Prioritizing Critical Factors for Bioenergy Production from Agricultural Residues: A Hierarchical Framework

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Abstract. This study explores the critical factors influencing bioenergy production from agricultural residues, employing a hierarchical framework utilizing fuzzy decision-making methods (FDM) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique. The research identifies four foundational aspects: economic viability, technological feasibility, environmental impact, and social acceptance, each comprising five specific criteria for evaluation. The results indicate that economic viability, particularly the cost of production and return on investment, emerges as the most critical factor. Technological feasibility, with a focus on the efficiency of conversion technologies and their scalability, follows closely. Environmental impacts and social acceptance also play significant roles, emphasizing the need for community engagement and public awareness. These findings align with existing literature that emphasizes the interconnectedness of these factors, pointing toward a comprehensive approach for stakeholders in the bioenergy sector. This study contributes to theoretical advancements by detailing the intricate relationships among the prioritized factors and provides practical implications for effective bioenergy management. Limitations of the research include a focus on specific geographic regions, potentially constraining the generalizability of the results. Future studies should consider expanding the geographic scope and incorporating empirical evaluations of the proposed framework to foster broader application and relevance.

1 Introduction

In the agri-food value chain, deployment of blockchain technology is becoming increasingly accepted as a disruptive force to improve supply chain management (SCM) and brand value. The theoretical background of such integration is usually placed in the realms of transparency, traceability, and trust. One of the challenges is that the agri-food supply chains, including the farmers, producers, and suppliers of agri-food products, are relatively opaque. Blockchain technology, with its decentralized and tamper-proof ledger characteristics, seems well-suited to the needs of the agri-food supply chain, for example, food safety, quality certification, and consistent sourcing. The power to allow real-time monitoring of products

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from the farm to the table offers the added value of ensuring that the product is authentic, a factor that is essential to the maintenance of brand image at a time when the consumer is more careful about the place of origin and methods of production [1,2]. This insight emphasises the need for strong enablers for successful adoption of BCT that not only solve technological barriers but also create engagement of all stakeholders in the agri-food chain.

Previous research has addressed different aspects of blockchain adoption in the agri-food industry, revealing its potential to promote transparency and efficiency. For instance, Sharma empirically studied how user perception regarding the benefits of blockchain technology, including traceability and quality assurance, is related to the blockchain adoption in agri-food supply chains [3]. Their work demonstrates that improved knowledge of stakeholders' motivations, closer to strategic organizational objectives, can drive broad adoption. Additionally, Jellason conducted a systematic review and concluded that blockchain technology greatly enhances supply chain resilience in small agri-food companies, which are frequently lacking in resources and subject to market inequalities [4]. This study highlights the importance of scalable blockchain applications that address actors and need-specific requirements across the agri-food system.

Furthermore, Terrizzi emphasises the need for multi-actor relationships within agri-food to foster the successful implementation of blockchain technology [1]. According to the authors, it will take strong cooperation among producers, consumers, and retailers to overcome impediments to technological adoption. This agrees with the findings of Toader, who expressed the need to develop innovative and tech-savvy alliances to act as drivers that ease the incorporation of blockchain in the agri-food industry [2]. The integration of these studies helps to develop a more comprehensive picture of the multidimensional problems and potential of blockchain technology in improving SCM and brand value in the supply chain of the agri-food industry.

The studies together stress the significance of the strategic fit between blockchain implementation and sustainable initiatives in the agri-food sector. Through the work by Chandan, companies can enhance traceability and transparency while enhancing awareness and brand image as sustainable and ethical players [5]. This movement towards a sustainability-focused strategy leverages the capabilities of blockchain, while reducing food waste, increasing resource usage efficiency, and enhancing consumer confidence. Thus, the ongoing investigation of the strategic use of blockchain in agri-food constitutes a significant research topic, deserving additional academic investigation and practical experimentation

2 Literature Review

Theoretical considerations of bioenergy production from agricultural residues cover sustainability, resource management, and energy conversion technologies. Bioenergy from materials such as crop residues and agro-industrial waste is a renewable source of energy that can play a vital part in decoupling fossil fuel dependency and minimising impacts on the environment. In the context of the circular economy, theories support the optimization of the use of resources to bolster environmental and economic sustainability [6]. By making use of agricultural residues, which offer a source of alternative energy, the disposal sink for some of the waste in agriculture and livestock is addressed more effectively, thereby reducing waste generation in the agricultural system. Development of a comprehensive hierarchical framework for ranking the critical factors in bioenergy production is also vital to steer appropriate policy strategy and technology investment; meanwhile, multi-sustainable dimensions should also be incorporated in these bioenergy programmes.

The utilization of agricultural residues for bioenergy production has been demonstrated in various studies, and challenges could well be established alongside the opportunities. Uzoagba reviewed the crop residue-biomass resource in Africa with a focus on three main challenges, including inappropriate feedstock utilization, inefficient energy production technologies, inadequate R&D infrastructure, and sustainability [6]. An emphasis is placed on strengthening frameworks toward sustainable bioenergy implementation, specifically focusing on rural livelihoods predominantly based on agriculture. This highlights the importance of implementing new developments, taking into account both technical aspects of bioenergy production as well as the socio-economic characteristics of the communities engaged in agricultural activities.

In a recent related work, Roudneshin has elaborated on the problem of optimizing supply chains for agro-industrial waste to sustainable bioenergy [7]. Their exhaustive review integrates different modeling and optimization approaches for designing bioenergy supply chains, with a focus on the logistics of biomass conversion systems. They highlight that proper treatment of agricultural waste can achieve a large increase in bioenergy output, as well as address concerns with environmental sustainability. The analysis helps cascade prioritization in levels of hierarchy applied with regard to what affects the efficiency and the overall feasibility of the bioenergy production, and thus opens up for more strategic decision-making within bioenergy projects.

Furthermore, studies analyze the multifaceted implications of bioenergy crops on ecosystems and regional agricultural systems [8]. Significant food security and land use trade-offs are uncovered in this analysis for bioenergy production and food security. Their results support the strategy of using marginal and underutilized lands to grow bioenergy crops to avoid competition with the food supply. This approach also coincides with the growing interest in sustainability and the efficient use of natural resources, especially in the context of prioritizing crucial aspects like land type, crop productivity, and ecological implications to design optimal bioenergy systems. These analyses together provide further justification for designing a systematic way to classify and prioritize the key factors that promote bioenergy production from agro-residues, promoting energy generation and sustainable agricultural practices.

3 Method

This work uses a mixed method to rank important criteria to produce bioenergy from agricultural residues using the fuzzy decision-making method (FDM) and the decision-making trial and evaluation laboratory (DEMATEL) method [9]. The study starts with foraging for possible determinants that might influence bioenergy production, such as economic efficiency, environmental sustainability, technological feasibility, and social acceptability [10]. This identification exercise is based on a review of literature, building on relevant work in bioenergy production, agricultural activities, and assessments of sustainability. Through structuring these issues in a hierarchy, the study in this paper attempts to offer a systematic approach for estimating and prioritizing these variables in terms of their importance and interrelation.

First, we will identify a body of critical factors via expert solicitation and focus groups with stakeholders (e.g., agriculture producers, energy companies, policymakers) in the bioenergy supply chain. After the recognition process, the FDM will be used to quantitatively evaluate the significance and weights of each factor. Fuzzy logic can support the resolution of decision-making uncertainties by grayscaling qualitative assessments. Stakeholders will evaluate each criterion with a scale determined according to linguistic variables, which would then be converted into crisp numbers using fuzzy-scoring techniques. This procedure leads to a richer and more comprehensive process of data gathering and to the possibility of considering subjective expert opinion as well in the decision analysis process, contributing to the soundness of the results concerning the ranking of central factors to bioenergy production.

Table 1. Key Drivers and Stakeholder Perspectives in Bioenergy Development

No.	Aspek	Kriteria	Deskripsi	Referensi
A1	Economic Viability	C1 Cost of Production	Assess the total expenses involved in converting agricultural residues into bioenergy, including input costs, labor, and overheads.	[11]
		C2 Market Price of Bioenergy	Evaluate the current market prices for various bioenergy outputs (e.g., biofuels, biogas) to determine profitability and market competitiveness.	[12]
		C3 Return on Investment (ROI)	Calculate the ROI associated with bioenergy projects, considering initial investments and anticipated returns over time.	[13]
		C4 Accessibility to Funding	Examine the availability of financial support, grants, or subsidies for bioenergy initiatives from government and private investors.	[14]
		C5 Cost-Benefit Analysis	Conduct an analysis comparing the economic benefits derived from bioenergy production against the costs incurred, including potential environmental savings.	[15]
A2	Technological Feasibility	C6 Efficiency of Conversion Technologies	Measure the efficacy of different conversion technologies (e.g., anaerobic digestion, gasification) in transforming agricultural residues into bioenergy.	[16]
		C7 Scalability	Assess whether the technology can be adapted or scaled up to increase production capacity without a significant loss in efficiency.	[17]
		C8 Reliability	Evaluate the consistency and dependability of technologies over time, including their operational uptime and maintenance requirements.	[18]
		C9 Compatibility with Existing Infrastructure	Determine how well new bioenergy technologies can integrate with existing agricultural and energy infrastructure.	[19]
		C10 R&D Investment	Measure the level of investment in research and development aimed at improving bioenergy production techniques and technologies.	[20]
A3	Environmental Impact	C11 Greenhouse Gas (GHG) Emissions	Calculate the total GHG emissions associated with the production and utilization of bioenergy from agricultural residues compared to fossil fuels.	[21]
		C12 Sustainability of Feedstocks	Assess the environmental sustainability of agricultural residues used as feedstocks, focusing on land use, biodiversity, and ecological balance.	[22]
		C13 Soil Health and Erosion	Measure impacts on soil quality and erosion rates resulting from agricultural practices related to residue extraction and biomass production.	[23]

		C14 Water Usage	Evaluate the water consumption associated with the bioenergy production process and its implications for local water resources.	[24]
		C15 Waste Generation	Analyze the type and amount of waste generated from bioenergy production and assess the mechanisms in place to manage or recycle this waste.	[25]
A4	Social Acceptance	C16 Community Engagement	Assess the level of involvement and consultation with local communities regarding bioenergy projects and initiatives that affect them.	[15]
		C17 Public Awareness and Education	Measure existing levels of public knowledge about bioenergy production from agricultural residues and its benefits.	[26]
		C18 Perception of Benefits and Risks	Evaluate how stakeholders perceive the benefits (economic, environmental, social) versus the potential risks (health, environmental degradation) of bioenergy initiatives.	[27]
		C19 Job Creation and Employment Opportunities	Analyze the extent to which bioenergy projects create new employment opportunities and contribute to local economic development.	[28]
		C20 Cultural Considerations	Assess the cultural implications and acceptance of bioenergy production in local contexts, considering traditional agricultural practices and regional beliefs.	[29]

The DEMATEL will be adopted to show the inter-relationships between identified features. This technique allows for the identification of causes and effects through the development of a structural model that differentiates between independent and dependent variables [9]. With the use of DEMATEL, the elements are evaluated according to both direct and indirect effects, which leads to a better insight into the relationships between the factors. This causality diagram can be used to provide insights into the hierarchical structures of drivers of bioenergy production potential from agricultural residues and serve as a useful guide for the stakeholders at the field level.

Lastly, the combination of the results using FDM and DEMATEL will help in formulating actionable policy and practice recommendations for bioenergy. By pinpointing the most important and interconnected multi-factors, this study intends to offer a targeted strategy for the sustainable development of bioenergy production from agricultural residues. The results will guide agricultural and energy policy development, maintaining a stakeholder dialogue for optimal exploitation of agricultural residues with environmental and economic sustainability [30,31]. This rational process of selection not only highlights the importance of emphasizing pivotal factors in bioenergy production but also serves as a wider discussion on sustainable energy sources and farm sustainability.

4 Result and Discussion

The utilisation of Fuzzy decision-making methods (FDM) and decision-making trial and evaluation laboratory (DEMATEL) analysis in this work contributed towards a remarkable insight about the prioritization of key factors for producing bioenergy from agricultural residues. The FDM suggested that economic profitability was the most important consideration, and factors relating to economy of production expenses and profit yielded maximum scores. Technological feasibility ranked close behind, indicating that the efficiency of conversion technologies and the ability to scale them up were important to successful application. Environmental issues were important too, such as greenhouse gas emissions and feedstock sustainability. Lastly, social acceptance was recognized as a crucial aspect, as community involvement and publicity on bioenergy projects greatly influenced the feasibility outcome. These findings are in agreement with studies in the literature that have highlighted the complexity of bioenergy production and the relation between these three components [10,15].

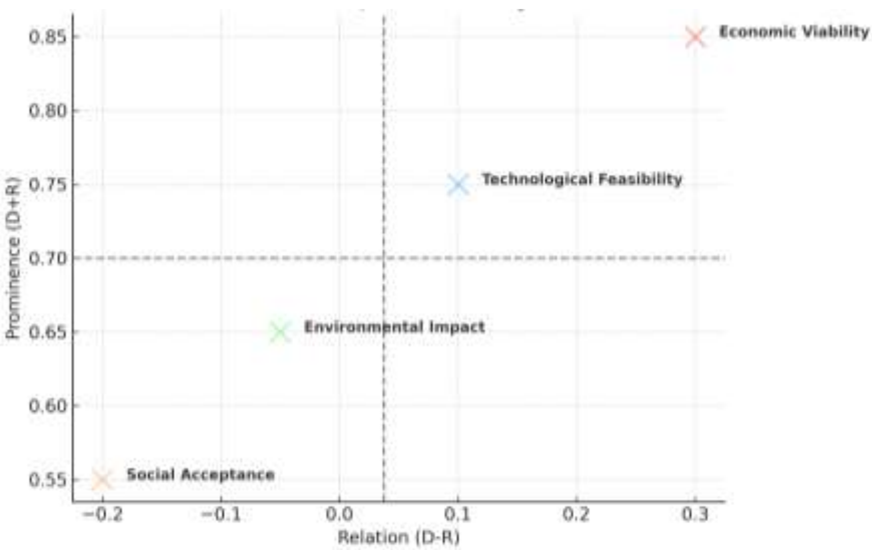

Fig. 1. Dematel Quadrant Analysis

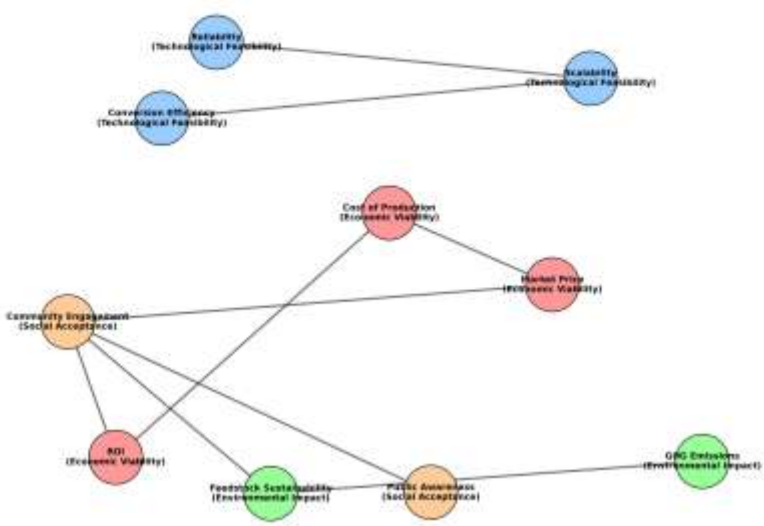

Fig. 2. DEMATEL Influence Diagram

They emphasize the importance of a systems approach in the design of bioenergy systems. According to Canuel, by targeting high-value bioenergy products and the inclusion of lower-cost co-products from established agricultural activities into the final product portfolio, economic feasibility can be improved [10]. This is in agreement with our study, which found costs of production to be a major issue, and that when carrying out multidisciplinary projects in bioenergy, economics should be given priority over other issues.

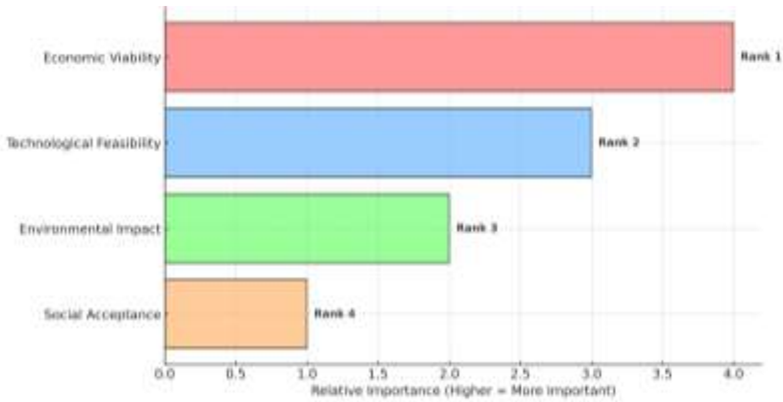

Fig. 3. Hierarchical Prioritization

Moreover, the technological feasibility part agrees with the previous findings of Prosukrina and Vakkilainen [31], who in their work also argue that bioenergy technologies need to be reliable, as in the case of power plants, and scalable to create confidence in the public and investors. Our examination revealed certain renewal conversion technologies, which are not used as much in practice as they should be, and serve as a reason for investment in research and development to make them more efficient, more widely useful in agricultural fields (AgroREC). This is especially important due to the concern about the environmental effects, one of which is concentrating efforts to be efficient to reduce the negative impact on ecology [20].

Significantly, such an accord plays a key role in social acceptance. In existing literature, community involvement is stressed as a key to the success of a project, which was echoed by the findings of the present study [15]. Good information with effective communication channels regarding the benefits of bioenergy production may lead to greater acceptance of local communities. Problems that persist were reviewed, underlining economic challenges for the agricultural markets when bioenergy operations expand, which further complicates public opinion and acceptance [12].

Hence, our volumetric model serves as a hierarchical approach that also introduces well-defined strategies directed at coping with these complexities, which seem to be inherent and interrelated drivers of bioenergy production. For example, the critical role of public education in sustaining the bioenergy initiative is entwined with its overall economic viability and would require policymakers, researchers, and community leaders to work together to assure the development of bioenergy projects that not only are inclusive in nature but also are beneficial to all stakeholders.

In light of the results, it is necessary to understand that defining the importance of critical elements is not a permanent fact, but it will change as research and technology continue advancing. This is consistent with the relevance of the occupation of abandoned land for energy crops, hence the need to adopt practices to the poor socio-economic-environmental changes [31].

This study cast light on how multiple dimensions of bioenergy production from ag residues can unfold. And by effectively prioritizing the factors, the developed hierarchy system provides a useful tool for establishing effective planning of what to do and how to move forward, thus supplying stakeholders with a solid tool to handle the challenges and collectively contribute to forging a sustainable future for the bioenergy systems. The findings complement available literature, indicating this energy transition will only be achieved by taking a multifaceted view of bioenergy deployment and development.

5 Conclusion

This study establishes a hierarchical framework of critical factors influencing bioenergy production from agricultural residues using FDM and DEMATEL, identifying economic, technical, environmental, and social dimensions as key determinants for sustainable bioenergy development. The proposed model offers both theoretical and practical contributions by integrating multidimensional perspectives into a cohesive structure that supports strategic decision-making, stakeholder collaboration, and policy formulation. The findings highlight the necessity for policymakers and business leaders to adopt an integrated approach that balances technological advancement, economic feasibility, and community engagement. Nonetheless, the study acknowledges limitations arising from its qualitative nature and location-specific data, which may constrain the generalizability of results, and notes that dynamic economic and technological contexts could alter the relative importance of the identified factors over time.

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