

Article

Prioritizing Socioeconomic Impacts of Oil Palm Residue Valorization in Meta, Colombia: A Case from the Orinoquia Region

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Abstract

The rapid expansion of oil palm cultivation in the Colombian Orinoquia has generated economic benefits but also environmental and social pressures associated with biomass residue management. In this context, residue valorization through bioproduct production has gained relevance as a strategy linked to circular bioeconomy and regional sustainability. This article analyzes the prioritization of socioeconomic impacts associated with the reuse of oil palm residues in the department of Meta, Colombia, using a participatory multicriteria approach. The method combined the Analytic Hierarchy Process (AHP), the Ratings technique, and the DEMATEL method to evaluate social, economic, and environmental dimensions identified together with territorial stakeholders. The assessment process involved 31 participants representing academia, public institutions, productive sectors, financial entities, and civil society organizations. The results showed greater prioritization of impacts associated with employment generation and local economic development. The DEMATEL analysis revealed that economic and employment-related criteria exerted stronger influence within the evaluated system. Environmental sustainability also reached high relevance, whereas gender equity and post-pandemic regional resilience obtained lower relative weights in the prioritization process.

Keywords: circular bioeconomy; oil palm residues; socioeconomic impacts; multicriteria decision-making; AHP–DEMATEL; regional sustainability



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1. Introduction

The expansion of agro-industrial systems based on oil palm cultivation has generated significant economic contributions in several tropical regions; however, it has also increased concerns regarding the environmental and social impacts associated with agricultural waste management and the sustainable use of territorial resources [1,2]. In this context, the valorization of lignocellulosic residues derived from the oil palm agroindustry represents a promising alternative to strengthen circular bioeconomy strategies, promote regional sustainability processes, and contribute to the transition toward more sustainable agro-industrial systems [3,4]. In addition to reducing environmental pressures associated with the inadequate disposal of agricultural residues, these strategies may also generate positive effects on rural employment, local economic development, and the living conditions of communities linked to agricultural value chains [5].

In particular, residues generated throughout the oil palm production chain, such as empty fruit bunches, fibers, and shells, have gained relevance within contemporary ap-

proaches to sustainable biomass utilization [6]. Several studies have highlighted that these by-products can be incorporated into the production of bioproducts, bioenergy, and value-added materials, thereby supporting circular economy schemes and reducing dependence on fossil-based inputs [7,8]. Nevertheless, the implementation of these strategies requires consideration not only of technical and environmental criteria, but also of the socioeconomic impacts associated with their adoption in rural territories and among stakeholders connected to the agro-industrial supply chain [9].

The identification and prioritization of impacts associated with agricultural residue valorization strategies constitute a complex process due to the interaction among social, economic, and environmental dimensions [10]. In territorial scenarios characterized by multiple stakeholders, interests, and evaluation criteria, multicriteria decision-making techniques have become increasingly relevant as mechanisms for structuring analysis and prioritization processes [11,12]. In particular, methods such as AHP and DEMATEL allow the integration of expert judgments, the identification of influence relationships among criteria, and the support of decision-making processes in contexts characterized by interdependencies and multiple impacts [13,14]. Despite the growing interest in circular bioeconomy and the sustainability of agro-industrial systems, studies focused on prioritizing socioeconomic impacts derived from oil palm residue valorization from a territorial development perspective in rural Latin American contexts remain limited.

In the Colombian Orinoquia, and particularly in the department of Meta, oil palm production is embedded in a regional economy shaped by extensive tropical plains, livestock production, agriculture, and agro-industrial expansion. Meta is not only a location where palm oil is produced; it is a land-use-intensive territorial system in which permanent crops, processing facilities, transport services, local suppliers, and rural labor markets are connected. This matters because the socioeconomic effects of biomass valorization are mediated by local productive structures, municipal labor conditions, and the uneven capacity of rural actors to participate in new bioeconomy activities [15,16].

The department of Meta provides a specific territorial setting for examining the socioeconomic implications of oil palm residue valorization. Oil palm is the main permanent crop in the department, accounting for 43.9% of permanent crops, and Meta is part of Colombia's Eastern palm-growing zone [17]. The Department of Meta is also characterized by a land-intensive production structure, as UPRA reports that the department has approximately 8.55 million hectares, of which 5.0 million hectares are located within the agricultural frontier, representing 58.5% of the departmental area [18]. This territorial configuration is consistent with the regional importance of livestock systems, permanent crops, and agro-industrial activities. In 2019, agricultural survey data reported more than 5.5 million hectares under land use in Meta, with livestock use accounting for the largest share and agricultural use representing nearly 486,000 hectares. Oil palm should therefore be understood within a broader rural production system in which land availability, agro-industrial concentration, and the spatial organization of agricultural value chains are central to regional development.

Oil palm production in the department of Meta generates residual biomass along both agricultural and industrial stages. In this regional context, the main residual streams are associated with fresh fruit bunch processing and include empty fruit bunches, mesocarp fiber, palm kernel shell, palm oil mill effluents, and other lignocellulosic materials [19]. Some of these residues are incorporated into conventional uses within the agro-industrial system, such as soil amendment, composting, nutrient recycling, or energy recovery in processing operations [19]. Recent sectoral information also shows emerging initiatives related to the thermochemical valorization of oil palm biomass in Colombia, including pyrolysis experiences involving actors located in Meta [15].

Employment generated by the oil palm chain is concentrated mainly in the agricultural stage. Studies on labor use in oil palm cultivation in Colombia show that labor costs represent between 42% and 49% of the total production cost per ton of fresh fruit bunches, depending on the type of planting material [20]. This labor concentration in field activities contrasts with palm oil mills and residue valorization activities, where the relative weight of labor tends to be lower compared with capital costs, infrastructure, machinery, energy use, and technical process control.

As an indicative functional approximation, direct employment in the chain can be interpreted as follows: agricultural activities, including cultivation, harvesting, and maintenance, concentrate the largest share of the workforce, around 85%; processing in palm oil mills accounts for a smaller share, close to 12–14%; and residue valorization remains a more incipient segment, with an estimated participation between 1% and 3% [20]. These figures should be read as a sectoral approximation rather than as an official disaggregated measurement for the Department of Meta. Their relevance lies in showing that direct employment generation still depends mainly on field activities, while residue valorization requires more specialized infrastructure and generates a smaller amount of direct employment unless it is effectively connected to local suppliers, workers, and productive capacities.

At the sectoral level, studies on oil palm production in Meta have reported 244 oil palm growers, 17,634 direct jobs, and 26,451 indirect jobs [16]. However, these figures refer to the oil palm chain as a whole and do not allow the specific employment associated with the supply and valorization of residues to be isolated. It should also be considered that the oil palm agro-industry in the Orinoquia region has been associated with labor mobility from other regions. Therefore, part of the employment generated by the sector does not necessarily correspond to the population originally located in the producing municipalities.

Therefore, local employment associated with oil palm residue valorization exists, but it is partial and conditioned by the type of transformation, the location of the infrastructure, and the degree of territorial articulation. Its social relevance increases when residues are transformed within the department through biofertilizers, biogas, cogeneration, composting, or biodiesel, and when these activities involve local suppliers, workers, and productive capacities. In these cases, residue use can generate operational, economic, and environmental effects within the regional agro-industrial system.

For higher-value compounds such as 5-hydroxymethylfurfural (5-HMF) and furfural, the situation is different. No specialized industrial plants were identified in Meta for the production of these derivatives from lignocellulosic oil palm biomass, such as empty fruit bunches, fiber, or other solid residues. The transformation of this biomass into 5-HMF or furfural requires acid hydrolysis, controlled reaction conditions, separation, recovery, and chemical purification processes, which are generally associated with biorefineries or multiproduct industrial complexes. In Colombia, these advanced chemical valorization routes remain mainly linked to research, development, or technological validation, without evidence of consolidated industrial infrastructure in Meta for this type of transformation.

Biogas and bioenergy plants are present in Meta, but they are mainly linked to vertically integrated agro-industrial firms. These facilities are generally designed to support the energy requirements of the agro-industrial complex itself, rather than to operate as community-based energy projects. Although the Colombian State has supported the sector through biofuel policy, the construction and management of productive infrastructure have been led mainly by private capital, in many cases controlled by firms whose decision-making structures are external to the department. This reinforces the need to distinguish between the existence of residue valorization infrastructure and the extent to which its socioeconomic benefits are territorially distributed.

Publicly available information does not provide a precise quantification for Meta of the percentage of residues actually valorized by residue type, technology, and municipality. Disaggregated statistics on employment in residue valorization are also limited. For this reason, the study avoids assigning unsupported percentages to agricultural labor, processing activities, or biomass transformation. What can be observed is a differentiated structure: most employment remains associated with cultivation, harvesting, transport, processing, and related services, whereas residue valorization is still an emerging and heterogeneous segment within the regional value chain.

Residues that are not transformed into higher-value bioproducts are generally managed through conventional or lower-value practices. Part of the biomass may be returned to soils, used as organic amendment, or utilized as fuel in processing operations; other streams, especially liquid effluents or mixed residues, require treatment, storage, or management practices that do not necessarily generate additional territorial value. The issue is therefore not only whether residues exist, but whether the region has the institutional, technological, and organizational conditions to convert them into employment, local business opportunities, environmental improvements, and social benefits.

In response to this territorial problem, this article aims to prioritize the socioeconomic impacts derived from oil palm residue valorization through the integration of multicriteria techniques, considering their potential contribution to sustainable regional systems and circular bioeconomy approaches in the Colombian Orinoquia. The case of Meta is therefore not treated as a generic palm oil setting, but as a regional agro-industrial system where land use, biomass availability, productive specialization, and development expectations interact.

This article examines biomass valorization from a territorial sustainability perspective rather than from a purely technological or efficiency-oriented approach. The analysis focuses on how employment generation, local economic dynamics, environmental sustainability, and social inclusion interact within an agro-industrial region dependent on oil palm production. Through the combination of AHP–Ratings and DEMATEL, the study also incorporates interdependency relationships among socioeconomic dimensions that are often evaluated separately in biomass-related research.

2. Materials and Methods

2.1. Study Context and Definition of the Decision Problem

The empirical case was delimited to the department of Meta, in eastern Colombia, within the Colombian Orinoquia region. This territorial delimitation was adopted because Meta combines oil palm production, agro-industrial processing, rural labor markets, and biomass management challenges within the same regional system. Villavicencio, the departmental capital, was used as the main urban and administrative reference point because of its role in connecting institutional actors, productive activities, and regional services.

Within this context, the decision problem was defined as the prioritization of socioeconomic impacts associated with the valorization of oil palm residues. The analysis did not seek to rank specific technologies or production pathways. Instead, it focused on evaluating the relative importance of impacts linked to employment generation, local economic development, living conditions, environmental sustainability, gender equity, and regional resilience.

The case of Meta provides a suitable setting for applying a participatory multicriteria approach because biomass valorization involves different types of actors, criteria, and expected effects. Economic, social, environmental, and territorial objectives coexist in the same decision context, which makes it necessary to use methods capable of structuring preferences and identifying interdependencies among evaluation dimensions. Figure 1 shows the location of the department of Meta within Colombia and the Colombian Orinoquia region.

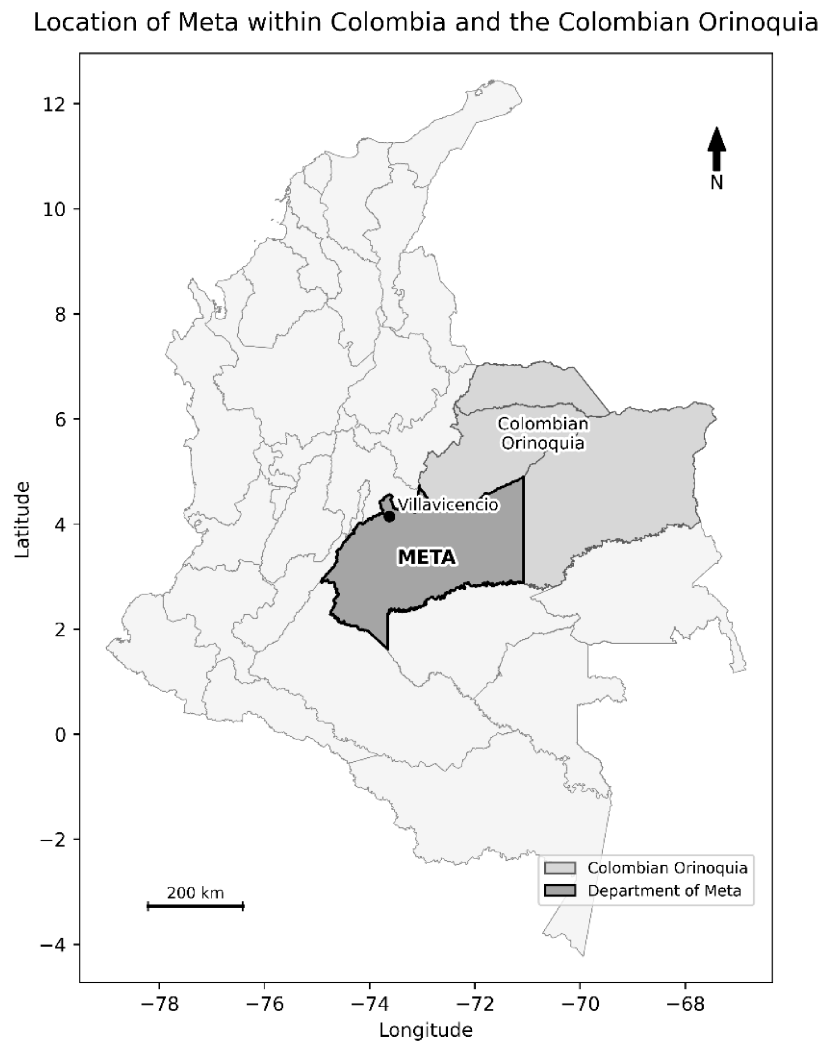


Figure 1. Location of the department of Meta within Colombia and the Colombian Orinoquia region. Administrative boundaries were prepared using official geospatial data from DANE, MGN 2024, department-level administrative boundaries. Villavicencio is shown as the departmental capital and main urban reference point.

The department of Meta is located in the eastern part of Colombia, within the Colombian Orinoquia, and includes a transition zone between the Andean foothills of the Eastern Cordillera and the Eastern Plains. The region is characterized by warm tropical conditions and a marked seasonal rainfall regime, with wet and dry periods that influence agricultural cycles, biomass availability, and residue management practices. Predominant land uses are associated with extensive cattle ranching, oil palm cultivation, rice production, commercial agriculture, and agro-industrial activities. Hydrologically, the department is structured by an extensive river network, including the Meta, Ariari, Guatiquía, Guayuriba, Manacacías, and Guaviare rivers, which shape settlement patterns, transport conditions, and the spatial distribution of productive activities. From a geomorphological perspective, Meta combines Andean foothill landscapes, alluvial plains, floodplains, high plains, and areas influenced by the Serranía de La Macarena. These characteristics are relevant to the decision problem because the generation, collection, transport, and potential valorization of oil palm residues depend on land-use patterns, hydrological connectivity, road accessibility, and the territorial concentration of agro-industrial facilities.

This study adopted a multicriteria framework to examine the socioeconomic implications associated with biomass valorization in an agro-industrial region of the Colombian

Orinoquia. The methodological approach combined prioritization and causal analysis techniques in order to evaluate the interactions among social, economic, and environmental dimensions linked to the utilization of oil palm residues. The proposed framework was structured to support the assessment of sustainability-oriented processes within agricultural systems increasingly influenced by circular bioeconomy strategies [7,21,22].

The proposed framework combined the AHP–Ratings approach with DEMATEL analysis in order to integrate prioritization and causal evaluation within the same decision structure. While AHP–Ratings facilitated the hierarchical assessment of socioeconomic impacts under multiple criteria, DEMATEL allowed the identification of influence relationships among the principal dimensions of the territorial system [10,23].

Figure 2 summarizes the general methodological framework adopted in this study. The analytical process began with the identification of socioeconomic dimensions associated with biomass valorization through literature review and stakeholder participation. Subsequently, the AHP–Ratings approach was applied to prioritize impacts under multiple evaluation criteria, while DEMATEL analysis was incorporated to examine influence relationships among the principal dimensions of the territorial system. Finally, sensitivity analysis was conducted to evaluate the stability and robustness of the prioritization results.

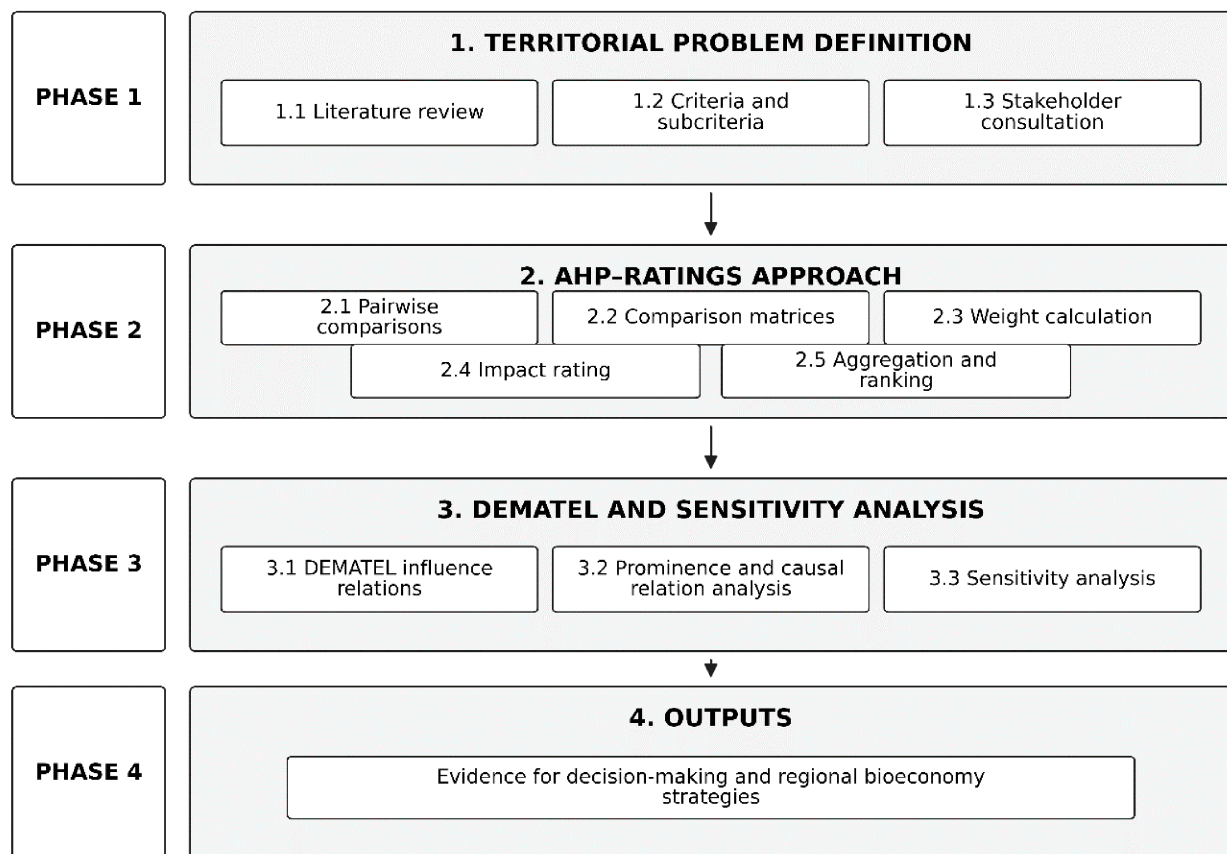


Figure 2. Methodological framework for the assessment and prioritization of socioeconomic impacts associated with oil palm biomass valorization in the Orinoquia region, Colombia. Note: AHP = Analytic Hierarchy Process; DEMATEL = Decision-Making Trial and Evaluation Laboratory.

2.2. Structure of the AHP–Ratings Model, Impact Dimension Definition, and Data Collection

The socioeconomic impact dimensions considered in this article were identified through a review of scientific literature addressing biomass valorization, circular bioeconomy, agro-industrial sustainability, and multicriteria decision-making approaches. Several studies have emphasized that biomass management strategies in agricultural regions

may generate implications that extend beyond waste reduction, particularly in territories where productive systems depend heavily on agro-industrial activities and natural resource use [21,24].

The literature review allowed the identification of recurrent socioeconomic impact dimensions associated with employment generation, local livelihoods, environmental sustainability, gender inclusion, regional economic activity, and territorial resilience. These dimensions were not treated as independent criteria for evaluating a different set of impacts. Nevertheless, it is important to clarify the distinct functional role assigned to each hierarchical level within the AHP–Ratings model. The first-level criteria (C1–C6) operate as evaluative dimensions that establish the normative framework for judging the socioeconomic outcomes of biomass valorization. Each criterion incorporates contextual specifiers that anchor it to the bioproduct value chain (e.g., C1 explicitly refers to employment generation within the bioproduct value chain; C5 addresses reduction of dependence on fossil-based inputs). The second-level subcriteria (C.i.j) constitute the measurable attributes against which the pairwise comparisons were performed and the Ratings evaluations were applied. For example, C.1.1 (creation of formal jobs in the agricultural and bioproduct sector) and C.1.2 (training and skills development in the bioproduct value chain) provide the concrete, operational basis for evaluating how each impact performs within the employment dimension. The socioeconomic impacts (I1–I5), in turn, represent the territorial outcomes to be prioritized, evaluated through the twelve subcriteria structure using the Ratings technique. Although criteria and impacts share related thematic domains—both derived from the same literature on socioeconomic dimensions of biomass valorization—they occupy structurally distinct roles: criteria and subcriteria provide the evaluative framework, while impacts are the objects assessed within that framework. This distinction is consistent with the absolute measurement logic of AHP–Ratings described by Saaty [25], in which alternatives are rated against predefined standards rather than compared directly against each other. Rather, they were used as the main dimensions of the socioeconomic impact structure to be prioritized and analyzed within the territorial system. Similar combinations of multicriteria methods have been reported in sustainability studies involving complex territorial systems and multiple stakeholders. Recent applications developed in agri-food systems of Meta, Colombia, have also shown the usefulness of integrating DEMATEL and ANP for the prioritization of territorial sustainability strategies under participatory contexts [16,20,26].

The analytical procedure integrated literature review, stakeholder participation, multicriteria prioritization, causal analysis, and robustness assessment. Socioeconomic dimensions associated with biomass valorization were first organized into a hierarchical structure that supported the evaluation process. The AHP–Ratings approach was then used to estimate the relative importance of the evaluated impacts, while DEMATEL analysis helped identify influence relationships among the principal dimensions of the system. The hierarchical structure adopted in the evaluation process is presented in Figure 3. The model integrates socioeconomic, environmental and regional dimensions associated with biomass valorization within the context of the oil palm agroindustry in the Colombian Orinoquia.

The decision problem was structured hierarchically to support the prioritization of socioeconomic impacts associated with oil palm residue valorization. The hierarchy included the overall objective, six first-level criteria, twelve second-level criteria, and five socioeconomic impacts evaluated as alternatives. To facilitate the interpretation of Figure 2 and the subsequent results, Table 1 defines the codes used throughout the manuscript.

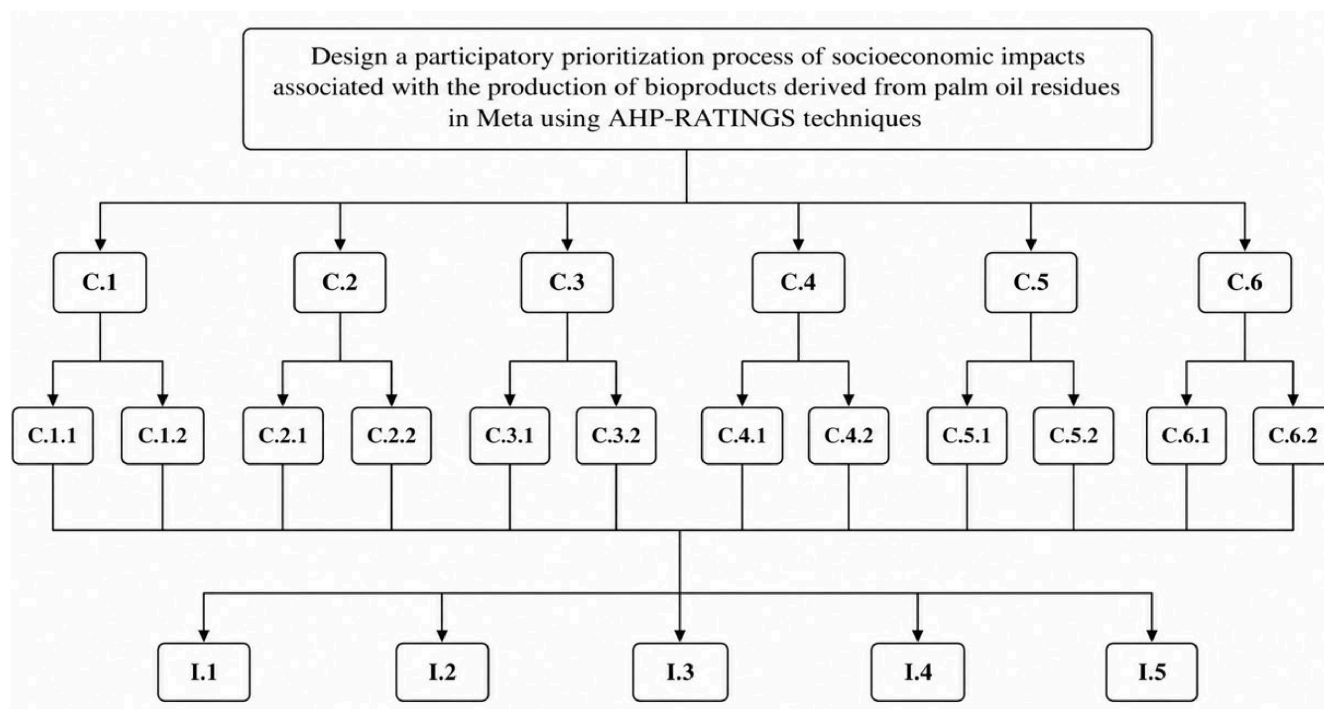


Figure 3. Hierarchical structure of the AHP–Ratings model for prioritizing the socioeconomic impacts associated with the valorization of oil palm residues within the regional bioeconomy.

Although some first-level criteria and socioeconomic impacts use similar thematic labels, they play different roles in the model. The criteria and subcriteria define the evaluation dimensions used to structure and weight expert judgments, whereas the impacts I.1–I.5 correspond to the alternatives assessed and prioritized through the AHP–Ratings procedure. For example, C.1 is an employment-related first-level criterion that is operationalized through C.1.1 and C.1.2, while I.1 represents the socioeconomic impact related to employment generation and formalization evaluated as an alternative. In this context, formalization refers to the transition of labor activities toward stable and regulated working arrangements, encompassing formal contracts, social security coverage, occupational safety, and skills development within the bioproduct value chain.

The model was organized into four levels, including the overall objective, evaluation criteria, subcriteria, and the socioeconomic impacts considered in the analysis.

A second level of subcriteria was incorporated to provide a more detailed representation of the social, economic, environmental, and regional dimensions considered in the analysis. This structure allowed the incorporation of social, economic, environmental, and regional perspectives into the evaluation process.

The information used to construct the pairwise comparison matrices was obtained through participatory instruments applied to actors linked to the oil palm value chain and regional development initiatives in the department of Meta. Participants included representatives from academia, productive sectors, local organizations, and stakeholders associated with biomass utilization processes in the region. Previous studies have highlighted the importance of participatory approaches in sustainability assessment processes involving agricultural systems and regional resource management [24,27].

The information was collected through two structured questionnaires administered to experts with experience in the oil palm sector, bioeconomy, and regional development. The first instrument (Appendix A) was developed under the AHP–Ratings approach and aimed to capture the relative importance assigned to the evaluation criteria as well as the performance of the identified socioeconomic impacts. The questionnaire included

pairwise comparison matrices for first- and second-level criteria using Saaty's fundamental 1–9 scale, together with a categorical Ratings system adapted from previous multicriteria applications [11].

Table 1. Codes used in the hierarchical AHP–Ratings model.

Code	Meaning
C.1	Employment generation and formalization within the bioproduct value chain
C.2	Improvement in the living conditions of local communities
C.3	Promotion of gender equity in productive processes
C.4	Local economic development through new business opportunities
C.5	Reduction of dependence on fossil-based inputs and environmental sustainability
C.6	Regional recovery and resilience in the post-COVID-19 context
C.1.1	Creation of formal employment opportunities in agricultural and bioproduct sectors
C.1.2	Capacity building and skills development within the bioproduct value chain
C.2.1	Access to quality basic services, including healthcare, education, and housing
C.2.2	Increase in average household income in local communities
C.3.1	Equal opportunities for women in leadership and decision-making positions
C.3.2	Inclusion of women in technical training and access to productive resources
C.4.1	Promotion of local entrepreneurship associated with bioproduct production
C.4.2	Development of collaboration networks between small firms and large agro-industrial actors
C.5.1	Use of clean technologies and renewable energy in bioproduct production
C.5.2	Implementation of sustainable agricultural practices within the value chain
C.6.1	Rehabilitation of affected infrastructure and support for local productive activities
C.6.2	Strengthening adaptive capacity and resilience against future economic or health shocks
I.1	Employment generation and formalization within the bioproduct value chain
I.2	Improvement in the living conditions of local communities
I.3	Promotion of gender equity in productive processes
I.4	Local economic development through new business opportunities
I.5	Reduction of dependence on fossil-based inputs and promotion of environmental sustainability

The second instrument was specifically designed for the application of the DEMATEL method. In this questionnaire (Appendix B), experts evaluated the degree of influence between pairs of criteria and impacts using a scale from 0 to 5, where 0 represents no influence and 5 indicates very high influence. The combined use of both instruments captured expert preferences together with the interdependencies among system elements, providing a broader understanding of the decision problem. The instruments used for data collection are presented in Appendices A and B.

2.3. Analytical Procedure: AHP–Ratings, DEMATEL, and Robustness Analysis

The data were collected through the participation of 31 stakeholders linked to the oil palm value chain in the study region. Participants included producers, local entrepreneurs, service providers, and representatives of community and institutional organizations associated with biomass valorization processes, regional development, and agro-industrial sustainability. The participants were selected using a non-probabilistic purposive sampling

approach based on expert judgment, a technique widely applied in multicriteria studies and decision-making processes that require specialized knowledge of the problem under analysis [28]. This approach made it possible to incorporate heterogeneous perspectives associated with the social, economic, and environmental dimensions of the evaluated system. As an inclusion criterion, participants were required to have direct or indirect experience in activities related to the oil palm sector, its value chain, or processes associated with bioeconomy and the valorization of agro-industrial residues.

The empirical information used in this study was cross-sectional and reflected stakeholder judgments collected at a single point in time. Therefore, the model captures a context-specific prioritization structure rather than temporal changes in perceptions or impacts. The results should be interpreted as reflecting the institutional, productive, and stakeholder conditions of the department of Meta, rather than as directly generalizable evidence for all oil palm-producing regions.

The AHP–Ratings procedure was implemented in two complementary stages. First, pairwise comparison matrices were constructed to estimate the relative importance of the criteria within the decision structure. Expert judgments were aggregated using the geometric mean, a procedure commonly adopted in group decision-making studies to consolidate individual evaluations. Once the matrices satisfied the consistency requirements, priority vectors were obtained through normalization. The consistency of the AHP pairwise comparison matrices was assessed before deriving the final priority vectors. Consistency indicators were used to verify the internal coherence of expert judgments in the comparison of criteria and subcriteria. Following conventional AHP practice, judgments were considered acceptable when the consistency ratio remained within the recommended threshold. This procedure helped identify and control logical inconsistencies in the AHP stage of the model. However, this consistency assessment should not be interpreted as a full uncertainty analysis of expert judgments, since it evaluates the coherence of pairwise comparisons rather than the robustness of results under alternative judgment scenarios.

In the second stage, the Ratings approach was applied to evaluate the relative performance of the socioeconomic impacts with respect to each criterion. Qualitative categories were subsequently transformed into numerical values, allowing the construction of a quantitative evaluation matrix used in the final prioritization process [25,29].

Subsequently, the matrices were normalized to obtain the priority vectors, which represent the relative importance of each criterion within the model.

The global priority of each impact was obtained through a weighted aggregation process, according to the following expression:

$$P_i = \sum_{j=1}^n w_j \cdot r_{ij} \quad (1)$$

where P_i represents the global priority of impact i . w_j corresponds to the weight of criterion or subcriterion j . r_{ij} represents the value assigned to impact i with respect to criterion or subcriterion j , and n is the total number of criteria or subcriteria considered in the aggregation process. This procedure integrates the hierarchical structure with the performance evaluation of the alternatives, obtaining a synthetic measure of priority.

Subsequently, the obtained priorities were normalized to express the results in comparable percentage terms, according to the following relationship:

$$P_i^* = \frac{P_i}{\sum_{i=1}^m P_i} \times 100 \quad (2)$$

where P_i^* represents the normalized percentage priority of impact i . P_i corresponds to the initial priority obtained through weighted aggregation, and m is the total number of evaluated impacts.

To complement the hierarchical evaluation, the DEMATEL method was incorporated to examine the influence relationships among the first-level criteria and the aggregated socioeconomic impacts. Given the large number of potential interactions generated by multi-level structures, the causal analysis was restricted to the first-level criteria and the aggregated impact node. This decision aimed to reduce cognitive burden during the evaluation process and improve the consistency of expert judgments in identifying causal relationships within the system [23,30].

Based on the information obtained through the second questionnaire, the direct-relation matrix was constructed to represent the intensity of influence among the elements of the system [31].

The individual matrices were aggregated using the average of the values assigned by the participants, according to the following expression:

$$a_{ij}^{agr} = \frac{1}{n} \sum_{k=1}^n a_{ij}^{(k)} \quad (3)$$

where a_{ij}^{agr} represents the aggregated influence value of element i over element j , $a_{ij}^{(k)}$ corresponds to the judgment provided by participant k , and n is the total number of participants.

After aggregation, the direct-relation matrix was normalized and used to derive the total relation matrix, which incorporates both direct and indirect effects among the evaluated elements. The normalization process was carried out using the following expression:

$$X = \frac{A}{\max_i \left(\sum_{j=1}^n a_{ij} \right)} \quad (4)$$

where X represents the normalized direct-influence matrix. A corresponds to the aggregated direct-relation matrix, and a_{ij} represents each element of that matrix.

The total relation matrix was obtained using the following expression:

$$T = X(I - X)^{-1} \quad (5)$$

where T represents the total relation matrix. X corresponds to the normalized direct-influence matrix, I is the identity matrix, and $(I - X)^{-1}$ represents the matrix inverse used to capture direct and indirect effects within the analyzed structure. The total relation matrix is not presented due to its size; however, it was used as the basis for calculating the prominence ($D + R$) and causality ($D - R$) indicators.

Finally, a sensitivity analysis was conducted by introducing individual 10% increases in the weights of the first-level criteria, followed by renormalization and recalculation of the final priorities. This procedure allowed the evaluation of the robustness and stability of the prioritization results under controlled weighting variations [32,33].

3. Results

3.1. Relationship Between Oil Palm Residues, Valorization Pathways, and Socioeconomic Impacts

Oil palm residue valorization represents an intermediate process between the availability of residual biomass and the generation of socioeconomic impacts. In this context, effects related to employment generation, local economic development, living conditions, gender equity, and environmental sustainability do not arise solely from the existence of

agricultural residues, but from the technological, organizational, and productive pathways through which these materials are transformed into bioproducts. Therefore, before presenting the prioritization results obtained through the AHP–Ratings approach, it is necessary to establish the relationship between the different types of residues, the potential valorization pathways, and the expected impacts within the territorial context [34,35].

The prioritized socioeconomic impacts are not generated directly by the residues themselves, but depend on the technological pathways through which biomass is transformed into bioproducts. Therefore, these pathways do not constitute the object of prioritization within the multicriteria model; rather, they operate as intermediate mechanisms through which the analyzed effects are materialized. This distinction allows the model to differentiate, from a methodological perspective, between system outcomes (impacts) and the productive mechanisms that generate them (valorization pathways). As a result, the analysis is oriented toward the evaluation of socioeconomic outcomes rather than toward the prioritization of specific technological alternatives [10,36].

In this context, oil palm residues such as palm kernel shell, empty fruit bunches, and lignocellulosic biomass can be utilized for the production of different bioproducts, including biofertilizers, bioenergy, carbon-based materials, and platform compounds such as 5-hydroxymethylfurfural (5-HMF) and furfural. This type of biomass utilization may be interpreted from circularity and life cycle assessment perspectives, where residue valorization is evaluated not only according to its reuse potential but also according to its contribution to sustainability strategies within complex productive systems [2]. Valorization pathways characterized by lower technological complexity tend to generate more immediate effects in terms of employment and social inclusion due to their labor-intensive nature, whereas more advanced pathways are associated with higher levels of innovation, productive sophistication, and regional competitiveness. Each of these alternatives is associated with different types of socioeconomic impacts, as presented in Table 2 [37].

Table 2. Conceptual relationship between oil palm residues, valorization pathways, and associated socioeconomic impacts.

Oil Palm Residue	Pathway/Bioproduct	Main Application	Expected Socioeconomic Impacts	Status in Meta/Orinoquia
Empty fruit bunches	Compost, biofertilizers, and organic amendments	Soil improvement and partial replacement of synthetic fertilizers	Rural employment; lower production costs; sustainable agricultural practices	Documented or near-term relevance. Composting and organic amendments are technically relevant in oil palm-producing areas. Low-carbon practices in the oil palm chain have also been promoted through institutional initiatives such as Biocarbono Orinoquia, including pilots and capacity-building activities in Meta and Casanare.
Mesocarp fiber	Bioenergy, pellets, briquettes, and lignocellulosic materials	Thermal energy, solid fuels, and bio-based materials	Local economic development; productive diversification; reduced dependence on fossil-based inputs	Documented or near-term relevance in Meta. In San Carlos de Guaroa, oil palm agro-industrial facilities have reported the use of palm biomass and industrial residues for renewable energy generation and reduced chemical inputs.

Table 2. *Cont.*

Oil Palm Residue	Pathway/Bioprodut	Main Application	Expected Socioeconomic Impacts	Status in Meta/Orinoquia
Palm kernel shell	Activated carbon, biochar, and carbon-based materials	Adsorption, water treatment, catalysis, and environmental applications	Productive innovation; new business opportunities; environmental sustainability	Potential regional route. Activated carbon and biochar are technically feasible uses of palm biomass, but no clear public evidence was identified of consolidated commercial-scale facilities in Meta producing these materials from palm residues.
Palm shell	Activated carbon, monoliths, and catalytic supports	Catalysis, green chemistry, and specialized industrial processes	Technological development; regional competitiveness; added value generation	Potential or emerging regional route. This pathway should be interpreted as prospective. Its local socioeconomic impact would depend on future investment, local preprocessing, and regional industrial capacity.
Lignocellulosic biomass	5-HMF, furfural, and other platform compounds	Petrochemical substitutes and raw materials for advanced bioproducts	Economic growth; productive sophistication; environmental sustainability	Prospective route, not consolidated in Meta. No clear public evidence was identified of commercial-scale 5-HMF or furfural production from oil palm residues in Meta.
Palm oil mill effluents	Biogas, bioenergy, and nutrient recovery	Energy production, liquid waste treatment, and circular resource use	Reduced environmental impacts; energy efficiency; local investment opportunities	Documented relevance in Meta. Evidence from the oil palm sector reports biogas, composting, and circular use of palm oil mill effluents in San Carlos de Guaroa.
Mixed oil palm agro-industrial residues	Functionalized catalysts and intermediate bioproducts	Chemical processes, industrial valorization, and circular economy applications	Technological development; university–industry articulation; regional competitiveness	Research and prospective route. These applications remain mainly prospective for Meta/Orinoquia. Their territorial impact would depend on local research capacity, investment, and industrial scaling.

Note. The last column distinguishes between documented or near-term practices in the Colombian oil palm sector and prospective technological routes. For Meta and the broader Orinoquia region, stronger socioeconomic impacts are expected when residue collection, preprocessing, transformation, plant operation, and related services are located within the producing region and involve local workers, firms, producer organizations, and institutions. When residues are sold and transported outside the region, local effects may be mainly limited to additional income from residue sales.

In Meta/Orinoquia, public evidence shows that oil palm residue valorization is more closely associated with agro-industrial transformation, biodiesel production, biomass use, biogas/energy generation, composting, and other palm-related by-products, particularly in San Carlos de Guaroa, Meta. Fedepalma reports the biodiesel plant of Aceites Manuelita in this municipality and indicates that the company had 6500 own hectares and 14,000 hectares cultivated by oil palm suppliers in Meta [38]. In addition, Fedepalma and Cenipalma document technological activities related to biomass use at the Yaguarito oil palm mill, also located in San Carlos de Guaroa [39]. These references support the territorial relevance of bioenergy, biogas, composting, biodiesel, and circular biomass management in the regional oil palm sector. However, more specialized routes, such as 5-HMF, furfural, activated carbon monoliths, catalytic supports, and functionalized catalysts, should be interpreted as prospective technological pathways rather than consolidated industrial facilities currently

operating in Meta/Orinoquia. Table 2 summarizes the conceptual relationship between oil palm residues, valorization pathways, and their associated socioeconomic impacts.

Lower-complexity alternatives such as composting, biofertilizers, or small-scale bioenergy production usually remain closer to local agricultural activities. Their effects on employment and local participation therefore tend to appear more directly. In many rural areas, these activities are integrated into existing productive dynamics rather than into highly specialized industrial structures.

Other valorization pathways operate differently. Carbon-based materials and platform compounds are more associated with innovation processes, industrial transformation, and productive diversification [40,41]. The effects on employment are less immediate in these cases. Sometimes they are concentrated in technical or specialized activities instead of local labor-intensive processes.

The results obtained in the model do not indicate that one dimension completely dominates the others. Employment generation and local economic development occupied important positions during the prioritization process, although environmental sustainability also maintained a relevant role across the evaluations. Social inclusion appeared with lower weights, but it remained part of the interaction structure evaluated by the experts.

Part of these differences may be associated with the productive characteristics of each valorization pathway. Composting and local biomass utilization, for example, are usually more connected with rural productive chains and agricultural activities. More advanced chemical processes follow another logic. Their contribution is often related to innovation capacity, technological upgrading, or productive sophistication. However, these processes do not necessarily generate the same territorial employment effects as lower-complexity pathways. In some cases, technological upgrading may concentrate benefits in specialized activities while reducing the participation of local labor-intensive processes. Because of this, the model concentrated on socioeconomic impacts rather than on ranking technologies individually.

3.2. Impact Evaluation and Prioritization Through AHP–Ratings

The AHP–Ratings approach was applied to organize the prioritization structure associated with the socioeconomic impacts of oil palm biomass valorization. Expert judgments were aggregated through the geometric mean. After normalization, the priorities were expressed as percentages [42,43].

The evaluation process included two matrix structures. Table 3 presents the pairwise comparison matrix constructed for the first-level criteria according to Saaty’s scale. This matrix represents the relative preferences assigned among the six criteria included in the model. Reciprocal relationships among the matrix elements allowed the estimation of the priority vector associated with each criterion.

Table 3. Pairwise Comparison Matrix of Criteria (AHP).

Criteria	C1	C2	C3	C4	C5	C6
C1	1	6	2	4	4	2
C2	1/6	1	5	6	6	2
C3	1/2	1/5	1	5	7	2
C4	1/4	1/6	1/5	1	5	5
C5	1/4	1/6	1/7	1/5	1	3
C6	1/2	1/2	1/2	1/5	1/3	1

Note. The matrix presents the pairwise comparisons among the first-level criteria. Reciprocal values indicate the inverse importance relationship between criteria.

In the analyzed case, local economic development obtained the highest relative weight. Environmental sustainability and employment generation also occupied important positions within the model. Gender equity and post-pandemic recovery reached comparatively lower values. The differences among criteria were nevertheless not excessively large, which suggests that the experts did not perceive the evaluated dimensions as completely independent from one another.

Second, Table 4 presents the Ratings-based evaluation matrix, in which each socio-economic impact was assessed with respect to the subcriteria defined in the second hierarchical level. Unlike the AHP matrix, which was used to estimate criterion weights, the Ratings matrix represents the relative performance of each impact through numerical values derived from previously defined qualitative categories. Accordingly, impacts I1 to I5 were evaluated against subcriteria such as C1.1, C1.2, C2.1, and C2.2 using scores that represent their relative contribution within the model.

Table 4. Ratings-Based Evaluation Matrix of Impacts.

Impact	C.1.1	C.1.2	C.2.1	C.2.2	C.3.1	C.3.2	C.4.1	C.4.2	C.5.1	C.5.2	C.6.1	C.6.2
I.1	0.750	0.75	0.25	0.75	0.750	0.50	0.25	0.50	0.25	0.50	0.50	0.25
I.2	0.025	0.50	0.025	0.50	0.025	0.50	0.75	0.50	0.25	0.25	0.50	0.50
I.3	0.025	0.50	0.025	0.50	0.025	0.50	0.50	0.50	0.25	0.50	0.50	0.50
I.4	0.50	0.75	0.50	0.75	0.75	0.50	0.25	0.25	0.25	0.25	0.25	0.25
I.5	0.025	0.75	0.75	0.50	0.025	0.75	0.75	0.50	0.25	0.50	0.50	0.50

Note. The values correspond to the Ratings-based evaluation matrix, in which qualitative categories were transformed into a numerical scale ranging from 0 to 1 to represent the relative performance of impacts with respect to each subcriterion.

The final ranking therefore reflects the combined effect of stakeholder preferences and the relative performance of each impact within the evaluated dimensions, in accordance with the weighting and normalization process adopted in the study.

The results obtained through aggregation and normalization using the geometric mean allowed the establishment of a consistent prioritization structure for criteria, subcriteria, and evaluated impacts. Table 5 presents the final results of the AHP–Ratings model.

At the first-level criterion stage, local economic development (C4) achieved the highest relative weight (22.05%), followed by environmental sustainability (C5) with 20.08% and employment generation and formalization (C1) with 19.45%. In contrast, gender equity (C3) presented the lowest relative participation (10.63%), suggesting a lower perceived influence within the evaluated structure. These findings indicate that economic dimensions tend to operate as central drivers within territorial dynamics, influencing the behavior of social and environmental dimensions.

Regarding second-level criteria, the results revealed a stronger concentration in dimensions associated with productive strengthening and technological development, particularly C4.1 (12.89%) and C5.1 (11.34%). This finding reflects the relevance attributed to innovation and sustainable technologies within the regional bioeconomy model.

The prioritization of alternatives showed that the impacts associated with employment generation and formalization (I1) and local economic development (I4) occupied the highest positions, with nearly identical values (23.032% and 23.031%, respectively). Improvement in living conditions (I2) and environmental sustainability (I5) formed a second priority group, whereas gender equity (I3) obtained the lowest relative weight (15.031%).

The outcomes of the analysis reveal a high level of internal coherence within the model, as the highest-priority alternatives correspond to the criteria with the largest weights within the hierarchical structure, confirming the consistency of the aggregation procedure.

Table 5. Normalized G.M. Results in the Prioritization of Criteria and Alternatives.

Category	Element	Description	Weight (%)
First-level criteria	C4	Local economic development	22.05
	C5	Environmental sustainability	20.08
	C1	Employment generation and formalization	19.45
	C2	Improvement in living conditions	16.89
	C6	Regional recovery and resilience	10.90
	C3	Gender equity	10.63
Second-level criteria	C.4.1	Economic development subcriterion	12.89
	C.5.1	Sustainability subcriterion	11.34
	C.5.2	Sustainability subcriterion	11.18
	C.2.1	Living conditions subcriterion	9.83
	C.1.2	Employment subcriterion	9.53
	C.4.2	Economic development subcriterion	9.27
	C.2.2	Living conditions subcriterion	8.57
	C.1.1	Employment subcriterion	8.51
	C.3.1	Gender equity subcriterion	5.67
	C.6.1	Resilience subcriterion	5.08
	C.6.2	Resilience subcriterion	4.06
	C.3.2	Gender equity subcriterion	4.06
Impacts (alternatives)	I1	Employment generation and formalization	23.03
	I4	Local economic development	23.03
	I2	Improvement in living conditions	19.48
	I5	Environmental sustainability	19.42
	I3	Gender equity	15.03

Note. The weights correspond to the normalized geometric mean of expert judgments within the AHP–Ratings model.

3.3. DEMATEL Causal Analysis

As part of the expert evaluation process, direct-influence matrices were constructed to represent the relationships among the components of the decision model. Table 6 presents an example of an individual direct-influence matrix showing the relationships established among first-level criteria (C1–C6) and the aggregated socioeconomic impact node (I). This representation allows the identification of influence intensity among the evaluated system elements [44,45].

Table 6. DEMATEL Matrix. Direct Influence among First-Level Criteria and Impacts.

Criteria	C1	C2	C3	C4	C5	C6	I
C1	0	3	3	3	3	2	5
C2	2	0	2	3	3	2	4
C3	1	2	0	2	2	2	3
C4	4	4	3	0	5	3	5
C5	3	3	3	4	0	2	5
C6	2	2	1	2	3	0	5
I	3	4	3	5	4	5	0

Note. This matrix corresponds to an individual response example. The values were assigned using a scale from 0 to 5, where 0 indicates no influence and 5 represents very high influence. C refers to the first-level criteria, while I refer to the socioeconomic impacts.

The individual matrices were subsequently aggregated to obtain the consolidated DEMATEL direct-influence matrix presented in Table 7. Based on this aggregated matrix, the vectors D (row sums) and R (column sums) were calculated in order to derive the prominence ($D + R$) and causality ($D - R$) indicators [46,47].

Table 7. Aggregated DEMATEL Direct Influence Matrix.

Criteria	C1	C2	C3	C4	C5	C6	I
C1	0.00	3.10	1.87	4.0	3.06	1.97	4.74
C2	1.74	0.00	2.03	2.9	3.16	1.90	4.06
C3	1.23	2.00	0.00	2.19	1.71	1.97	3.13
C4	4.13	3.84	2.87	0.0	4.81	3.03	4.81
C5	2.77	2.84	2.23	4.06	0.00	2.90	4.77
C6	1.97	2.00	1.97	3.13	2.94	0.00	4.06
I	4.03	4.06	3.10	4.87	4.84	4.16	0.00

Note. The values in this matrix were calculated from the average of the individual matrices completed by the participants.

The total relation matrix was used to calculate the prominence ($D + R$) and causality ($D - R$) indicators. The vector D represents the influences exerted by each element, whereas R corresponds to the influences received. Positive $D - R$ values indicate DEMATEL-based causal factors, understood as elements with greater net influence within the evaluated interdependency structure, whereas negative $D - R$ values indicate effect factors, corresponding to elements that receive greater net influence from the system.

Table 6 summarizes the aggregated DEMATEL results obtained from the consolidation of expert judgments.

The total relation matrix is not presented due to its size; however, it served as the basis for calculating the prominence and causality indicators shown in Table 8.

Table 8. Aggregated DEMATEL Results: D, R, $D + R$ and $D - R$.

Criteria	D	R	$D + R$	$D - R$	Group
C1	3.0642	2.6425	5.7067	0.4217	Cause
C2	2.6023	2.8909	5.4932	−0.2886	Effect
C3	2.0278	2.3093	4.3371	−0.2816	Effect
C4	3.6616	3.3531	7.0146	0.3085	Cause
C5	3.1631	3.2979	6.4610	−0.1348	Effect
C6	2.6454	2.6242	5.2695	0.0212	Cause
I	3.8477	3.8941	7.7418	−0.0465	Effect

Note. The values correspond to the aggregated DEMATEL analysis, D represents the influences exerted, R the influences received, $D + R$ the total importance of the element, and $D - R$ its causal role. Positive $D - R$ values indicate causal elements, whereas negative values indicate receiving elements.

Based on the prominence ($D + R$) and causality ($D - R$) values, Figure 4 presents the DEMATEL causal diagram, which illustrates the relative position of the evaluated criteria within the identified interdependency structure.

The graph shows that C1, C4, and C6 present positive causal values and belong to the causal group of the system. Among them, C4, which represents local economic development, exhibits the highest prominence level, indicating a more central role within the interaction structure. This result suggests that local economic development exerts an important influence on the behavior of the remaining criteria. In contrast, although C1 (employment generation and formalization) and C6 (regional resilience) also belong to the causal group, their lower prominence values indicate more limited interaction levels within the system [48,49].

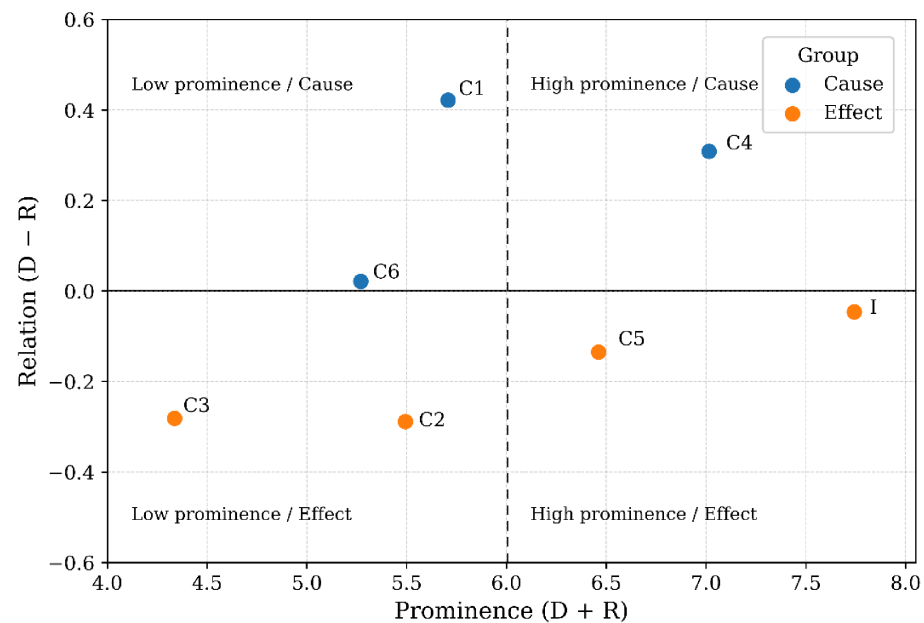


Figure 4. DEMATEL causal diagram based on $D + R$ and $D - R$ values for the evaluated criteria and the aggregated impact node.

3.4. Model Robustness: Consistency and Sensitivity Analysis

In order to evaluate the stability of the results obtained through the AHP–Ratings approach, a sensitivity analysis was conducted based on individual 10% increases in the weights of the first-level criteria. After each variation, the weights were renormalized and the final priorities of the socioeconomic impacts were recalculated. This procedure allowed the examination of the model’s response to controlled changes in the weighting structure and the verification of the robustness of the obtained prioritization [32].

The results indicate that the prioritization structure presents a high degree of stability, as shown in Table 9. This behavior is explained by the internal configuration of the model, in which the best-positioned alternatives concentrate high values within subcriteria characterized by larger relative weights in the hierarchy [50].

Table 9. Sensitivity Analysis of the AHP–Ratings Model through 10% Variations in First-Level Criteria.

Scenario	Increased Criterion	I.1 (%)	I.2 (%)	I.3 (%)	I.4 (%)	I.5 (%)	Ranking
Base	—	23.032	19.484	15.031	23.031	19.422	I.1 > I.4 > I.2 > I.5 > I.3
S1	C1 + 10%	23.204	19.360	14.938	23.179	19.319	I.1 > I.4 > I.2 > I.5 > I.3
S2	C2 + 10%	23.010	19.355	14.933	23.199	19.503	I.4 > I.1 > I.5 > I.2 > I.3
S3	C3 + 10%	23.106	19.412	14.977	23.147	19.359	I.4 > I.1 > I.2 > I.5 > I.3
S4	C4 + 10%	22.841	19.766	15.123	22.769	19.501	I.1 > I.4 > I.2 > I.5 > I.3
S5	C5 + 10%	23.042	19.458	15.129	22.948	19.424	I.1 > I.4 > I.2 > I.5 > I.3
S6	C6 + 10%	22.991	19.552	15.086	22.946	19.425	I.1 > I.4 > I.2 > I.5 > I.3

Note. The values correspond to a sensitivity analysis based on individual 10% increases in the first-level criteria, followed by renormalization and recalculation of priorities using the AHP–Ratings model. I.1 = Employment; I.4 = Economic development; I.2 = Living conditions; I.5 = Sustainability; I.3 = Gender equity.

The results additionally show that the overall ranking structure remains stable across the evaluated scenarios. Under the baseline scenario, the impacts associated with employment generation and formalization (I1) and local economic development (I4) occupy the two highest positions with almost identical values. This minimal difference allows both impacts to be interpreted as a technical tie, which explains the occasional ranking exchanges observed in some sensitivity scenarios [51].

In most scenarios, I1 and I4 maintain the highest-ranking positions, whereas I2, I5, and I3 remain relatively stable. The weighting variations introduced into the first-level criteria generated only marginal changes in the final priorities without substantially altering the overall prioritization structure [50]. This behavior suggests that the results do not depend on a single dominant criterion, but rather on a relatively stable weighted configuration within the multicriteria model.

The observed stability may also be interpreted through the interdependency structure identified by the DEMATEL analysis. The criteria with the greatest causal capacity, particularly those associated with local economic development and employment generation, play an articulating role within the system. Consequently, moderate variations in weights tend to produce limited changes in the final ranking, reinforcing the consistency of the model and its usefulness for supporting decisions related to regional bioeconomy strategies.

This behavior is consistent with previous studies on sensitivity analysis and robustness in multicriteria decision-making models, where result stability depends on the interaction between weight distribution and alternative evaluation structures [51]. Likewise, normalization and aggregation procedures have been identified as important mechanisms for reducing model sensitivity under moderate perturbations, thereby strengthening the robustness of the obtained solutions.

The second-order sensitivity analysis—incrementing each of the twelve second-level criteria weights by 10% individually—confirms the structural robustness of the AHP–Ratings model. Seven of the twelve scenarios preserve the base ranking $I.1 > I.4 > I.2 > I.5 > I.3$ without alteration, and the average score order across all scenarios remains $I.1 \approx I.4 > I.2 > I.5 > I.3$ (Table 10).

Table 10. Sensitivity analysis under +10% variations in second-level criteria weights.

Scenario	Increased Criterion	I.1 (%)	I.2 (%)	I.3 (%)	I.4 (%)	I.5 (%)	Ranking
Base	—	23.032	19.484	15.031	23.031	19.422	$I.1 > I.4 > I.2 > I.5 > I.3$
S1	C1.1 + 10%	23.241	19.448	14.979	23.012	19.396	$I.1 > I.4 > I.2 > I.5 > I.3$
S2	C1.2 + 10%	23.218	19.437	14.986	23.005	19.381	$I.1 > I.4 > I.2 > I.5 > I.3$
S3	C2.1 + 10%	23.019	19.648	14.994	22.987	19.405	$I.1 > I.4 > I.2 > I.5 > I.3$
S4	C2.2 + 10%	23.011	19.671	14.981	22.994	19.372	$I.1 > I.4 > I.2 > I.5 > I.3$
S5	C3.1 + 10%	22.991	19.451	15.218	23.001	19.374	$I.1 > I.4 > I.2 > I.5 > I.3$
S6	C3.2 + 10%	22.983	19.443	15.231	23.013	19.362	$I.4 > I.1 > I.2 > I.5 > I.3$
S7	C4.1 + 10%	22.987	19.446	14.968	23.241	19.371	$I.4 > I.1 > I.2 > I.5 > I.3$
S8	C4.2 + 10%	22.991	19.439	14.962	23.228	19.388	$I.4 > I.1 > I.2 > I.5 > I.3$
S9	C5.1 + 10%	23.018	19.458	14.997	23.024	19.617	$I.4 > I.1 > I.5 > I.2 > I.3$
S10	C5.2 + 10%	23.014	19.449	14.963	23.008	19.598	$I.1 > I.4 > I.5 > I.2 > I.3$
S11	C6.1 + 10%	23.098	19.521	15.058	23.087	19.463	$I.1 > I.4 > I.2 > I.5 > I.3$
S12	C6.2 + 10%	23.079	19.509	15.071	23.075	19.457	$I.1 > I.4 > I.2 > I.5 > I.3$

Note: Values correspond to normalized final priorities expressed as percentages. Each scenario increases one second-level criterion weight by 10%, followed by renormalization of the complete second-level criteria weight vector.

4. Discussion

4.1. Socioeconomic Implications of Biomass Valorization in Regional Bioeconomy

The prioritization results indicate that employment generation and local economic development occupy a central position within the evaluated structure. In practice, this may reflect the economic dynamics of the Colombian Orinoquia, where agro-industrial activities continue to play an important role in territorial income generation and local labor markets [52]. In Meta, the agricultural frontier represents a large share of the departmental territory, and the Eastern palm-growing zone, composed mainly of Meta and Casanare, accounts for a substantial proportion of national palm oil production [53]. Under these condi-

tions, stakeholders appear to associate biomass valorization less with abstract sustainability objectives and more with concrete economic opportunities linked to productive activities.

Part of this behavior may also be explained by the characteristics of lower-complexity valorization pathways. Activities associated with biomass collection, transport, composting, organic amendment, and decentralized bioenergy production tend to be more closely connected to local logistics, agricultural labor, and small productive units than highly specialized biorefinery routes [54]. Because of this, some impacts become more visible at the territorial level, especially in rural areas where agricultural economies remain strongly connected with local production chains.

In practice, these territorial dynamics are not always homogeneous. Some municipalities may benefit more rapidly from biomass-related activities, while others continue to depend on traditional agricultural structures with lower productive diversification [55]. Under these conditions, the territorial effects associated with biomass valorization may remain uneven across the region.

Local economic development also obtained one of the highest positions in the model. This suggests that residue reutilization is not perceived only as a waste-management strategy. In regions dependent on agro-industrial activities, biomass valorization may also become associated with productive diversification processes, local business opportunities, and new forms of interaction between agricultural actors and small enterprises [56]. Part of the interest in circular bioeconomy strategies may therefore be related to expectations regarding territorial economic stability rather than exclusively environmental concerns.

Improvement in living conditions remained in an intermediate position within the prioritization structure. This result may indicate that social effects associated with biomass valorization are perceived as less immediate or more dependent on institutional capacity and territorial implementation conditions [57]. In many rural systems, improvements in income distribution, access to services, or community well-being tend to emerge gradually and unevenly. Biomass valorization therefore should not be interpreted only as a technological alternative, since part of its territorial effects depends on governance conditions, productive articulation, and regional development processes.

Gender equity obtained lower relative values compared with the remaining impacts. Even so, its incorporation into the model remains relevant because sustainability transitions increasingly involve discussions about participation, inclusion, and access to productive opportunities [58]. The lower prioritization observed in this case may reflect the predominance of economic and productive concerns within the evaluated territorial context. Similar situations have been described in other rural bioeconomy initiatives where social inclusion dimensions tend to receive less attention during the initial stages of productive transformation [59].

More generally, the results suggest that biomass valorization may contribute to broader sustainability processes in agro-industrial regions. However, these effects are not generated automatically by residue reutilization itself. Their scope depends on how biomass becomes integrated into local productive systems, regional institutions, and territorial development strategies. In some cases, circular bioeconomy initiatives may support economic diversification and more efficient resource utilization practices, although these outcomes can vary considerably across territories [60].

4.2. Environmental Sustainability and Circular Resource Management

Environmental sustainability obtained one of the highest values in the model. Stakeholders appear to associate biomass valorization with residue management and resource use efficiency in agro-industrial regions [61].

Oil palm residues have become an environmental problem in different agricultural territories. Conventional disposal practices may increase environmental pressures associated with agro-industrial production systems. In this context, biomass reutilization may reduce part of these effects through the incorporation of residues into productive activities linked to bioenergy and biomaterials [62].

Processes related to biomass recovery may also support cleaner production practices. Energy recovery and material reutilization become relevant in regions affected by agricultural expansion and land-use pressure [63,64].

The results also showed that environmental sustainability is connected with economic and social dimensions within the system. DEMATEL identified interaction relationships among these criteria. This suggests that biomass valorization depends not only on technological processes but also on institutional and regional conditions [65].

More generally, biomass reutilization may contribute to sustainability strategies in agro-industrial regions. Some of these effects are associated with residue reduction and more efficient resource utilization practices.

4.3. Methodological Contributions and Robustness of the Multicriteria Approach

The methodological structure adopted in this study allowed the integration of social, economic, and environmental dimensions into a unified multicriteria framework oriented toward the evaluation of socioeconomic impacts associated with biomass valorization. The combination of AHP–Ratings and DEMATEL provided a complementary perspective for examining both the relative prioritization of impacts and the influence relationships among the principal dimensions of the decision system. This integration facilitated a broader interpretation of the territorial implications associated with agro-industrial residue utilization.

The AHP–Ratings approach proved useful for addressing evaluation contexts involving qualitative criteria and heterogeneous impacts. Unlike conventional hierarchical prioritization methods that require exhaustive pairwise comparisons among all alternatives, the Ratings approach simplified the evaluation process by reducing the number of required judgments while maintaining consistency within the decision structure. This characteristic becomes particularly relevant in studies involving multiple criteria, territorial dimensions, and stakeholder-based evaluations, where excessive cognitive burden may affect the coherence of expert assessments [36].

At the same time, the incorporation of DEMATEL strengthened the analytical capacity of the model by allowing the identification of influence relationships among first-level criteria and aggregated socioeconomic impacts. The DEMATEL results revealed that the evaluated dimensions do not operate independently, but rather form part of an interconnected territorial system where economic, social, and environmental effects interact dynamically.

Similar studies have highlighted the usefulness of DEMATEL for identifying complex interdependencies within sustainability-oriented decision-making processes [23].

Meanwhile, C5 (environmental sustainability) and the aggregated impact node (I) belong to the effect group and present relatively high prominence values, whereas C2 and C3, associated with improvement in living conditions and gender equity, behave as effect criteria with lower prominence. Under these conditions, strategies aimed at strengthening the causal factors identified in the DEMATEL-based causal factors—C1, employment generation and formalization in the bioproduct value chain; C4, local economic development through new business opportunities; and C6, Regional recovery and resilience in the post COVID-19 context—could indirectly contribute to promoting social and environmental dimensions within regional bioeconomy systems [66,67].

In addition, the interdependency network identified through DEMATEL helps explain the stability observed later in the sensitivity analysis. Criteria with higher causal influence

maintain relatively consolidated positions within the system structure. As a result, the general prioritization scheme remains stable even under moderate changes in the evaluation weights. This pattern indicates that the prioritization obtained presents an important degree of robustness within the analyzed framework.

The sensitivity analysis also contributed to evaluating the robustness and stability of the prioritization results. The prioritization structure remained robust under moderate variations in criterion weights, particularly for the highest-priority impacts. Although occasional changes occurred between the two highest-ranked impacts, these variations were mainly associated with the proximity of their initial weights rather than with instability in the model itself. Consequently, the final prioritization remains coherent with both the preference structure obtained through AHP–Ratings and the causal relationships identified through DEMATEL. This result is consistent with previous research on multicriteria decision-making, which emphasizes sensitivity analysis as an important component for assessing the reliability of prioritization structures under uncertainty conditions [10].

Another relevant methodological contribution lies in the possibility of adapting the proposed framework to other territorial contexts characterized by agro-industrial activities and biomass generation. Although the criteria and impacts evaluated in this study were defined according to the characteristics of the analyzed region, the general structure of the model may be replicated in different agricultural systems where sustainability, resource efficiency, and circular bioeconomy objectives are increasingly relevant. In this sense, the methodological approach may serve as a decision-support mechanism for territorial planning and sustainability-oriented policy evaluation.

Overall, the proposed multicriteria framework demonstrated the potential to support integrated sustainability assessments in agro-industrial regions where environmental pressures, socioeconomic needs, and territorial development objectives converge simultaneously. By combining prioritization, causal analysis, and robustness evaluation, the methodology provides a more comprehensive perspective for examining the implications of circular bioeconomy strategies in land-use intensive systems.

4.4. Policy Implications, Study Limitations, and Future Research

The results provide useful elements for the design of sustainability strategies in agro-industrial regions with increasing biomass generation. In the case analyzed, biomass valorization should not be treated only as an environmental issue. Employment generation, local productive activity, and regional diversification also appeared as relevant aspects in the prioritization model [56].

The DEMATEL results provide a more specific interpretation of the interaction structure among the evaluated dimensions. In methodological terms, the elements with positive D-R values can be interpreted as causal factors within the DEMATEL analysis. However, because C1–C6 correspond to socioeconomic evaluation dimensions in this study, they are discussed here as causal dimensions. Local economic development (C4), employment generation and formalization (C1), and regional resilience (C6) behaved as causal dimensions because they presented positive D-R values.

Among them, local economic development showed the highest prominence, indicating that it plays a central role in the network of socioeconomic and environmental relationships associated with oil palm residue valorization. In contrast, improvement in living conditions (C2), gender equity (C3), environmental sustainability (C5), and the aggregated impact node presented negative D – R values and therefore behaved mainly as effect factors within the DEMATEL structure. Their performance may therefore be influenced by changes in DEMATEL-based causal factors, particularly local economic development (C4), employment generation and formalization (C1), and regional recovery and resilience (C6).

These results suggest that policy measures should not be limited to promoting biomass use in general terms. In Meta, more specific instruments are needed to connect oil palm residue valorization with local employment, supplier development, and territorial productive capacity. These instruments could include technical training programs for rural workers and young people; support for small local firms involved in residue collection, transport, preprocessing, composting, biofertilizer production, biogas, and bioenergy activities; and public–private agreements with local hiring clauses, skills certification, and monitoring indicators for formal employment and local value creation. Such measures could help translate biomass valorization into broader effects on social well-being and environmental sustainability [57].

Policies aimed at strengthening local entrepreneurship, formal employment, productive linkages, and regional adaptive capacity may indirectly improve social and environmental outcomes. This is relevant for Meta, where oil palm residue valorization is connected not only with residue management, but also with rural labor markets, agro-industrial concentration, and the capacity of local actors to participate in new bioeconomy activities.

Circular economy principles may also be incorporated into regional development agendas. This is especially relevant in territories where agricultural expansion increases pressure on land use and residue management. In these contexts, biomass valorization can support more efficient use of resources and the creation of alternative productive activities [58,59].

The study has some limitations that should be considered when interpreting the results. First, the analysis was conducted in the specific territorial context of the department of Meta, Colombia, using cross-sectional information collected at a single point in time. Therefore, the findings reflect the institutional, productive, and stakeholder conditions observed in this region and should not be directly generalized to other oil palm-producing areas without further empirical validation.

Although the participant group included women and actors with knowledge of the oil palm value chain and regional development processes, the sampling design was not intended to compare specific social subgroups. For this reason, the study did not conduct a differentiated analysis of smallholders, Indigenous communities, or rural women as independent stakeholder categories. These groups may experience oil palm expansion and residue valorization processes differently, particularly in relation to employment opportunities, access to productive benefits, participation in decision-making spaces, and social inclusion. Future research could incorporate these groups more explicitly through stratified or comparative sampling designs and examine how divergent interests among smallholders, Indigenous communities, rural women, firms, and institutional actors influence consensus formation in participatory multicriteria assessments.

Second, the AHP–Ratings and DEMATEL results depend on expert judgments collected through structured participatory instruments. Although aggregation procedures and sensitivity analysis were used to examine the consistency and stability of the results, these procedures do not eliminate all uncertainty associated with individual perceptions. The sensitivity analysis was limited to controlled 10% variations in the weights of first-level criteria; therefore, it assessed ranking stability under moderate weighting changes, but not the full uncertainty associated with expert judgments.

In addition, the DEMATEL analysis was limited to first-level criteria and aggregated socioeconomic impacts. This decision reduced the complexity of the evaluation, but it may have left out other relationships within the system, particularly among subcriteria or technology-specific effects. Future research could combine participatory multicriteria assessment with subcriteria-level causal analysis and quantitative indicators to examine these relationships in greater detail.

Finally, the study did not conduct a quantitative comparison of the socioeconomic benefits and costs associated with specific oil palm residue valorization technologies. Valorization pathways such as composting, biofertilizer production, activated carbon, bioenergy, and platform chemical production were considered as intermediate mechanisms through which socioeconomic impacts may be generated, rather than as technological alternatives directly ranked in the multicriteria model. This choice allowed the analysis to focus on territorial impacts, but it also limits the capacity of the study to identify technology-specific trade-offs. Low-complexity pathways may generate more direct employment and local participation, whereas more advanced technological routes may be more closely associated with innovation, productive diversification, and regional competitiveness. Future research could compare these pathways using technology-specific indicators, cost–benefit analysis, life cycle assessment, or scenario-based approaches in order to provide more detailed evidence for policy and investment decisions.

Although this study incorporated the perspectives of stakeholders from academia, public institutions, productive sectors, and civil society, the composition of the stakeholder group represents a limitation. Some actors directly affected by oil palm agro-industrial dynamics, particularly smallholders, Afro-Colombian or Indigenous groups, were not analyzed as differentiated stakeholder categories. Their inclusion could provide a more detailed understanding of how socioeconomic priorities are perceived across territorial, ethnic, and productive positions within the Orinoquia region.

A second limitation concerns the level of technological specificity. The study evaluates socioeconomic priorities associated with the valorization of oil palm residual biomass, but it does not compare individual technological pathways in depth, such as composting, bioenergy, biogas, biofertilizers, or advanced biorefinery routes for platform chemicals. Therefore, the results should be interpreted as a territorial and multicriteria prioritization of expected socioeconomic impacts, rather than as a technical, financial, or life-cycle assessment of each valorization technology.

Future research could combine stakeholder-based multicriteria analysis with technology-specific feasibility studies to examine how different valorization routes may generate distinct employment, income, gender equity, environmental sustainability, and institutional articulation in the region.

5. Conclusions

This article examined the socioeconomic impacts associated with oil palm residue valorization through the combination of AHP–Ratings and DEMATEL. Employment generation and local economic development obtained the highest positions in the prioritization structure. Stakeholders appear to associate biomass utilization with economic activities capable of generating direct territorial effects. Environmental sustainability and social inclusion also remained relevant within the model, although with different influence levels across the evaluated dimensions.

The methodological approach made it possible to examine interaction relationships among social, economic, and environmental criteria linked to circular bioeconomy processes. DEMATEL was useful for examining the interaction relationships among the evaluated dimensions. During the sensitivity analysis, the ranking structure did not present major variations after moderate changes in the weights. The highest-priority impacts generally remained in similar positions. Comparable situations have been described in other multicriteria studies developed under uncertainty conditions.

In agro-industrial regions, biomass valorization is not limited to technical efficiency or residue reduction processes. In the Colombian Orinoquia, for example, these activities may also affect employment dynamics, local productive activities, and regional economic pro-

cesses. Some of these effects are associated with biomass utilization and the development of alternative productive practices linked to circular bioeconomy strategies.

There are also some limitations in the study. The model was developed from expert judgments obtained within a specific territorial context. Because of this, part of the prioritization may reflect local institutional conditions and regional perceptions associated with the study area. The analysis also concentrated on socioeconomic impacts and not on the direct performance of biomass conversion technologies. Other variables could produce different interaction structures.

Future studies may incorporate empirical indicators, territorial comparisons, spatial variables, or longitudinal information related to biomass utilization processes in agro-industrial systems. These elements may help examine how some of the identified relationships evolve under different regional conditions.

The framework proposed in this article may also be applied in other agricultural regions characterized by biomass generation, multiple actors, and interaction among economic, environmental, and social dimensions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land15071238/s1>, File S1: Questionnaire 1 and Questionnaire 2.

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Institutional Review Board Statement: This non-interventional study was conducted in accordance with the ethical principles established by the World Medical Association in the Declaration of Helsinki and was approved by the Bioethics Committee of Universidad de los Llanos (Act No. 013. 13 December 2024), approved on 16 December 2024.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy and confidentiality restrictions. Supplementary Materials containing sample AHP questionnaires and sample DEMATEL matrices were provided during submission to illustrate the data collection and processing procedures. The complete raw questionnaires are not publicly available because they contain individual judgments and contextual information from stakeholders that could potentially allow the identification of participants or institutions. An anonymized version of the minimum dataset necessary to support the findings may be provided upon reasonable request for academic and verification purposes.

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Abbreviations

AHP	Analytic Hierarchy Process
AHP–Ratings	Analytic Hierarchy Process with Ratings Approach
DEMATEL	Decision-Making Trial and Evaluation Laboratory
MCDM	Multi-Criteria Decision Making
ANP	Analytic Network Process
MCDA	Multi-Criteria Decision Analysis
5-HMF	5-Hydroxymethylfurfural
APC	Article Processing Charge
C1–C6	First-level criteria
C.i.j	Second-level criteria
I.1–I.5	Evaluated socioeconomic impacts
M.G.	Geometric Mean

Appendix A

Questionnaire No. 1

The questionnaire was designed to elicit expert judgments for the prioritization of socioeconomic impacts associated with the valorization of oil palm residues for bioproduct generation in the Orinoquia region (Colombia). The instrument follows the AHP–Ratings approach, integrating pairwise comparisons and categorical evaluation.

The decision problem was structured hierarchically into three levels: (i) the objective of prioritizing socioeconomic impacts; (ii) six first-level criteria, namely employment generation and formalization, improvement in living conditions, promotion of gender equity, local economic development, environmental sustainability, and regional resilience; and (iii) twelve second-level criteria associated with these dimensions. Five socioeconomic impacts were evaluated as alternatives.

Pairwise comparisons were conducted among criteria using the Saaty fundamental scale (1–9), where higher values indicate greater relative importance.

FIRST-LEVEL CRITERIA

Contribution to the objective: Prioritizing the socioeconomic impact of oil palm residue valorization through bioproduct production in the Orinoquia region.

SECOND-LEVEL CRITERIA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SECOND-LEVEL CRITERIA
C.1																		C.2
...																		...
C.5																		C.6

SECOND-LEVEL CRITERIA

Compare in pairs the importance of the second-level criteria with respect to the first-level criteria. Next, compare in pairs the importance of the second-level criteria with respect to C.1 Employment generation and formalization within the bioproduct value chain.

SECOND-LEVEL CRITERIA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SECOND-LEVEL CRITERIA
C.1.1																		C.1.2

The AHP–Ratings approach was used to evaluate the performance of each alternative with respect to each criterion. Once the criteria were weighted, each alternative was assigned to a predefined category (Rating) according to its level of contribution.

The categories included very high, high, medium, low, and very low, with corresponding numerical scores ranging from 1.00 to 0.025. This procedure allowed the integration of expert judgments regarding the degree to which each alternative satisfies each criterion.

STRATEGIES/ ALTERNATIVES	C.1.1	C.1.2	C.2.1	C.2.2	C.3.1	C.3.2	C.4.1	C.4.2	C.5.1	C.5.2	C.6.1	C.6.2
I.1												
...												
I.5												

Appendix B

Questionnaire No. 2 was designed to collect expert judgments for the third phase of the research project, focusing on the analysis of socioeconomic impacts derived from the valorization of oil palm residues for bioproduct generation in the Orinoquia region. It serves as an input for the application of the DEMATEL method, aimed at identifying and prioritizing the interdependencies among criteria and impacts.

Experts evaluated the degree of influence between elements using a scale from 0 (no influence) to 5 (very high influence). The analysis included five socioeconomic impacts: employment generation and formalization, improvement in living conditions, promotion of gender equity, local economic development, and environmental sustainability.

FIRST-LEVEL CRITERIA AND IMPACTS

FIRST-LEVEL CRITERIA	C.1	C.2	C.3	C.4	C.5	C.6	IMPACTS
C.1	0						
...							
IMPACTS							0

SECOND-LEVEL CRITERIA AND IMPACTS

	C.1.1	C.1.2	C.2.1	C.2.2	C.3.1	C.3.2	C.4.1	C.4.2	C.5.1	C.5.2	C.6.1	C.6.2	I.1	I.2	I.3	I.4	I.5
C.1.1	0																
...																	
I.5																	0

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