrating exceptional alignment with optimal soil nutrient levels and environmental parameters. Large-scale producers and cooperatives seeking to maximize average yields under typical conditions should consider kidney beans as their primary choice.

## Risk-mitigation recommendation

Papaya emerged as the leading compromise solution in VIKOR, minimizing the worst-case shortfalls across individual criteria. Resource-constrained or risk-averse farmers, particularly those with limited tolerance for underperformance in any single factor, will find papaya a robust and reliable alternative.

Both recommendations remained stable under ±10% perturbations of expert weights and over 1000 bootstrap resamples, underscoring the framework’s resilience to judgment variability and data noise.

By offering a dual-path recommendation, our approach empowers extension agents and policy makers to tailor advisories according to local priorities, be it maximizing aggregate productivity or safeguarding against critical vulnerabilities. This human-centered decision tool facilitates transparent, context-sensitive guidance and bridges the gap between complex MCDM theory and practical agricultural decision-making.

## Limitations and Future Directions

While our framework delivers robust biophysical recommendations, it is currently region-specific and omits economic, market, and sociocultural factors. Future research should:

* Validation and recalibration of the model across diverse agroecological zones.
* Real-time sensor data and temporal dynamics are integrated for adaptive recommendations.
* Incorporate cost–benefit analyses, market pricing, and supply chain considerations.
* Engage end-users directly in a participatory AHP process to refine criterion importance and increase adoption.

Overall, this bipolar fuzzy MCDM methodology represents a significant step toward more resilient, data-driven precision agriculture. By accommodating both efficiency-driven and risk-averse strategies, it lays the groundwork for sustainable crop planning that enhances productivity, reduces vulnerability, and ultimately supports farmer livelihoods.

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