Integrating Multidimensional Scaling and MICMAC-Based Structural Analysis for Assessing Sustainability and Key Drivers of Cassava Waste Management Systems

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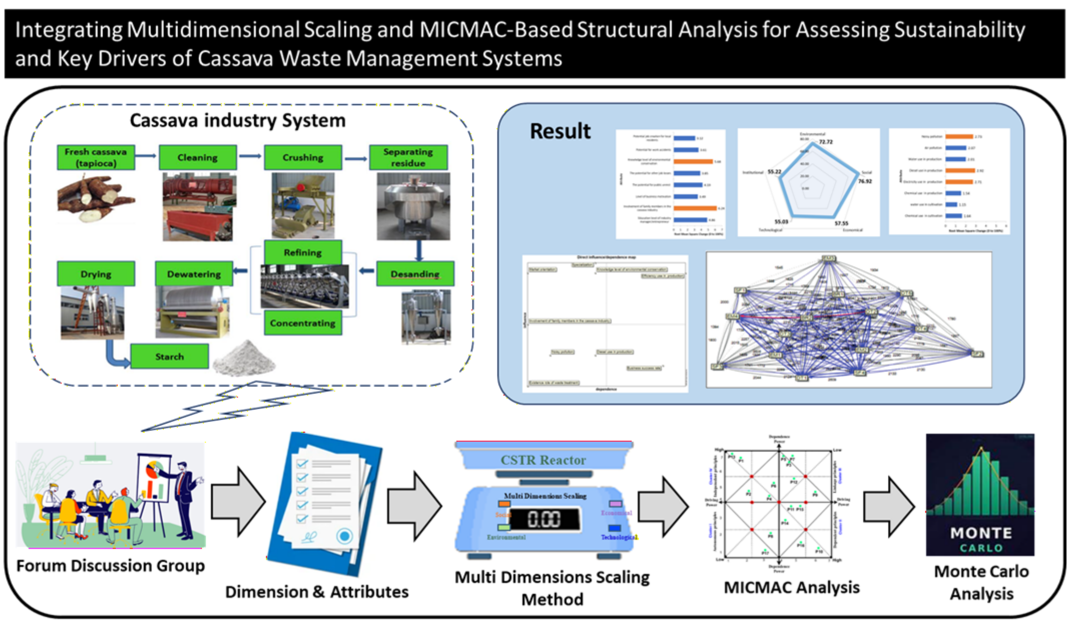
GRAPHICAL ABSTRACT



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Developing sustainable regional agro-industrial practices is essential for countries like Indonesia. Cassava (*Manihot esculenta* Crantz), significant for food security and commercial use, continues to demonstrate productivity levels beneath worldwide benchmarks. This research assesses the sustainability of Lampung's cassava agro-industry by integrating Multidimensional Scaling (MDS) and Cross-Impact Matrix Multiplication Applied for Classification (MICMAC). MDS generates a sustainability index including ecological, economic, social, technological, and institutional dimensions. MICMAC analysis determines causal interdependencies among attributes and categorizes them based on driving power and dependence. Data obtained from expert questionnaires and focus group discussions conducted between January and March 2024 indicated a moderate sustainability index of 63.5%. The environmental dimension achieved the highest score of 72.7%, while the technological and institutional dimensions obtained the lowest at 55.03% and 55.2% respectively. The main variables influencing sustainability consist of energy efficiency, waste management, market orientation, and the skill levels of the workforce. The combination of MDS and MICMAC offers an extensive diagnostic and structural perspective. This study proposes recommendations for energy schemes, the development of managerial training programs, and the strengthening of institutional policies. The insights have significance for the development of the cassava agro-industry in Lampung and comparable regions.

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Keywords: Cassava agro-industry; Smallholder industry; Sustainability index assessment; Multidimensional scaling (MDS)

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INTRODUCTION

Regional potential-based agro-industry development is a crucial industrialization strategy for developing countries, including Indonesia (Meyer and Neethling 2016). Among the agro-industrial commodities with significant food and energy crop development are cassava, maize, rice, wheat, and potato (Food and Agriculture Organization of the United Nations 2018). Cassava (*Manihot esculenta* Crantz) is particularly noteworthy as a major food crop in the tropics, including Indonesia, due to its ease of cultivation and its role in addressing food security issues (Yenugula *et al.* 2023). Despite its importance, Indonesia's domestic cassava productivity, ranging from 16 to 20 tons per hectare, is inferior to that of countries such as Nigeria, Thailand, and Brazil (Rozi *et al.* 2022). Nevertheless, cassava is an essential crop, with important production hubs located in provinces including Lampung, Central Java, East Java, West Java, and North Sumatera, making substantial contributions to the national yield. Lampung, the focus of this study, produces an average of 7.885 million tons of tapioca annually, accounting for about 36% of Indonesia's total cassava production (Food and Agriculture Organization of the United Nations 2023).

The Indonesian government has recognized the importance of cassava and aims to boost its production by expanding cultivation areas by 4% to 607 hectares by 2024, which is expected to increase cassava output 26.6 t ha^{-1} (Food and Agriculture Organization of the United Nations 2018). The adaptability of cassava transcends food security, functioning as a raw material for numerous industrial applications. Tapioca, derived from cassava, is used in the food industry as a thickening agent, filler, and binder (Macdalyna *et al*. 2025). It can be processed into several derivative products such as glucose syrup (Morales *et al.* 2008), lactic acid (Wang *et al.* 2010), acetone, butanol, ethanol (Li *et al.* 2014), bioethanol (Wangpor *et al.* 2017), bio-nanocomposite (Campos *et al.* 2017), bioplastic (Wahyuningtyas and Suryanto 2017), edible film (Mantovan *et al.* 2018), and dextrin (Trithavisup *et al.* 2019). These derivatives support various industries, including the pharmaceutical, confectionery, fermentation, textile, and food and beverage industries.

However, there are obstacles to the growth of the tapioca agro-industry. Production, market, institutional, human resources, and environmental risks are among the inherent risks that make it difficult to obtain financing (Hardaker *et al.* 2015). The industry in Indonesia is predominantly composed of small-scale operations that rely on simple machinery and labor-intensive processes (Banowati *et al.* 2018). These small industries are vital but produce significant waste, including solid, liquid, and gaseous wastes, which pose environmental challenges (Setyawaty *et al.* 2011). Liquid waste contributes to environmental pollution due to its high organic material content and potential methane emissions (Kamahara *et al.* 2010).

Implementing sustainability principles into the agricultural industry is essential to maintaining high competitiveness and supporting sustainable economic growth. Sustainable agriculture seeks to address current and future human needs while enhancing environmental quality, conserving natural resources, and promoting technological and institutional improvements (Mockshell and Kamanda 2018). Sustainability includes three interdependent dimensions: economic, social and ecological (Idowu *et al.* 2023). Evaluating the sustainability status of agro-industries helps policymakers and stakeholders to make informed decisions that promote sustainable development.

A useful method for assessing sustainability is MDS. This was initially implemented for fisheries sustainability assessment but is now used across other sectors, including agriculture (Muhsoni *et al.* 2021). Studies have utilized MDS to determine sustainability indices for agricultural products including algal biomass (Santoso *et al.* 2023c), duck farming (Rohaeni *et al.* 2021), garlic (Pączka *et al.* 2021), chocolate (Fairuzia *et al.* 2020), compost (Santoso *et al.* 2023a), corn (Ariningsih *et al.* 2021), chili (Mailena *et al.* 2021), beef (Rohaeni *et al.* 2024), dairy (Lovarelli *et al.* 2020), buffalo (Rohaeni *et al.* 2023), shrimp (Sivaraman *et al.* 2019), coffee (Yusuf *et al.* 2022), rice (Rachman *et al.* 2022), sago (Allaily *et al.* 2024), black soldier fly (Santoso *et al.* 2023b), coconut sugar (Handayani *et al.* 2025), integrated farming (Widjaja *et al.* 2024), waste management (Ismail *et al.* 2025), and landslide management (Sittadewi *et al.* 2025).

The cassava agro-industry in Indonesia, particularly in Lampung, is at a critical juncture where sustainability practices must be integrated into its development to ensure long-term viability and competitiveness. Given the widespread use of cassava in various industrial forms, it is important to clarify the terminology used in this study. In this study, the term "cassava" refers to the broader agro-industrial system based on *Manihot esculenta* Crantz, while "tapioca" specifically denotes the starch product derived from cassava roots. The focus on tapioca processing reflects its dominance in industrial cassava utilization in Lampung Province, particularly in relation to waste generation and management practices. Therefore, while the analysis is framed at the cassava system level, several discussions emphasize tapioca processing as the primary source of industrial waste. While previous studies have highlighted the significance of cassava as a staple food and industrial raw material, there is a pressing need to explore innovative strategies that not only enhance productivity but also minimize environmental impact and promote socio-economic development. This study takes a novel approach by applying a MDS methodology, which has primarily been used in fisheries and other agricultural sectors, to assess the sustainability of the cassava industry. This would fill a gap in existing literature, particularly in the context of developing countries where the cassava industry plays a crucial role in food security and rural livelihoods.

Moreover, this study advances the discourse on agro-industrial sustainability by integrating technological and institutional dimensions into the MDS framework, offering a comprehensive evaluation that transcends traditional economic and environmental assessments. The introduction of these dimensions allows for a more holistic understanding of the factors influencing sustainability, particularly in smallholder-dominated industries like cassava processing, where access to technology and institutional support is often limited. This expanded scope of analysis not only provides valuable insights for policymakers in Indonesia but also contributes to the global dialogue on sustainable agricultural practices, offering a model that can be adapted to other regions and crops.

In addition to MDS, the present study incorporates the MICMAC method to strengthen the analysis. While MDS effectively determines the sustainability index and highlights sensitive attributes, it does not explicitly reveal the structural interdependencies among factors. MICMAC addresses this gap by classifying variables based on their influence and dependence, this identifies determinant drivers and dependent outcomes within the system (Yenugula *et al.* 2023). This structural mapping facilitates the reduction of complexity, enabling the prioritization of key variables that serve as leverage points for intervention and policy formulation. Recent studies have demonstrated the relevance of MICMAC in sustainability research (Venegas *et al.* 2022). MICMAC was applied to examine critical drivers of municipal solid waste management (Rachman *et al.* 2022; Bakrie *et al.* 2023) and combined MDS and MICMAC to identify critical drivers of circular food systems. These applications highlight MICMAC's utility in transforming diverse attributes into actionable strategies, making it a valuable complement to MDS in the present research.

This study aimed to assess the sustainability state of the cassava sector by integrating MICMAC with MDS and to investigate the underlying causal architecture of the system. The combination of both methods enhances the robustness of the analysis, supports the formulation of targeted policy interventions and provides a strategic roadmap for promoting sustainable cassava agro-industry development in Indonesia.

EXPERIMENTAL

Location of Study

The study was conducted in Lampung from January to March 2024, as shown in Fig. 1. Focus group discussions (FGDs) included Lampung entrepreneurs and experts from several cassava businesses (Table 1). The expert panel was selected using a purposive sampling approach to ensure adequate representation of the cassava waste management system. A total of 17 experts participated, representing key stakeholders across the value chain, including solid and wastewater management, cassava factory workers, industry practitioners, environmental specialists, policymakers, and technical experts. All respondents had a minimum of five years of relevant professional experience and demonstrated expertise not only in waste management practices but also in broader aspects of sustainable cassava agro-industry systems. This composition ensures both structural and functional representativeness of the evaluated system, consistent with established practices in Rapfish-based MDS analysis. Focus groups were used to investigate the conditions of business stakeholders and the support for industry resources in the research area to determine dimensions and permanent attributes.

Characteristics of the Indonesian Cassava Industry

The cassava industry in Indonesia encompasses various downstream products, with tapioca starch representing one of the most dominant industrial outputs. In Lampung Province, the tapioca industry exhibits a clear division into three distinct production scales: small-scale, large-scale, and super large-scale industries. These categories are distinguished by their respective production capacities, technological sophistication, and resource utilization, each of which has considerable implications for both productivity and environmental management.

Production Scale and Technology

Small-scale tapioca industries, which typically process less than 80 tons of cassava roots per day, rely on traditional processing technologies. These industries utilize simple machines and equipment, particularly in the purification and sedimentation stages, where natural sedimentation processes are employed. In contrast, large-scale industries, processing between 600 to 800 tons of raw materials daily and super large-scale industries handling up to 1,800 tons per day are characterized by using advanced process technologies. These include centrifugal separators for sedimentation and complex drying systems, as well as sophisticated waste treatment installations. The difference in technological sophistication not only enhances the efficiency of large-scale operations but also allows for better waste management and energy use optimization. Details of the differences between small and large-scale tapioca industries, related to the number of raw materials, energy, and waste are presented in Table 1.

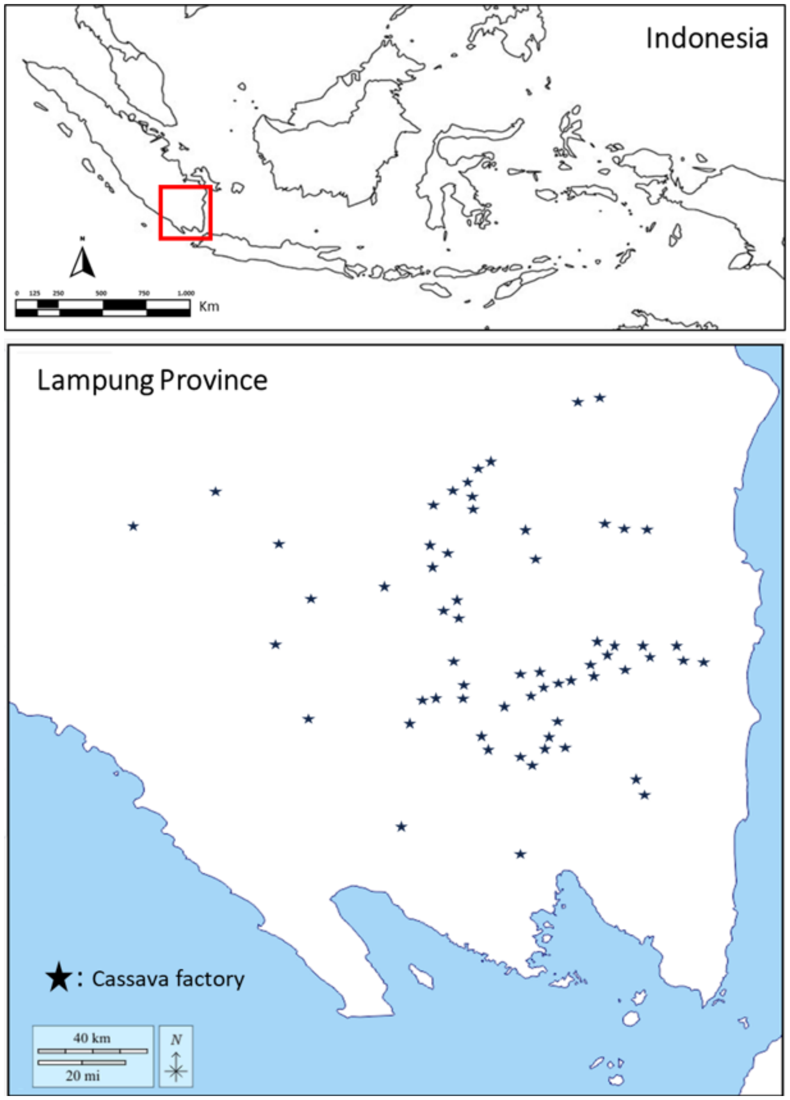

Fig. 1. Map of the study area showing the distribution of cassava processing industries in Lampung

Table 1. Differences Between Small, Large, and Super-large Tapioca Industries, Related to the Number of Raw Materials, Energy, and Waste

Criteria	Tapioca Industry Scale		
	Small	**Large**	**Super Large**
Cassava root consumption (ton/day)	< 80	600 to 800	1,800
Tapioca production (ton/day)	20.5	150 to 190	450
Water consumption (m^3/day)	400	2,640 to 3,420	7,713
Water index (m^3/ton tapioca)	19.5	17.6 to 19.7	17.1
Energy source	Grid	Grid and self	Grid and self
Energy consumption (kWh)	NA	193.5 to 207.4	NA
Wastewater production (m^3/ton)	4.94	2.82 to 4.54	3.17

Resources Utilization and Waste Management

The resource consumption patterns of the tapioca industry vary significantly with the scale of operation. For instance, while small-scale industries consume approximately 400 m^3 of water per day, large, and super large-scale industries require 2,640 to 3,420 m^3/day and 7,713 m^3/day, respectively. The water index indicating water use per ton of tapioca also varies slightly across scales, with super large industries demonstrating a marginally more efficient water use at 17.1 m^3/ton compared to small-scale industries at 19.5 m^3/ton. Energy consumption follows a similar pattern, with larger industries relying on a combination of grid electricity and self-generated energy, while small-scale industries' data on energy consumption remain less documented.

Waste management, particularly the handling of wastewater, is one of the most critical challenges facing the tapioca industry. The production of large volumes of wastewater, which in small-scale operations reach about 4.94 m^3/day, poses significant environmental risks due to the high organic load and potential for water pollution. This problem is exacerbated in larger operations where even more substantial volumes of wastewater are generated. Despite the availability of modern waste treatment facilities in large-scale industries, suboptimal waste management practices are still prevalent, leading to the discharge of untreated or partially treated wastewater into water bodies. This not only contributes to environmental degradation but also represents a missed opportunity for resource recovery and reuse (Kamahara *et al.* 2010; Olukanni and Olatunji 2018).

Productivity and operational challenges

Productivity challenges in the tapioca industry are associated in a complex manner with the management of production resources such as labor, raw materials, machinery, and energy. Small-scale operations frequently depend on manual labor and conventional machinery, which can cause inefficiencies in production planning and control, which ultimately contribute to reducing productivity levels. Large-scale industries, despite leveraging advanced technologies, encounter challenges in optimizing production processes and managing resources effectively. The incorporation of contemporary process control systems and the implementation of optimal resource management practices are crucial for improving productivity in tapioca production at all levels (Hardaker *et al.* 2015; Rozi *et al.* 2022). Table 2 presents the differences between the cassava factory and total production in Lampung Province compared to other provinces (Food and Agriculture Organization of the United Nations 2023; Ministry of Agriculture (MoA) 2023).

Table 2. Cassava Factory and Total Production in Lampung Province and Other Provinces

Province	Tapioca Production (Million Ton)						Average	%
	2017	2018	2019	2020	2021	2022		
Lampung	5.45	5.01	5.44	5.82	5.64	5.95	5.55	39.74
Centre Java	3.14	2.54	2.88	3.26	2.86	2.49	2.86	16.58
East Java	2.91	2.24	1.89	1.55	1.62	1.43	1.94	9.58
West Java	1.90	1.59	1.58	1.31	1.29	1.03	1.45	6.91
Yogyakarta	1.03	0.85	0.76	0.76	0.76	0.81	0.83	5.43
North Sumatera	0.98	0.89	1.22	1.09	1.06	0.87	1.02	5.87
Other province	3.65	3.01	2.58	2.48	3.5	2.4	2.94	15.89
Indonesia	19.05	16.12	16.35	16.27	16.73	14.98	16.58	100

The tapioca business is afflicted with low production and ineffective waste management. Problems with productivity include planning, controlling, and managing the resources needed for production, such as labor, raw materials, machines, work methods, energy resources, and capital. Problems with waste include liquid waste that is still being discharged into rivers.

Data Interpretation

The focus group discussion was held to determine the current conditions of business players and support for the management of cassava industry resources at the research site, which will be used to develop dimensions and sustainability attributes. There are five dimensions, which are constructed by 37 attributes in Table 3: environment/ecology, economics, social, technology, and institutional dimensions.

Table 3. Dimensions and Attributes for the Rap-Cassava

Dimensions	Attributes
Environment/Ecology	1. Chemical use in cultivation
	2. Water use in cultivation
	3. Chemical use in production
	4. Electricity use in production
	5. Diesel use in production
	6. Water use in production
	7. Air pollution
	8. Noise pollution
Economy	9. Productivity
	10. Management level
	11. Business success rate
	12. Welfare of managers/workers
	13. Availability of raw materials
	14. Profit margin
	15. Salary
	16. Market orientation
	17. Market demand
Social	18. Education level of industry manager/entrepreneur
	19. Involvement of family members in the cassava industry
	20. Level of business motivation
	21. The potential for public unrest
	22. The potential for other job losses
	23. Knowledge level of environmental conservation
	24. Potential for work accidents
	25. Potential job creation for local residents
Technology	26. The level of adoption of production system
	27. Specialization/expertise/skills required
	28. Facilities and infrastructure
	29. Increasing technology/cultivation methods
	30. Level of method sensitivity to the quality and quantity
Institutional	31. Existence of corporation
	32. Existence role of waste treatment
	33. Stakeholder support
	34. Existence of entrepreneurs' community
	35. Availability of finance agency
	36. Support from research agency
	37. Compliance with existing regulations

The MDS Rap-Cassava, an adaptation of the Rapid Appraisal (Rap) technique, was used to analyze the questionnaire data. The Rapid Appraisal technique is a multidimensional assessment approach designed to evaluate the sustainability of complex systems in a rapid and systematic manner using limited but representative data. Rapfish (Rapid Appraisal for Fisheries) applies MDS to integrate multiple sustainability attributes and generate a sustainability index. In this study, the Rapfish framework was adapted into Rap-Cassava to determine sustainability status and identify leverage attributes of the tapioca industry ((Lloyd Chrispin *et al.* 2022).

These include a) selecting attributes for the assessment of sustainability status and leveraged attributes of tapioca industry technology referring to good benchmarks, b) assessing attributes on an ordinal scale referring to each dimension sustainability criteria, and c) compiling an index of sustainability status and leverage attributes of tapioca industry. Furthermore, analysis results show a) the status or index of each dimension and b) the leverage/sensitive attributes affecting sustainability status of the tapioca industry. The position of sustainability status can be described in vertical and horizontal ordinates and represented by a flat line. The lousy and excellent extreme has index values of 0% and 100%, respectively. Meanwhile, the scale of value in sustainability status index of tapioca industry ranges between 0 to 100%. A sustainability status index value exceeding 50% is interpreted as indicating a sustainable condition, where the index represents the overall level of sustainability derived from the ordination results. Values below this threshold indicate lower levels of sustainability. Sustainability status ordination is an overview of each dimension, referring to the attribute of the dimension. Index value point on the axis (x) reflects sustainability status of tapioca industry technology, and the ordinate (y) shows the variation in scores. This supplements the ordination analysis by testing the normalization of the S-stress value (S) and squared correlation (R^2) of the model. Furthermore, the model is rated good when the S < 0.25% value and R^2 are close to 1. The value of S and the R^2 also determine the need to add attributes and simultaneously reflect the accuracy of the dimensions studied with the actual state. Leverage analysis is used to determine attributes sensitive to sustainability, and analysis selects the attribute with the highest influence on each dimension as a lever factor influencing the value. The most sensitive indicators are indicated by the highest Root Mean Square (RMS) values (Lloyd Chrispin *et al.* 2022). Meanwhile, Monte Carlo analysis examines a) the Influence of attribute scoring errors, b) the effect of scoring variations due to differences of opinion or judgments by experts, c) the stability of MDS analysis process, d) data entry errors or the presence of missing data and e) the high-stress value of MDS analysis results. The system under study is excellent or corresponds to actual conditions when the difference between MDS and Monte Carlo calculation results is less than one. The MDS ordination is represented by a circle with variable values, references, and anchors. The x-axis for Good and Bad has a maximum and minimum value of 100 and 0, while the y-axis for Up and Down is half the maximum and minimum attribute scores of 50 and -50. In MDS method, points are plotted for the distance between objects to become proportional to their similarity. In addition, the ordination technique or distance determination is based on the Euclidian distance in n-space using Eq. 1 (Lloyd Chrispin *et al.* 2022):

$$d = \sqrt{(|x_1 - x_2|^2 + |y_1 - y_2|^2 + |z_1 - x_2|^2 + \cdots)} \tag{1}$$

Configurations of objects or points in MDS are approximated by regressing Euclidian distance (d_{ij}) from point i to j with point of origin (o_{ij}) using Eq. 2 (Lloyd Chrispin *et al.* 2022):

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \tag{2}$$

The ALSCAL algorithm is used for regression in the equation, and the method optimizes squared distance (d_{ij}) against data (o_{ij}), which in three dimensions (i, j, and k) are recognized as S-stress using Eq. 3 (Lloyd Chrispin *et al.* 2022):

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \tag{3}$$

The Euclidian distance is given a value using Eq. 4 (Lloyd Chrispin *et al.* 2022):

$$d_{ijk} = \sum_{a=1}^{r} w_{ka}\left(x_{ia} - x_{ja}\right)^2 \tag{4}$$

The levels of sustainability performance are divided into 4 levels, resulting in intervals of 0, 25%, 50%, 75%, and 100%. The assessment categories are as follows: 0.00 to 25, poor category and unsustainable; 25.01 to 50, less category and less sustainable; 50.01 to 75, adequate category, fairly sustainable; and 75.01 to 100, good category, sustainable (Arofi *et al.* 2015). The values of the leverage factors (Table 4) fall within the range of 2 to 8%, indicating a moderate to good impact. If < 2%, the factor is considered not influential. If > 8%, the factor is considered dominant (sustainable) (Pitcher and Preikshot 2001). Table 4 presents the factors that have an impact and are dominant.

Table 4. Parameter Values of the Leverage Factor

No.	Factor Value	Category	Description
1	< 2.0%	Neutral	Not Influential
2	2 - 8%	Influential	Moderate to Good Impact
3	> 8.0%	Significant	Dominant

Utilizing leverage analysis, traits that demonstrate sustainability sensitivity are identified. According to Wadchasit *et al*.(2023) the indicators that exhibit the highest root mean square (RMS) values are those that are the most sensitive. When assessing uncertainty and calculating error in MDS, Monte Carlo analysis is a useful technique. When there is little difference between the MDS value and the equivalent Monte Carlo value, the MDS analysis used to evaluate sustainability is sufficiently accurate to yield a 95% confidence interval.

MICMAC Analysis

To complement the MDS results and further uncover the structural interdependencies among sustainability attributes, this study employed MICMAC analysis. MICMAC is a systematic structural analysis tool designed to classify variables according to their driving power (influence) and dependence. The primary objective of MICMAC is to identify determinant variables that act as a key driver of system dynamics, as well as dependent variables that represent system outcomes (Rozi *et al.* 2022; Food and Agriculture Organization of the United Nations 2023).

MICMAC technique steps:

1. Identification of Attributes: MICMAC used attributes identified by MDS leverage analysis as input variables. These criteria indicated cassava waste management's ecological, economic, social, technological, and institutional sustainability.

2. Expert Questionnaire: A cross-impact matrix was constructed by distributing structured questionnaires to seventeen experts (cassava industry practitioners, environmental specialists, and policy stakeholders). Each attribute was rated on a four-point scale: no influence (0), weak influence (1), moderate influence (2), and high influence (3).
3. Cross-Impact Matrix Construction: A square matrix was constructed to illustrate direct influences across qualities among the gathered responses. Multiplying the matrix iteratively captured indirect influences, creating a stable matrix that reflects direct and indirect interrelations.
4. Variable Classification: Attributes were grouped into four quadrants based on their influence-dependence map position (determinants, relays, dependents, and autonomous variable exist).
5. Interpretation: The analysis demonstrated critical policy intervention leverage points through a structural map. Determinants were systematic improvement aims, whereas dependent variables showed intervention outcomes.

The integration of MICMAC into the methodology ensures that this study not only assessed the sustainability status using MDS but also mapped the causal architecture of the system. This combined approach enhances the robustness of the findings by bridging quantitative index measurement with structural causal analysis, thereby providing a more comprehensive framework for designing sustainable development strategies in the cassava agro-industry in Lampung Province.

RESULTS AND DISCUSSION

Sustainability Status

The results of the MDS analysis for the performance of the cassava industry were 63.49% on a sustainability scale 0 to 100, with $R^2 > 0.90$, indicating that it is quite category and fairly sustainable.

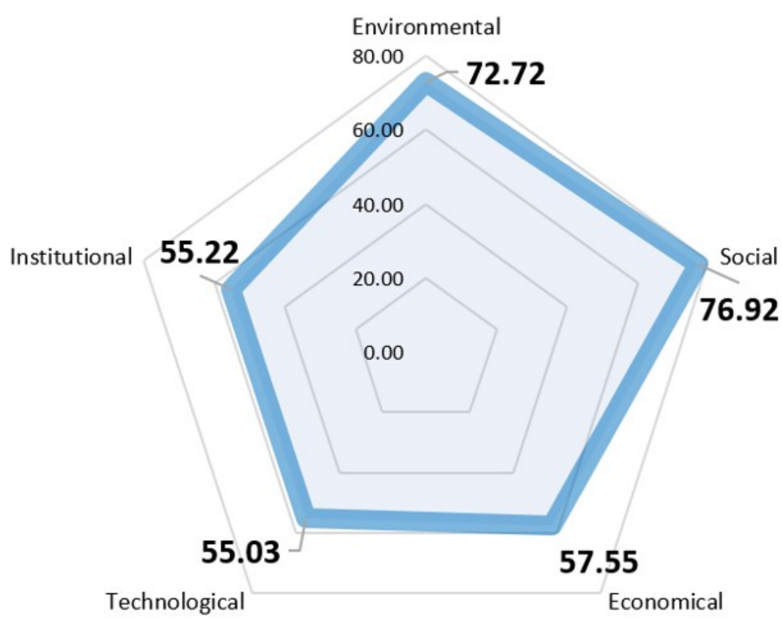

Fig. 2. The sustainability index of environmental, economic, social, technological, and institutional dimensions

This value is the result of an evaluation of 37 attributes covered over five dimensions: environmental, social, economic, technological, and institutional. The environmental dimension has an index value of 72.72%, the social dimension has 76.92%, the economical dimension has 57.55%, the technological dimension has 55.03%, and the institutional dimension has 63.49%. The outcomes of the sustainability analysis are presented in Fig. 2 and Table 5.

Table 5. The Sustainability Index Results for All Dimensions

Dimension	Index (%)	Stress	R^2	Status
Environmental	72.72	0.1338	0.9524	Fairly sustainable
Social	76.92	0.1392	0.9488	Sustainable
Economical	57.55	0.1441	0.9469	Fairly sustainable
Technological	55.03	0.1644	0.9366	Fairly sustainable
Institutional	55.22	0.1633	0.9341	Fairly sustainable
Average	63.49			Fairly sustainable

Environment Dimensions

The environmental sustainability of the cassava industry in Lampung province demonstrates promising outcomes, with a sustainability index value of 72.7% (Table 5). This positive evaluation is attributed to 8 key attributes, each contributing between 1.3% and 4.2% to the overall sustainability (Fig. 3). Notably, the attribute leverage analysis highlights three critical factors: the efficiency of diesel utilization, electricity consumption, and the management of water pollution associated with production processes. In addition, the leverage analysis further identifies noisy pollution, diesel use, and electricity use as dominant attributes, as indicated by their higher RMS values. These attributes reflect key environmental pressures within the production system, where inefficient diesel and electricity use contribute to increased emissions and resource inefficiency, while noise pollution represents an often-overlooked environmental disturbance affecting surrounding communities. Improvements in these areas are therefore expected to directly enhance environmental sustainability by reducing environmental burdens, improving energy efficiency, and promoting more responsible industrial practices. Enhancing the management of these attributes is essential to achieving a higher level of sustainability. While other attributes show a lower influence on the overall sustainability index, they still require careful management to maintain the integrity of the environmental dimension. The findings align with previous research, which underscores energy efficiency as a pivotal issue in improving productivity across cassava industrial activities (Wadchasit *et al.* 2023).

Energy consumption is pervasive throughout cassava production, encompassing stages such as raw material transportation, washing, cutting, grating, filtering, settling, drying, sieving, and packaging. Innovative solutions to substitute conventional energy sources with renewable alternatives are crucial. Utilizing wastewater generated during production as a resource for electricity and biogas is suggested. This strategy is supported by empirical studies (Wattanasilp *et al.* 2021). It was demonstrated that tapioca wastewater could produce 312 Megajoules (MJ) of energy and 30.34 kWh of electricity per ton of cassava (Hasanudin *et al.* 2019). Additionally, wastewater can be repurposed into valuable products, such as the cultivation of *Acetobacter xylinum* bacteria in waste media to produce nata de cassava (Alfarisi *et al.* 2021) and the use of tapioca wastewater to create bio floc as a supplementary food source for aquaculture (Khanjani and Sharifinia 2020).

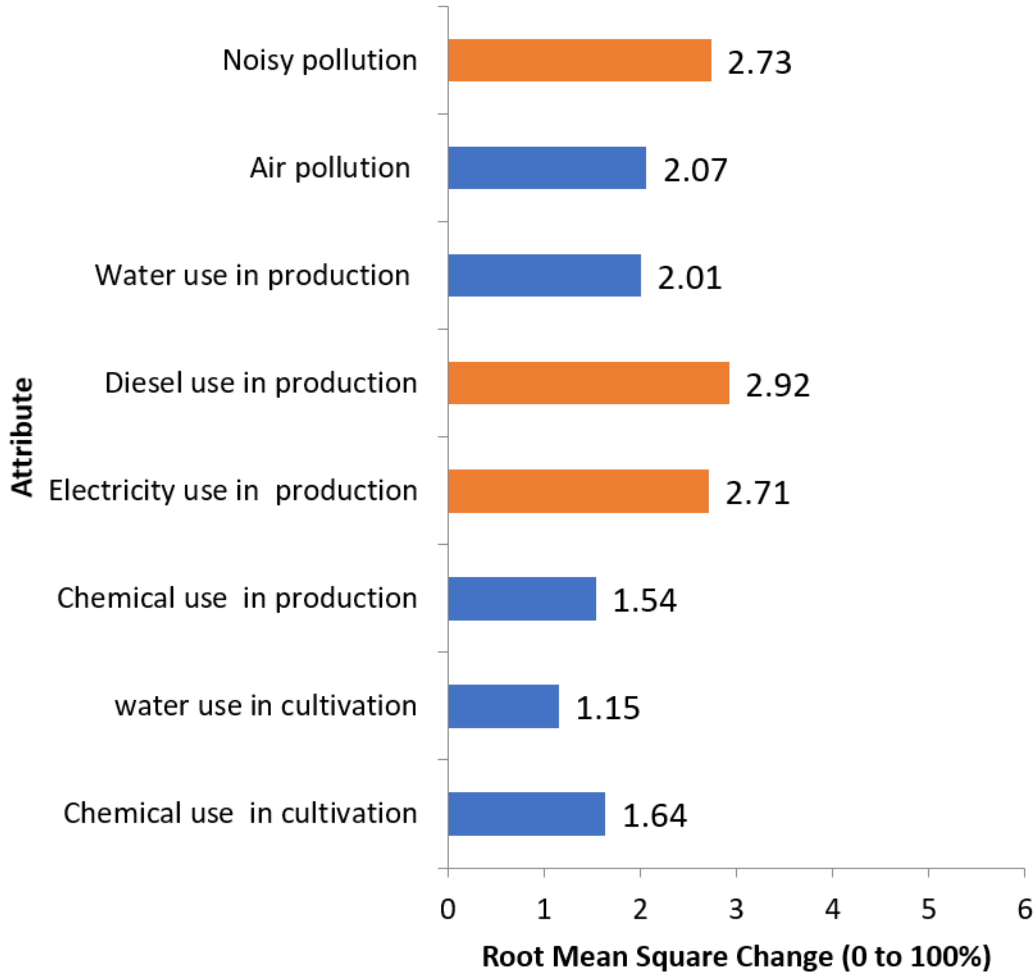

Fig. 2. Leverage of environment attributes

Agricultural wastewater recycling and reuse are essential for environmental sustainability. Effective wastewater management helps fulfil future renewable energy needs, reduce groundwater use, and prevent soil pollution. It is noted that biogas from cassava crop wastewater reduces pollution and provides renewable energy (Achi *et al.* 2020). Thus, energy efficiency, wastewater utilization, and environmental requirements are crucial to Lampung's cassava industry's survival. Ensuring these principles will strengthen the industry's sustainable development and reduce its environmental impact.

The Lampung cassava industry has a 72.7% sustainability index, reflecting promising environmental results. However, further investigation shows that the industry's dependence on old energy sources and insufficient waste management offers major issues. Integrating circular economy principles into cassava production is an innovative approach in this study. The cassava business may reduce its environmental impact by recycling peels and wastewater into biofuel and organic fertilizers. This meets global environmental goals and is scalable for smallholder industries elsewhere. The leverage analysis of important qualities, particularly energy efficiency and waste management, reveals that renewable energy and improved waste treatment technology might improve the industry's sustainability index. These improvements, supported by data from related agro-industries, argue for redefining cassava processing environmental management.

Economic Dimensions

The sustainability index for the economic dimension of the cassava industry in Lampung Province stands at 57.6%, indicating moderate sustainability. Two key attributes, market orientation and business success rate, play an important role in shaping the performance of this dimension. The leverage analysis highlights several dominant attributes with higher RMS values, particularly market orientation, business success rate, and raw material availability (Fig. 4).

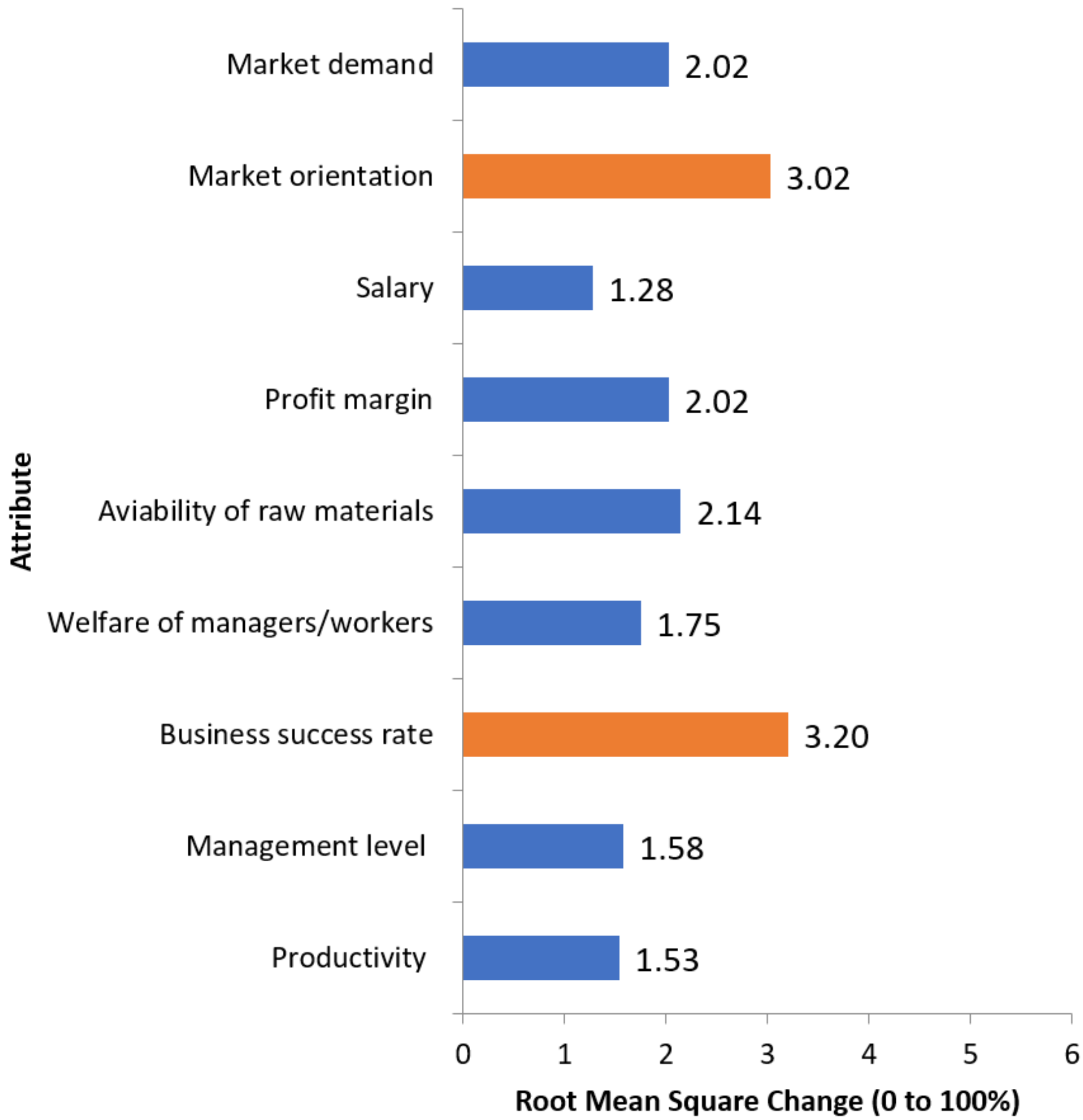

Fig. 3. Leverage of economic attributes

These attributes demonstrate greater sensitivity within the system, indicating that improvements in these areas can more strongly influence the economic sustainability index. Market orientation enhances the ability of enterprises to respond to changing demand and maintain competitiveness, while business success rate reflects the capacity of firms to sustain profitability and long-term operations. Similarly, stable raw material availability supports production continuity and cost efficiency, which are essential for maintaining economic performance. Conversely, weaknesses in these attributes may constrain economic sustainability and reduce the resilience of cassava-based enterprises. Market orientation is essential, since it guarantees that firms stay pertinent and responsive to market demands. Understanding customer preferences and demands for various cassava derivatives such as raw cassava, chips, tapioca, starch, glucose/fructose, and mocaf is essential (Jackson *et al.* 2020). This comprehension allows businesses to tailor their products and services effectively, thereby enhancing customer satisfaction and loyalty. Market-oriented businesses are more attuned to changes in consumer trends, enabling them to adapt swiftly to market dynamics and maintain product relevance (Varadarajan 2020).

Innovation driven by market understanding results in products that align closely with consumer needs, providing a competitive edge. Businesses with profound market orientation can devise more effective marketing strategies, including pricing, promotion, and distribution, aligning them with market preferences (Lee *et al.* 2015). Emphasizing customer feedback facilitates continuous product development and refinement, fostering customer loyalty and satisfaction (Unteawati *et al.* 2018). Consequently, businesses can maintain a competitive position and respond proactively to market shifts.

The business success rate, another critical attribute, reflects the cassava industry's ability to endure and thrive in the long term. A high success rate indicates profitability and a stable income stream, crucial for daily operations and future growth investments (Manganyi *et al.* 2023). Businesses with consistent success are more likely to attract investment and stakeholder support, essential for obtaining additional capital for innovation and development (Kulkarni 2024). Furthermore, a compelling reputation and positive image fostered by consistent success can lead to greater trust and loyalty from customers and new business opportunities.

The availability of raw materials is also vital in supporting market orientation and business success (Fig. 4). Without a reliable supply of raw materials, businesses face uncertainty, negatively impacting customer satisfaction, and business operations (Kulkarni 2024). The availability of raw materials affects production continuity, cost control, product quality, operational efficiency, business reputation, and the capacity for innovation (Suryani *et al.* 2023). Small-scale processing units may also offer logistical advantages, particularly through shorter transportation distances between cassava production sites and processing facilities, which can reduce costs and post-harvest losses. However, these benefits may be offset by limitations in technology adoption, waste management capacity, and regulatory compliance, as reflected in the broader sustainability assessment. Therefore, effective management of raw material supply is critical for ensuring business success and sustainability.

Economic sustainability rating of 57.6% shows moderate market orientation and company success in the cassava industry. However, the paper emphasizes value addition and product variety to improve economic resilience, an innovative approach. Adding high-value cassava derivatives including bioethanol and bioplastics to the industry's product mix may increase profits and market share. This study's economic analysis goes beyond typical measures by assessing global market patterns' effects on local cassava industries. Cassava-based bioplastics are profitable due to the increased need for sustainable packaging. The report also emphasizes the necessity of strong market links and product development innovation to improve the economic sustainability index. These studies provide a strategy to make the cassava industry more competitive and profitable.

Social Dimensions

The social sustainability of the cassava industry in Lampung province is evaluated at a sustainability index value of 76.9%, reflecting a very sustainable status. This positive evaluation underscores the robust social framework supporting cassava production in the region. The three most sensitive factors influencing social sustainability are the level of environmental conservation knowledge, the involvement of family members in the cassava industry, and the educational attainment of the industry manager or entrepreneur (Fig. 5).

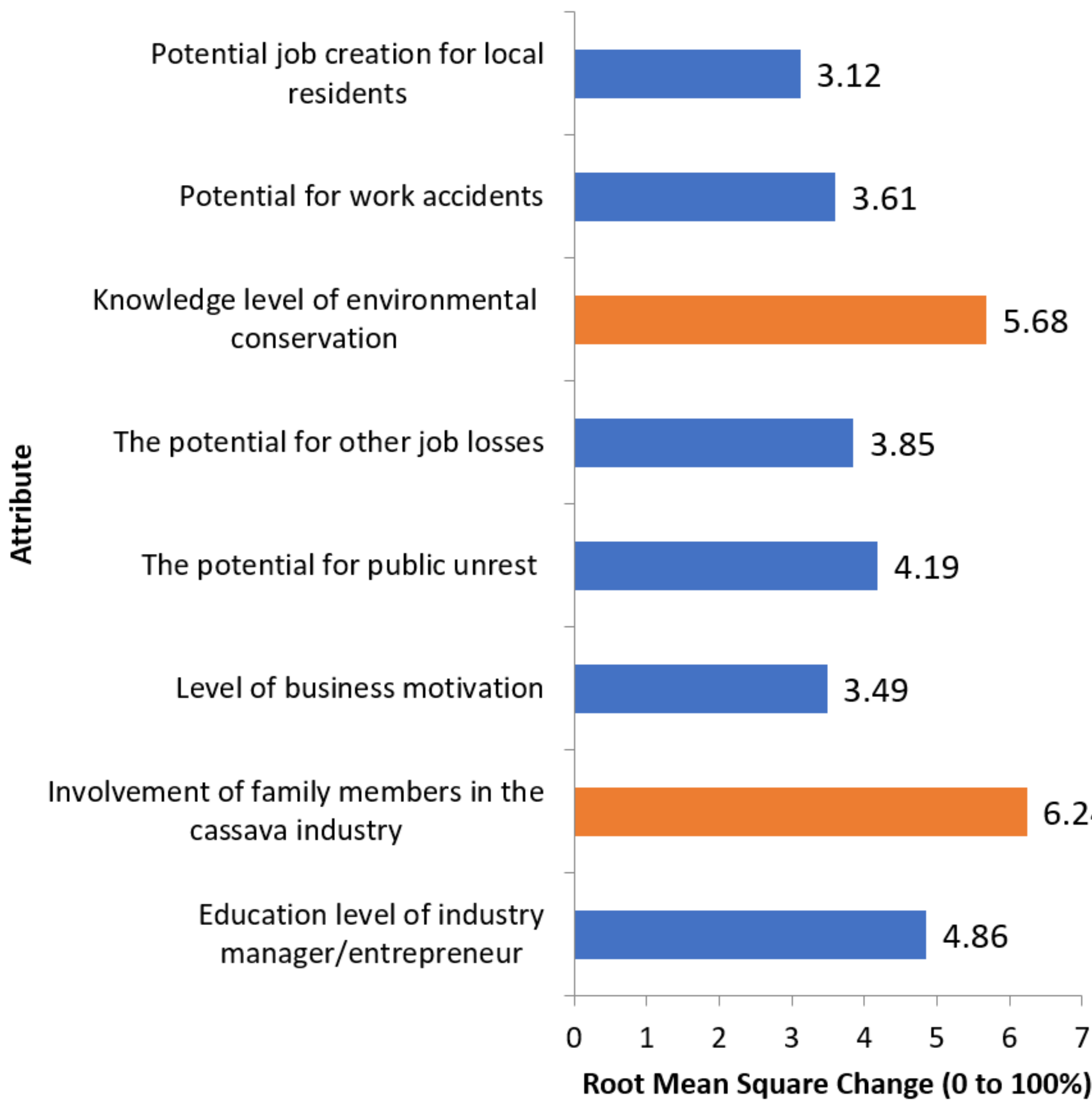

Fig. 4. Leverage of social attributes

In addition, the leverage analysis identifies these attributes as dominant factors with higher RMS values, indicating their greater sensitivity in shaping social sustainability outcomes. Improvements in environmental knowledge can promote more responsible and sustainable practices, while active family involvement strengthens social cohesion and ensures continuity of local knowledge. Similarly, higher educational attainment of managers enhances decision-making capacity and supports the adoption of innovative and sustainable management approaches. Conversely, limitations in these attributes may reduce the effectiveness of social systems in supporting long-term sustainability. These factors are critical levers in ensuring the long-term viability and resilience of the cassava agroindustry.

The knowledge level of environmental conservation among stakeholders in the cassava industry is essential for sustainable practices. Enhanced environmental knowledge leads to the adoption of practices that minimize negative ecological impacts, such as crop rotation, reduced chemical usage, and soil preservation techniques (Singh *et al.* 2021). Implementing regular training programs, workshops, and integrating environmental education into local curriculums are strategic efforts to improve this knowledge (Maurer *et al.* 2020). Such initiatives cultivate a community of informed farmers capable of making ecologically sound decisions, thereby promoting sustainability in cassava production.

The involvement of family members in the cassava industry significantly influences its sustainability. Family involvement fosters a committed and cohesive workforce, encouraging a sense of ownership and responsibility towards sustainable practices. This involvement ensures the transfer of traditional knowledge and sustainable agricultural practices across generations, contributing to the resilience of the industry (Bhujel and Joshi 2024). Strategies to enhance family participation include providing incentives, supporting family-run enterprises, and creating policies that promote family farming. Technical efforts, such as family-based agricultural extension services and community support networks, further reinforce this involvement.

The education level of the industry manager or entrepreneur is another crucial factor affecting the sustainability of cassava production. Higher education levels are associated with better managerial skills, innovative capabilities, and a greater understanding of sustainable practices (Shahzad *et al.* 2021). Educated managers are more likely to adopt advanced technologies and implement sustainable business models that improve efficiency and reduce environmental impact. Enhancing this factor involves providing scholarships for higher education in agricultural sciences, offering managerial training programs, and facilitating continuous professional development for industry leaders. Technical efforts could include partnerships with educational institutions to provide targeted training and resources for industry managers (Maurer *et al.* 2020).

The sustainability of Lampung's cassava agroindustry depends on increasing environmental awareness, family engagement, and managerial education. Strategic and technological efforts targeting these elements may increase the industry's sustainability index, creating a more resilient manufacturing system. These programs support agricultural industry goals of environmental conservation, community engagement, and education.

Lampung's cassava sector has a 76.9% social sustainability index, indicating a strong social framework. This study examines how social innovation drives sustainability. Family involvement in cassava production, a key feature, allows community-based agricultural models that emphasize cooperative management and collaborative ownership. This study shows that integrating social capital into the sustainability framework can strengthen rural communities. The research also introduces 'agroecological literacy,' an innovative way to improve stakeholder environmental understanding. The industry may educate farmers and management in agroecology to implement sustainable practices. These innovative methods improve social sustainability and cassava agroindustry resilience.

Technological Dimensions

Cassava production is sustainable; however, its technological sustainability index value is 55.0%, indicating space for development. Cassava production's technological sustainability is greatly impacted by industry ability and expertise (Fig. 6). The leverage analysis identifies key dominant attributes with higher RMS values, particularly specialization/expertise requirements, technological skills, and the ability to adopt and operate production technologies. These attributes exhibit greater sensitivity within the system, indicating that improvements in workforce capability and technological proficiency can substantially enhance the technological sustainability index. A lack of technical skills and limited expertise may constrain the effective use of available technologies, thereby reducing productivity and limiting innovation adoption. Conversely, strengthening these attributes can improve operational efficiency, support technological innovation, and reduce environmental impacts associated with inefficient production practices. The workforce's competence is key to the successful application of innovative agricultural technologies and creative waste-reducing initiatives. Skilled labor optimizes technology instruments and processes, improving productivity and reducing environmental impact (Javaid *et al.* 2022). The demand for specialization, high expertise, and talents dominated the score because it can limit production continuity and speed. Technology in production and agriculture are equally crucial to infrastructure development. Finally, as technology advances, technique sensitivity is also essential.

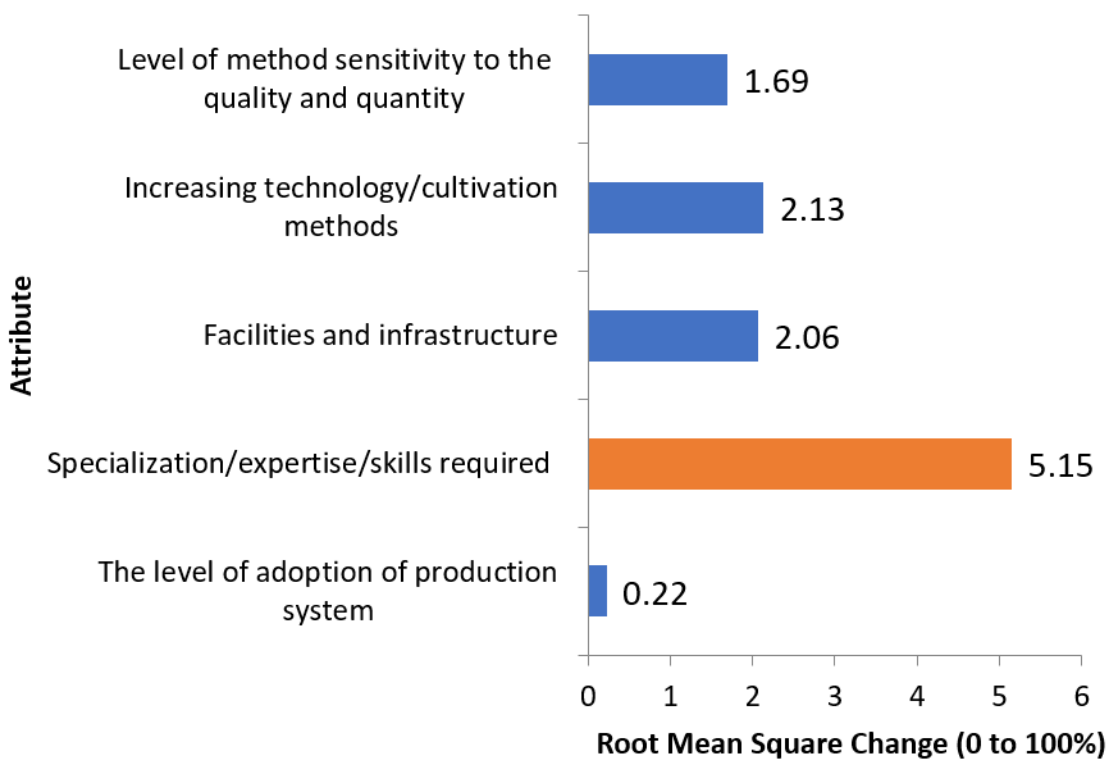

Fig. 5. Leverage of technological attributes

Strategy must focus on comprehensive training initiatives to improve cassava producers' technical skills to close the skill gap. These programs should address precision agriculture, sustainable farming, and creative waste management in cassava farming. Partnerships with agricultural colleges and research organizations can help develop and implement these training programs using the latest scientific and technological advances

(Tiwari 2008). Workshops, seminars, and field demonstrations can also spread industry's best practices and innovations (Shahzad *et al.* 2021).

The 55.0% technical sustainability rating shows space for growth, especially in talent development and technological adoption. This paper proposes precise farming for cassava growing an innovative approach. Precision agriculture using IoT and AI-driven analytics can improve crop yields, resource utilization, and environmental effects. Digital platforms may help smallholder farmers transmit information and embrace technology, according to the report. Mobile technology and online training modules can help the cassava industry close the skill gap and propagate sustainable technologies. The study also suggests that public-private partnerships can scale up these breakthroughs to give small-scale growers access to cutting-edge agricultural technologies. These technological advances and skill development programs could boost the industry's sustainability score.

Institutional Dimensions

The sustainability index value of cassava production in the institutional dimension was 55.2%. This indicates a relatively high level of sustainability but underscores the need for further improvement, particularly in addressing the role of waste treatment and compliance with regulations (Fig. 7).

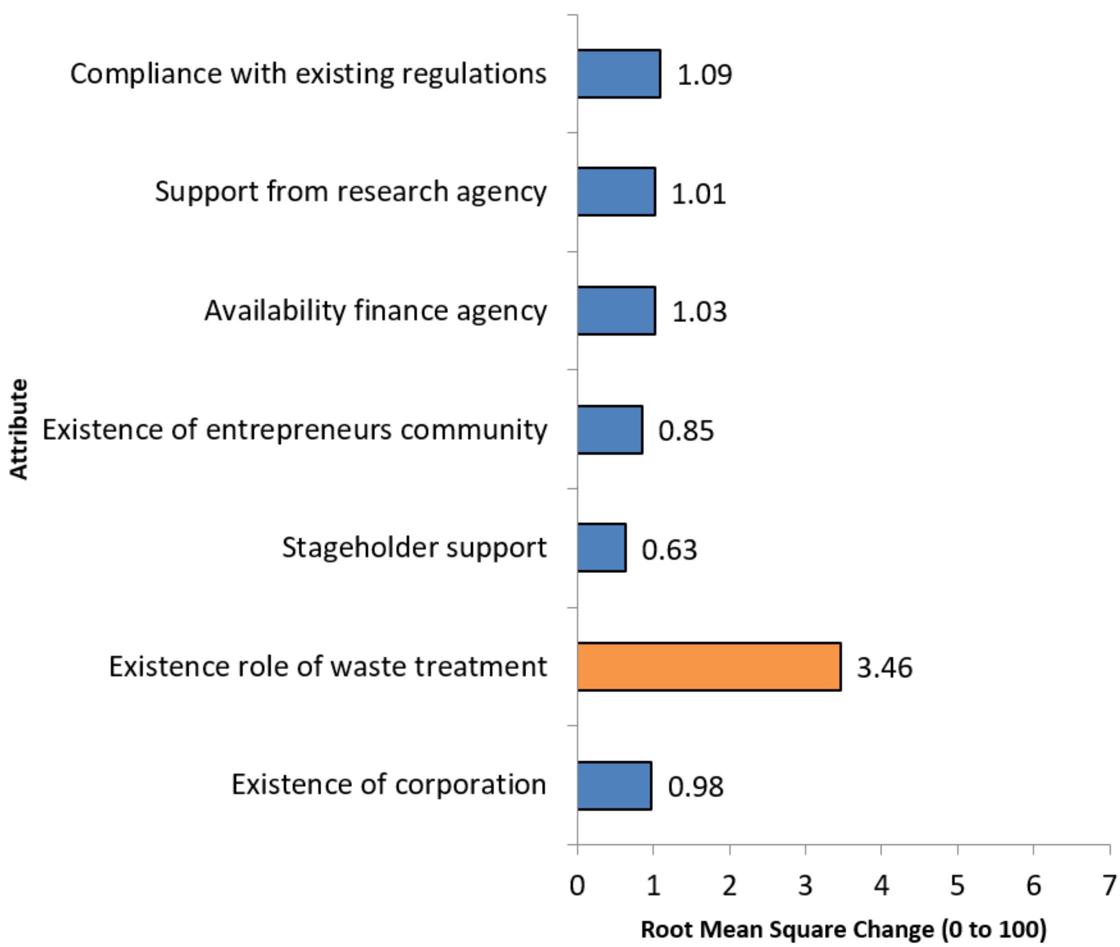

Fig. 6. Leverage of institutional attributes

In addition, the leverage analysis identifies waste treatment systems and regulatory compliance as dominant attributes with higher RMS values, indicating their strong sensitivity in influencing institutional sustainability. Improvements in waste treatment practices can significantly reduce environmental risks and enhance operational performance, while stronger regulatory compliance ensures alignment with environmental standards and promotes accountability within the industry. Conversely, weak enforcement of regulations and inadequate waste treatment infrastructure may limit institutional effectiveness and hinder sustainability progress. These two factors are critical levers because they directly influence the environmental and operational sustainability of the cassava industry. Effective waste treatment practices mitigate the environmental impact of production processes, while compliance with regulations ensures that industry practices aligning with national and international standards, promoting long-term sustainability (Olukanni and Olatunji 2018).

Waste treatment systems are crucial to cassava agroindustry sustainability. Poor waste management causes soil and water contamination, harming ecosystems and public health (Siddiqua *et al.* 2022). Thus, developing and implementing innovative waste treatment technologies for cassava processing by-products is crucial. Developing bioconversion technologies that convert cassava processing waste into value-added products such as bioenergy, animal feed, and organic fertilizers represents a promising strategy for enhancing resource efficiency and sustainability (Ngbede *et al.* 2019). Incentives for enterprises to follow circular economic concepts can improve waste management, reduce environmental impact, and improve sustainability (Romero-Hernández and Romero 2018).

Compliance with rules is another important issue in cassava production sustainability. Maintaining social license requires industry adherence to safe and ecologically beneficial regulations (Tumwesigye *et al.* 2016). Building institutional capacity through training and seminars can assist stakeholders understanding and compliance with regulations. Educational programs can raise industry awareness of environmental regulations and waste management best practices (Brown *et al.* 2009). Government authorities, cassava industry associations, and non government organizations (NGOs) can promote sustainability compliance and improvement through collaboration (Bas *et al.* 2022). Legislative instruments, including environmental regulations, enforcement mechanisms, and incentive-based policies, play a critical role in shaping industry behavior and encouraging compliance with sustainable practices. Experiences from other countries show that strict regulatory frameworks combined with economic incentives can significantly improve waste management performance in agro-industrial sectors. Improved waste treatment and regulatory compliance can help the cassava agroindustry achieve institutional sustainability and sector sustainability.

Regulatory frameworks and stakeholder participation influence the cassava industry's future, as shown by the institutional sustainability score of 55.2%. This paper suggests ‘adaptive governance,’ a new institutional sustainability strategy that emphasizes flexibility, stakeholder participation, and continual learning. The cassava sector can better address climate change and market variations by implementing adaptive governance concepts. The report also examines policy innovation’s role in sustainability. For instance, waste-to-energy incentives and sustainable cassava certification schemes can influence institutions. The research also highlights the significance of focused training for government officials and sector leaders to build institutional capacity. The cassava sector can improve its institutional sustainability and competitiveness by improving regulation and compliance.

Monte Carlo Analysis

Using the scatter plotting approach, Monte Carlo analysis was performed with 25 repeats at a 95% confidence level in each dimension to quantify the impact of random mistakes. The Monte Carlo analysis revealed minimal differences between the value of the sustainability index and the findings of the MDS research, indicating a very low number of flaws in the analytical and data analysis methodologies (Table 6).

Table 6. Differences in Ordination Values and Monte Carlo Values

Dimension	Ordination Index (%)	Monte Carlo Index (%)	Difference (%)
Environment	72.72	72.01	0.71
Social	76.92	74.29	0.86
Economic	57.55	55.59	0.94
Technology	55.03	55.12	0.95
Institutional	55.22	51.61	0.92

The environmental dimension's ordination index was 72.7%, while the social dimension's average was 76.9% over Monte Carlo simulations. The Monte Carlo analysis showed only limited variation in the cassava industry sustainability index within the 95% confidence interval. Table 6 compares the ordination index and Monte Carlo values, indicating a close agreement between the two results. This little mismatch between the ordination and Monte Carlo analyses suggests a modest analysis technique mistake and attribute score assignment conflict. Minor changes in MDS and Monte Carlo sustainability index values can minimize data entry errors and loss, maintain stability in repeated MDS analysis, and result in relatively tiny attribute scoring errors, which supports the findings of slight variations. Accordingly, researchers can trust the research analysis. The Rap-cassavea approach demonstrated that several features gave test results that were sufficient to quickly and quantitatively assess cassava agroindustry system sustainability.

Key Drivers and System Structure Based on MICMAC Analysis

To improve the sustainability index obtained from MDS, a MICMAC analysis was performed to categorize sustainability attributes based on their driving power and dependence.

Table 7. Attributes and Variables Used in MICMAC Analysis

Dimensions	Attributes	Variables
Environment	Efficiency in production	Efficiency
	Diesel uses in production	Diesel
	Noise pollution	Noise
Economy	Business success rate	Success
	Market orientation	Orientation
Social	Involvement of family members in the cassava industry	Family
	Knowledge level of environmental conservation	Knowledge
Technology	Specialization/expertise/skills required	Specialize
Institutional	Existence role of waste treatment	Role

The findings offer a structural framework that emphasizes the interconnections between attributes and pinpoints the key variables exerting substantial systemic influence. Table 7 presents the attributes of MDS utilized as variables in MICMAC.

The influence-dependence map (Fig. 8) divides variables into determinant, relay, dependent, and independent quadrants. This study found market orientation, specialization/expertise/skills needed, and environmental conservation knowledge as determinants. These elements exhibit high driving power and low dependence, indicating that targeted interventions in these areas could enhance the sustainability of cassava management systems. Efficiency as a relay variable demonstrated considerable influence and reliance, showing their dual role as systemic change agents and recipients. Efficiency use in production as a relay variable shows strong influence and dependency and a dual role as a systemic change recipient. Other drivers affected business success rate. Family participation in the cassava sector, diesel use in manufacturing, noise pollution, noise, diesel, and waste treatment were localized and less necessary for systemic reform.

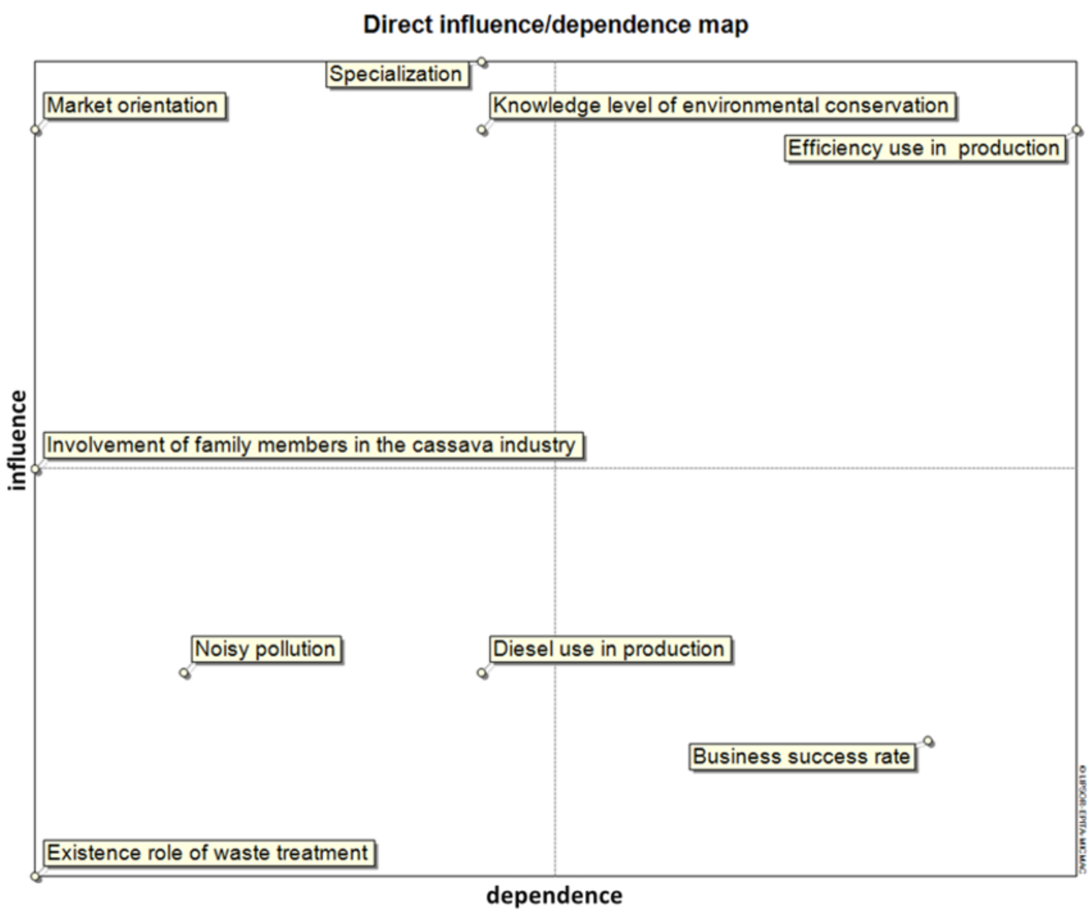

Fig. 7. Influence-dependence map of sustainability attributes based on MICMAC analysis

The cross-impact matrix (Fig. 9) further illustrates the causal architecture, emphasizing the strong interlinkages between market orientation, specialization/expertise/ skills required, efficiency use in production, and business success rate. These findings underscore that sustainability in cassava management system is not solely determined by ecological or economic performance but by a synergistic interplay of institutional and technological drivers. It was shown that institutional drivers and technical enablers drive agri-food supply chain sustainability (Venegas *et al.* 2022). It is noted that policy support and waste treatment technology determines municipal solid waste management system effectiveness (Bakrie *et al.* 2023). The MICMAC determinant variables can be leveraging points for circular food systems, emphasizing the necessity of targeting high-influence factors (Rachman *et al.* 2022).

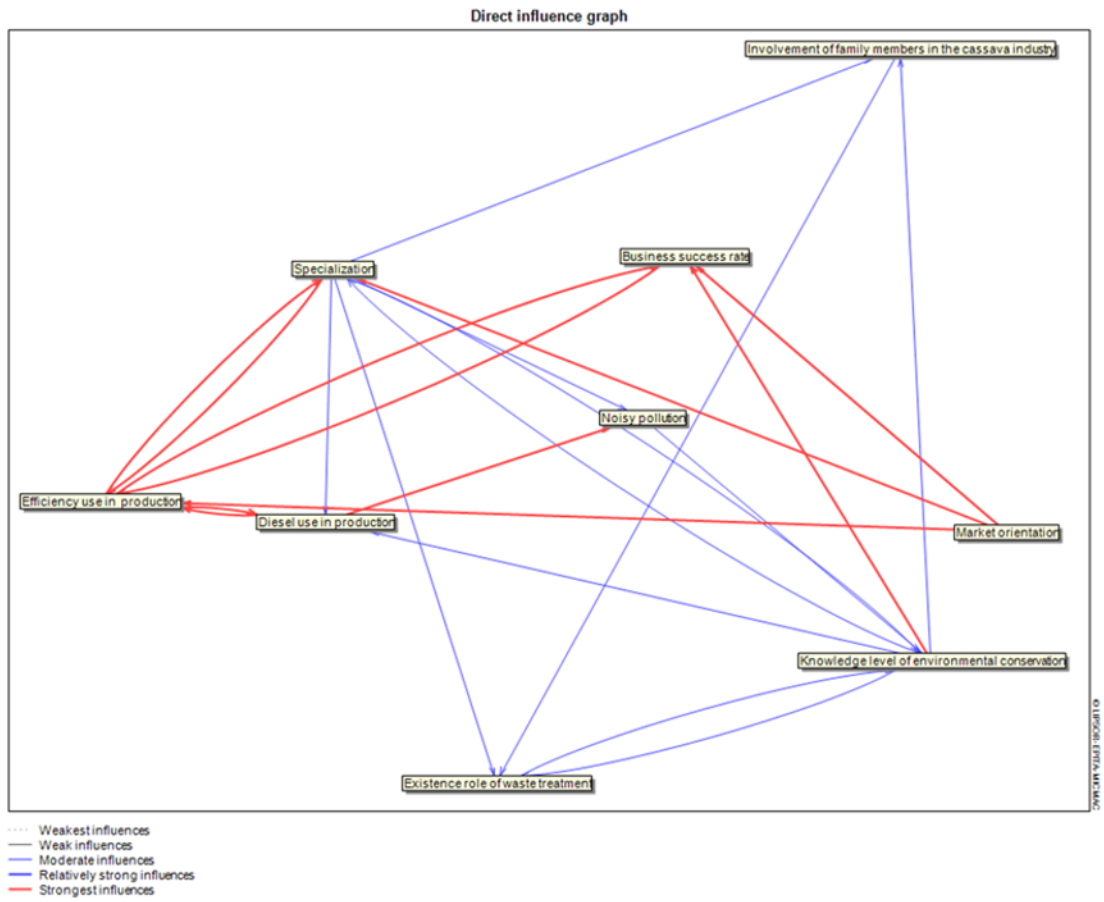

Fig. 8. Cross-impact matrix of key attributes in cassava waste management

The MICMAC analysis shows the sustainability attribute hierarchy, strengthening the MDS findings. The quantifies the sustainability index and identifies sensitive qualities, while MICMAC shows causal pathways, providing policy insights. Strengthening institutional support for cassava waste management will promote regulatory compliance, technology dissemination, and financial access, improving environmental and socio-economic results. To enhance systemic resilience, policymakers should prioritize determinant and relay variable interventions using this integrative approach. The cassava agro-industry may achieve sustainable waste management that balances environmental protection, economic viability, and social inclusion by simply doing accordingly.

Going Beyond: Improving the Sustainability Status

Improving the sustainability status of the cassava industry in Lampung province requires an integrated approach that leverages advancements and strategic initiatives across the five key dimensions: economic, environmental, social, technological, and institutional. The goal is to build on the current achievements, as identified in the MDS analysis, to enhance the industry's overall sustainability. This can be achieved through targeted efforts that address the specific challenges and opportunities within each dimension while fostering collaboration and innovation.

First, addressing the economic dimension involves enhancing market orientation and business success rates by diversifying product offerings and expanding market reach. Businesses should focus on value addition by processing cassava into various high-demand products, such as bioethanol, bioplastics, and dietary fibers, which can attract higher prices and open new markets (Andrés–Meza *et al.* 2024). Additionally, strengthening supply chain management to ensure a consistent supply of raw materials and improving access to financial resources for small and medium enterprises (SMEs) can bolster economic resilience (Brown *et al.* 2022). This can be supported by government policies that provide incentives for cassava-based product development and market expansion.

In the environmental dimension, improving energy efficiency and waste management practices are critical. The implementation of renewable energy solutions, such as utilizing cassava biomass for bioenergy production, can significantly reduce the industry's carbon footprint (Hasanudin *et al.* 2019). Furthermore, adopting advanced wastewater treatment technologies to recycle and repurpose production by-products can mitigate environmental pollution and enhance resource use efficiency (Wattanasilp *et al.* 2021). Encouraging the use of organic fertilizers derived from cassava waste can also improve soil health and productivity, contributing to sustainable agricultural practices (Achi *et al.* 2020).

The social dimension's sustainability can be enhanced by investing in community education and engagement programs that promote environmental stewardship and sustainable farming practices. Providing training and resources to farmers and industry workers can increase their knowledge and skills, leading to more sustainable production methods (Maurer *et al.* 2020). Additionally, policies that support family involvement in the cassava industry and provide social safety nets for workers can improve the overall well-being and resilience of the local communities (Bhujel and Joshi 2024). Strengthening social networks and cooperative structures can further enhance collaboration and knowledge sharing among stakeholders.

Technological advancements play a pivotal role in driving sustainability. Investing in research and development to innovate new processing techniques and improve existing ones can enhance productivity and reduce environmental impacts (Tiwari 2008). Training programs focused on enhancing the technical skills of the workforce can ensure that new technologies are effectively implemented and maintained. Collaborations with academic and research institutions can facilitate the transfer of technology and best practices to the industry, fostering continuous improvement and innovation (Shahzad *et al.* 2021).

Lastly, the institutional dimension requires robust governance frameworks and regulatory compliance to ensure sustainable practices. Strengthening institutional capacities through policy reforms and capacity-building initiatives can improve compliance with environmental and social regulations (Olukanni and Olatunji 2018). Establishing industry standards and certification schemes for sustainable cassava production can incentivize best practices and enhance market access for compliant producers. Collaborative efforts between government agencies, industry associations, and non-governmental organizations can promote transparency and accountability, driving the overall sustainability agenda forward (Bas *et al.* 2022).

While MDS provided a quantitative diagnosis of the sustainability level and highlighted sensitive attributes, the integration of MICMAC analysis allows for a more strategic interpretation by revealing the structural interdependencies among these attributes. The MICMAC results emphasize that determinant variables, such as technological innovation in waste treatment, institutional policy frameworks, and financial support mechanisms, serve as leverage points for systemic improvement. Through prioritizing interventions in these areas, systemic ripple effects can be achieved across dependent variables such as environmental quality and socio-economic well-being. For instance, the adoption of advanced waste treatment technology not only reduces ecological pollution but also enhances resource recovery, which strengthens economic viability and fosters community acceptance. Similarly, strong institutional frameworks ensure regulatory compliance and provide enabling conditions for technology dissemination and financing schemes, ultimately driving broader sustainability outcomes.

Relay variables, including community participation and knowledge dissemination, function as both influencers and recipients of systemic changes. Strengthening these variables is critical to ensuring that technological and institutional reforms are effectively adopted at the grassroots level. Dependent variables, such as environmental indicators and social welfare outcomes, reflect the end results of these systemic interventions and serve as benchmarks for evaluating progress. Autonomous variables, while less influential, still require monitoring to prevent potential bottlenecks in sustainability transitions.

The combination of MDS and MICMAC offers a comprehensive roadmap for improving sustainability. The MDS highlights where the system currently stands and what attributes are most sensitive, while MICMAC identifies which attributes should be prioritized for intervention and how they interrelate. This dual approach ensures that efforts to improve cassava waste management sustainability are both evidence-based and strategically targeted. These conclusions are in line with recent studies in agri-food systems that underline the necessity of combining diagnostic and structural methods to formulate effective sustainability strategies (Venegas *et al.* 2022).

In practical terms, enhancing the sustainability of cassava agro-industry in Lampung requires: (i) accelerating technological innovation in waste valorization, such as biogas recovery or composting systems; (ii) reinforcing institutional support through policies, incentives, and monitoring systems; (iii) facilitating access to financing mechanisms to encourage small-scale industries to adopt sustainable technologies; and (iv) fostering community engagement and capacity-building initiatives to strengthen the social fabric supporting sustainability transitions. These steps resonate with previous research highlighting the role of integrated interventions to strengthen ecological, social, and economic dimensions of agro-industrial systems (Rachman *et al.* 2022).

Adopting this integrative approach enables the cassava agro-industry to move beyond incremental improvements and establish a robust pathway toward long-term sustainability. The combination of MDS and MICMAC provides a powerful methodological foundation for designing policies and interventions that are not only technically sound but also structurally impactful, ensuring that sustainability transitions are both achievable and resilient.

CONCLUSIONS

Based on the results of the integrated MDS and MICMAC analyses, the main conclusions of this study can be summarized as follows:

1. The cassava waste management system in Lampung Province is classified as very sustainable, with an overall sustainability index of 63.5%, indicating a relatively strong foundation for long-term environmental and socio-economic performance.
2. The environmental (72.7%) and social (76.9%) dimensions exhibit strong performance, while the economic (57.6%), technological (55.0%), and institutional (55.2%) dimensions remain at moderate levels and require targeted improvement strategies.
3. Key leverage attributes influencing sustainability include energy use (diesel and electricity), noisy pollution, market orientation, business success rate, environmental knowledge, workforce skills, waste treatment systems, and regulatory compliance, highlighting priority areas for intervention across dimensions.
4. MICMAC analysis identifies waste treatment technology, institutional regulatory frameworks, and financial support mechanisms as primary driving variables with high influence and low dependence, indicating their strategic importance in shaping system-wide sustainability outcomes.
5. Community participation and knowledge dissemination act as critical relay variables, emphasizing the need for inclusive stakeholder engagement and continuous capacity building to maintain system stability and adaptability.
6. To enhance sustainability performance, decision-makers and practitioners should prioritize: (a) investment in efficient and renewable energy technologies to reduce environmental pressures; (b) strengthening waste treatment infrastructure and promoting circular economy practices; (c) improving market orientation and product diversification to increase economic resilience; (d) expanding technical training and digital capacity-building programs for the workforce; and (e) reinforcing institutional frameworks through stricter regulatory enforcement and incentive-based policies.
7. These targeted interventions provide a practical and region-specific pathway for improving cassava waste management systems in Lampung Province and can serve as a reference model for similar agro-industrial systems in developing regions.

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