

Using DEMATEL to Draw a Sustainable Performance Model in the Ricinus Communis L. Production System, Bahia - Brazil

Alexei Pérez Velázquez^{1,2} & Jorge Laurence Moya Rodriguez¹

¹ Polytechnic Institute, Federal University of Bahia, Brazil

² CETEC - Federal University of Recôncavo da Bahia, Brazil

Correspondence: Alexei Pérez Velázquez, Polytechnic Institute, Federal University of Bahia, Salvador, BA, Post Code: 40210-630, Brazil. Tel: 55-71-9-9203-8808. E-mail: alexei.perez@ufba.br

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Abstract

The search for levels of competitiveness among the players in the supply chain is an indispensable condition for innovation in the production services system. One sector that has experienced this dynamic is the supply of energy raw materials for biofuel production. The aim of this study is to propose a relational model of the criteria for the sustainable performance of Common Ricinus L. producers in the region of Irecê - BA. By identifying a set of criteria, the study enables the analysis of multiple dimensions that represent the production system of Ricinus Communis L. The research methodology implemented in the study is based on structural interpretive modeling as a reference model for sustainable performance in supply chain actors. The method used to analyze the relationships and trends between the selected criteria of the Ricinus Communis L. production system was the DEMATEL method. The data used is the result of interviews conducted with experts on the oilseed production system in the Northeast of Brazil, with questions about the cultivation of Ricinus Communis L. Among the findings of this study is the definition of a relational model of the criteria and theoretical frameworks that represent sustainable performance in the supply of raw materials by Ricinus Communis L. for the generation of biodiesel.

Keywords: sustainable, DEMATEL, interest group theory, biofuel supply, Ricinus Communis L, performance model

1. Introduction

1.1 Introduce the Problem

The role played by actors in the supply chain, especially suppliers, is directly related to ensuring that the needs for goods and services are met, and that value is created along the chain. The changes implemented in management assumptions over the last thirty years have raised questions about environmentally predatory practices and irresponsibility towards socio-economic factors, (Carter & Carter, 1998; Esty & Porter, 1998). The reformulation of policies of the firms to be allows the concept of sustainability to be approached within the supply chain. This paradigm directs companies' collective efforts towards eco-responsible practices, mutual benefit for companies' internal and external interest groups and, not least, rigorous scales for attributing value to companies' corporate performance.

The early concern for sustainability is recognized in the declaration "Our Common Future" (Brundtland et al., 1987), which represents a benchmark on the challenges of socio-economic development. In parallel with the change in the management paradigm, a series of conventions and summits were held with the political leaders of the day to lay the foundations for the sustainable development goals, which are summarized in seventeen goals, a proposal made by the United Nations (UN) (United Nations, 2019).

Environmental sustainability is one of the goals of sustainable development. This represents a response to the mitigation of environmental impacts and the readaptation of business activity and supply chains in the medium and long term. On the other hand, monitoring by the Intergovernmental Panel on Climate Change (IPCC) (Shukla et al., 2019), reaffirms the need to reduce greenhouse gas (GHG) emissions. The 2015 Paris Agreement (COP21) proposes strengthening nations in the fight against climate change and developing resilient and sustainable capacities, which is expressed in the supply chain.

The condition of sustainability for a company involves complying with management policies and monitoring

indicators, which correspond to economic, social and environmental performance, (Taticchi et al., 2013) and (Taticchi et al., 2015). According to (Pereira De Carvalho, 2011), this approach can begin with an internal supply chain initiative or a demand from customers and consumers. This requires a detailed survey of the production service system, that is the object of study and the constraints that companies face in implementing sustainable management.

The generic sustainability-oriented strategy must go into internal processes and establish policies to mitigate environmental and social impacts. From the macro-strategy point of view, the energy and fuel supply chains play a relevant role in the ODS, representing an alternative for diversifying energy sources and reducing GHG emissions.

The need for renewable energy has gained strategic relevance in the development of this sector for Brazil's economy. Biofuel supply chains, as a particular case, integrate multiple socio-economic sectors for the supply, processing and final consumption of this energy source. Understanding the combination that has been adopted by the economic activity of biofuels is of interest to this study, and it is recognized by sector policy, according to (Fernández-Coppel et al., 2018) - (Martinelli et al., 2022).

The environmental, social and economic trade-offs in the biofuel chains are significant because of the contradictions in agro-energy activity, (Geraldine Castanheira et al., 2014). Conflict over land use, the water footprint and illegal deforestation are among the problems affecting this activity in Brazil, (Aguiar et al., 2016) and (Reis et al., 2021). This calls into question the sustainability of the current biofuel production system. However, the biofuel chains are categorized by type of fuel (alcohol, biodiesel, jet fuel, etc.) and by type of manufacturing technology defined by generation (1st, 2nd, 3rd and 4th generation), which requires particularization on a case-by-case basis for a careful evaluation based on a case study to assess the sustainable performance of the actors in the supply chain.

About the biofuel chains, the RenovaBio Program, (BRASIL, 2018), according to Res. No. 758 of the National Agency of Petroleum, Natural Gas and Biofuels (ANP), established the certification of efficient biofuel production by decarbonization credits for the actors in the production chain of this sector. At this point, the performance approach gains relevance, since the conditions and incentives for implementing the RenovaBio Program are marked by the economic return for recognizing good practices by supply chain actors.

A model to strengthen socio-economic factors in the biofuels chain in tandem with environmental factors needs a holistic and multidimensional vision. This represents a gap to be addressed (A. M. Rocha et al., 2013) and (M. S. Silva, 2015). In response to the problem of sustainable management in biofuel supply chain, it is necessary to focus on segments of the chain, according to (Gold et al., 2010) and (Seuring e Müller, 2008). Another strategy is to identify innovative activities and improve the performance standards of the interconnected companies. The model of excellence recognized in Environmental, Social & Governance (ESG) practices according to (Dal Belo Leite et al., 2015) and (Eguchi et al., 2015), would be the third approach that this study to consider when analyzing performance this enterprises.

The sustainable performance measurement model (Govindan, Rajendran, et al., 2015) and (Meditati et al., 2018), for *Ricinus Communis L.* (Castor Bean) producers in the Irecê region respects the particularities of small producers of this oilseed. These producers, most of whom are classified as family farmers and cooperative farmers, represent a heterogeneous population that makes it difficult to standardize a model. Nevertheless, the risk management capabilities of these actors can be summarized and studied in the *Ricinus Communis L.* production system, of according reference model (Seuring & Müller, 2008).

The focus on the initial stages of biodiesel production, specifically the source of raw material supply, is a search for levels of evidence on the sustainable performance of this object of study. The delimitation is justified by the culture of management of this oilseed in the Northeast of Brazil and the potential for unprecedented modeling using a multi-criteria method to characterize the sustainable performance of this production system.

2. Theoretical Model of Study

Accompanying the assessment of the sustainable performance of *Ricinus Communis L.* producers is the presentation of a theoretical model of the study, which represents a combination of theoretical and practical aspects. In this case, the demarcation of the criteria to be questioned by the research is indispensable, according to (Pérez-Velázquez & Moya-Rodríguez, 2021) the criteria can be grouped into seven theoretical frameworks. This would resolve the barriers faced in the measurement process but may exclude items critical to the *Ricinus Communis L.* production system.

2.1 Indicators Adopted

Nevertheless, the theoretical position adopted by this study is based on three premises. The first is the evolutionary

nature of the sustainable supply chain concept (Carter et al., 2019). The second is the perspective of process-product greening strategies, considered by the literature review (Meditati et al., 2018). And the third, the theoretical-practical arguments that allow the evaluation of the supply chain, or segments of it, by the principle of sustainable supplier selection. (Luthra et al., 2017). The presentation of the theoretical frameworks starts with the group of criteria that are most dependent on the measurement problem, i.e. the sustainable performance of suppliers, (P_s).

P_s represents an estimate of the result / effort / state of circumstances faced by the actors in the supply chain in a specific period in order to meet the goals imposed or assumed before the market, (Gauthier, 2005) - (Santiteerakul et al., 2015). P_s should be based on verifying the competencies demonstrated by the actors in the chain, either through the fulfillment of companies' responsibilities or the assessment of performance by interest groups. P_s , according to (Hervani et al., 2005), (Hassini et al., 2012) and (Beske & Seuring, 2014), must be operationalized by indicators, which categorizes the development of this study for the production system of *Ricinus Communis L.* The following studies were considered (W. S. D. Silva, 2006), (Dal Belo Leite et al., 2015), (Ferreira-Primo, 2015) and (Reckziegel-da-Rocha, 2019), which made it possible to identify criteria for the production of biodiesel raw materials. According to the consultations carried out on the criteria that characterize the sustainable performance of the *Ricinus Communis L.* production system, Table 1:

Table 1. Criteria adopted for sustainable performance in the production of *Ricinus Communis L.*

Criteria	Code
Net energy ratio kg berries produced*ha ⁻¹	PS ₁
Environmental load ratio per production volume	PS ₂
Net impact reduction per functional unit	PS ₃
Land yield in quantity of biomass	PS ₄
Economic efficiency per functional unit	PS ₅
Investment and profit return ratio	PS ₆
Energy consumption/output per functional unit	PS ₇
Energy consumption/profit per functional unit	PS ₈
Net present value of the harvest	PS ₉

Based on the above criteria, such as the environmental load ratio and the reduction in net impact per functional unit produced, the second group of criteria can be delineated, which is the environmental performance of *Ricinus Communis L.* producers. This group of criteria adds interest in the environmental dimension to the measurement of sustainable performance, which requires the concept of sustainable supply chain management. It can also be used to estimate the aptitude of the production system for environmental responsibility (Er), which would represent an assessment of environmental management in the practices of *Ricinus Communis* producers. *Ricinus Communis L.*, (S. K. Srivastava, 2007) and (M. Srivastava et al., 2020), according to table 2:

Table 2. Criteria adopted for environmental responsibility in the production of *Ricinus Communis L.*

Criteria	Code
Use of pesticides in crop processes	Er ₁
Prevention of crop waste	Er ₂
Wastewater emissions	Er ₃
Terrestrial toxicity generated per functional unit	Er ₄
Water toxicity generated per functional unit	Er ₅
Total g CO ₂ -equivalent emissions per functional unit	Er ₆
Water footprint generated by agro-energy activities	Er ₇

On the other hand, attention to the physical-chemical properties (P_{Ch}) derived from the emissions generated during the production cycle would also complement an estimate of environmental performance. In this case, the criteria should pay attention to the estimation of waste and emissions in the production of *Ricinus Communis* L. P_{Ch} affects environmental performance, as (Schaltegger & Burritt, 2014) and should be incorporated into the theoretical model on sustainable performance. The combination of pressure-impact-state factors in this activity can be complemented by the following criteria P_{Ch-i} . Therefore, the determination of environmental responsibility must follow the following criteria, according to the ABNT 14000 family of standards:

Table 3. Criteria on physical - chemical prop. generated in production of *Ricinus Communis* L.

Criteria	Code
Greenhouse Gas Emissions	P_{Ch1}
Photochemical ozone creation potential	P_{Ch2}
Eutrophication - fresh water	P_{Ch3}
Eutrophication potential	P_{Ch4}
Human toxicity - carcinogenic effects	P_{Ch5}

In turn, social responsibility (Sr) represents a set of factors related to employment policies, labor protection and safety. This construct represents a dimension of sustainability with the largest gap between theoretical and practical views, (Seuring, 2013). This condition is determined by the complexity of social sustainability. Therefore, Sr is the combination of pressure-type criteria and results, which would contribute to sustainable performance, according to table 4:

Table 4. Criteria for Social Responsibility in the Production of *Ricinus Communis* L.

Criteria	Code
Estimated toxicity potential per worker	Sr_1
Access to workers' means of protection	Sr_2
Regularity of work standards	Sr_3
Competition with food agriculture	Sr_4
Damage to human health from phytosanitary activities	Sr_5

In addition to environmental and social issues, the study of measuring sustainable performance must pay attention to economic criteria by which the results of the production chain are evaluated. Besides, to bring together this set of criteria, this research considers the economic frontier construct, (Fc) as a dimension that groups together this type of criteria. The studies on sustainable performance are aimed at Fc , (Grisi et al., 2010), (Hervani et al., 2005), (Humphreys et al., 2003) and (Lee et al., 2009). Fc contributes to sustainable performance the necessary criteria on economic sustainability, (Li et al., 2020). In view of this, integrating different Fc criteria would close the third dimension of the concept of sustainable supply chain management, of according (Carter & Rogers, 2008), to see table 5:

Table 5. Economic frontier criteria in production of *Ricinus Communis* L.

Criteria	Code
Total costs per functional unit	<i>Fc₁</i>
Actual transportation costs at harvest	<i>Fc₂</i>
Energy costs per functional unit	<i>Fc₃</i>
Allocation of investment capital per functional unit	<i>Fc₄</i>
Profit issued per functional unit	<i>Fc₅</i>
Liabilities per harvest cycle per functional unit	<i>Fc₆</i>
Financial risks and use of insurance per functional unit	<i>Fc₇</i>
Gross increase in value per functional unit	<i>Fc₈</i>
Inventory maintenance costs per functional unit	<i>Fc₉</i>
Return on investment per functional unit	<i>Fc₁₀</i>
Availability of working capital for the harvest	<i>Fc₁₁</i>

As a result of *Ricinus Communis* L production activities, it is necessary to categorize the level of satisfaction with the infrastructure and logistical security (*I_{LS}*) that these actors operate under. This group of criteria characterizes the conditions faced in the production cycle and is a combination of pressure - state - result indicators. The factors that boost or slow down the results of the actors in the chain, according to (Nascimento, 2017) - (Awasthi et al., 2018), gain a place in this study. In view of this, it is important to give due consideration to the balance between the factors that optimize results and guarantee conditions for the sustainable performance of the *Ricinus Communis* L production system, to see Table 6:

Table 6. Criteria on logistics assurance in the production of *Ricinus Communis* L.

Criteria	Code
Location/allocation of crop support inputs	<i>I_{LS1}</i>
The degree of reliability of production recipients	<i>I_{LS2}</i>
Access to production technologies	<i>I_{LS3}</i>
Access to credit lines to support the harvest	<i>I_{LS4}</i>
Availability of technical advice to support the harvest	<i>I_{LS5}</i>

On the other hand, preparation for decision-making determines the last group of criteria. These criteria are geared towards the skills of decision-makers in managing risks/benefits (*Sk*). The decision-making process that comprises the *Ricinus Communis* L. production system is geared towards the skills demonstrated or required by the human factor. *Sk* capabilities for developing a sustainable performance model, (Schaltegger & Burritt, 2014), (Nascimento, 2017), (Alves De Freitas, 2017), (Carter & Rogers, 2008) - (López, 2017). Therefore, including it in the study is necessary according to the theoretical model discussed by (Pérez-Velázquez & Moya-Rodríguez, 2021), to see table 7:

Table 7. Criteria on the competences of the producers of *Ricinus Communis* L.

Criteria	Code
Purchase prices for castor bean bags	<i>Sk₁</i>
Skills in managing plantation diseases and pests	<i>Sk₂</i>
Skills in managing climatic conditions	<i>Sk₃</i>
Skills in managing soil conditions and nutrients	<i>Sk₄</i>
Skills in managing consortia in plantations	<i>Sk₅</i>

Given this formulation of the seven groups of criteria, we can conclude that the theoretical model for the study includes different dimensions of the *Ricinus Communis L.* production system, which makes it possible to evaluate sustainable performance. The criteria presented above correspond to apre-selection of indicators on context of *Ricinus Communis L.* producers. It is necessary to establish a hierarchy and an order of dependence between the criteria. To do this, the group of criteria will be identified by the name of the framework they were associated with to evaluate them using the DEMATEL method.

3. Materials and Methods

By describing the criteria of the sustainable performance model, the aim is to bring together the different dimensions that characterize this concept. The relationship between the criteria is the key to formulating a measurement model. A proposed relational structure for the criteria would justify the interpretative exercise about the links and relative weight that each one has in the evaluation procedure. Therefore, a discussion of the methods implemented is essential for presenting the study.

Different techniques are used to process the indicators, including ELECTRE, (de Almeida, 2007); PROMETHEE, (Calders & Van Assche, 2018); TOPSIS, (Kannan et al., 2009) - (Wang et al., 2009); VIKOR (Sayadi et al., 2009), which were implemented in the evaluation of supplier performance, specifically reinforcing the sustainable view. These techniques establish a decision-making support system, making it possible to define a measurement model by studying the relationship between indicators and determining the model's optimum decision-making region.

The system of indicators described above was treated using the DEMATEL, (Gabus, A., Fontela, 1972) and (Wu & Lee, 2007). This technique has variants such as classic DEMATEL, Fuzzy-DEMATEL, Grey-DEMATEL, ANP-DEMATEL and AHP-DEMATEL, which make it possible to order priorities and establish a causal relationship between the items considered. A reference for the application of this technique can be found in the studies by (Chiou et al., 2011) - (Govindan, Khodaverdi, et al., 2015), This leads to the choice of a classic DEMATEL to identify the degree of causality between the indicators that correspond to the selected criteria.

The development of DEMATEL starts from the premise of selecting the indicators that model sustainable performance in the *Ricinus communis L.* production system. This should guide the metrics for sustainable performance and how the criteria are related. Based on the evidence on the criteria and indicators of sustainable performance in a *Ricinus communis L.* production system, the following question must be answered:

How do the criteria and indicators that describe sustainable performance relate to supply chain actors according to the object of study?

The theoretical modeling of the criteria and the search for the answer to the research question this inquiry. It is worth noting that the selection of indicators is derived from the mapping of indicators on performance in the biofuel supply chain. The studies were consulted: (M. S. Silva, 2015), (M. S. da Rocha, 2014), (Ferreira-Primo, 2015) and (Reckziegel-da-Rocha, 2019) guided the choice of a group of criteria. Therefore, these indicators will be reviewed, chosen and evaluated by experts previously consulted through a questionnaire (Note 1). The use of DEMATEL is summarized in the diagram (see figure 1).

For the DEMATEL method, verification of the interviewees' competencies is required as a prerequisite for including the questionnaire response in the study. Experts with a competence coefficient of over 0.75 are accepted to evaluate the indicators of the sustainable performance model and thus make up the database for implementing DEMATEL.

3.1 Evaluation Method by Experts and DEMATEL

DEMATEL was a technique proposed by (Gabus, A., Fontela, 1972), which makes it possible to weight the items and define the degree of relationship or causality between them. In this case, the indicators that underpin each variable characterize the production system of *Ricinus communis L.* This study integrates the DEMATEL method by consulting a group of experts on the weighting and level of relationship between the criteria considered in the study. The application of this technique is based on the pre-established definition of the relationships between the indicators. Figure 1 illustrates the steps that preceded this study.

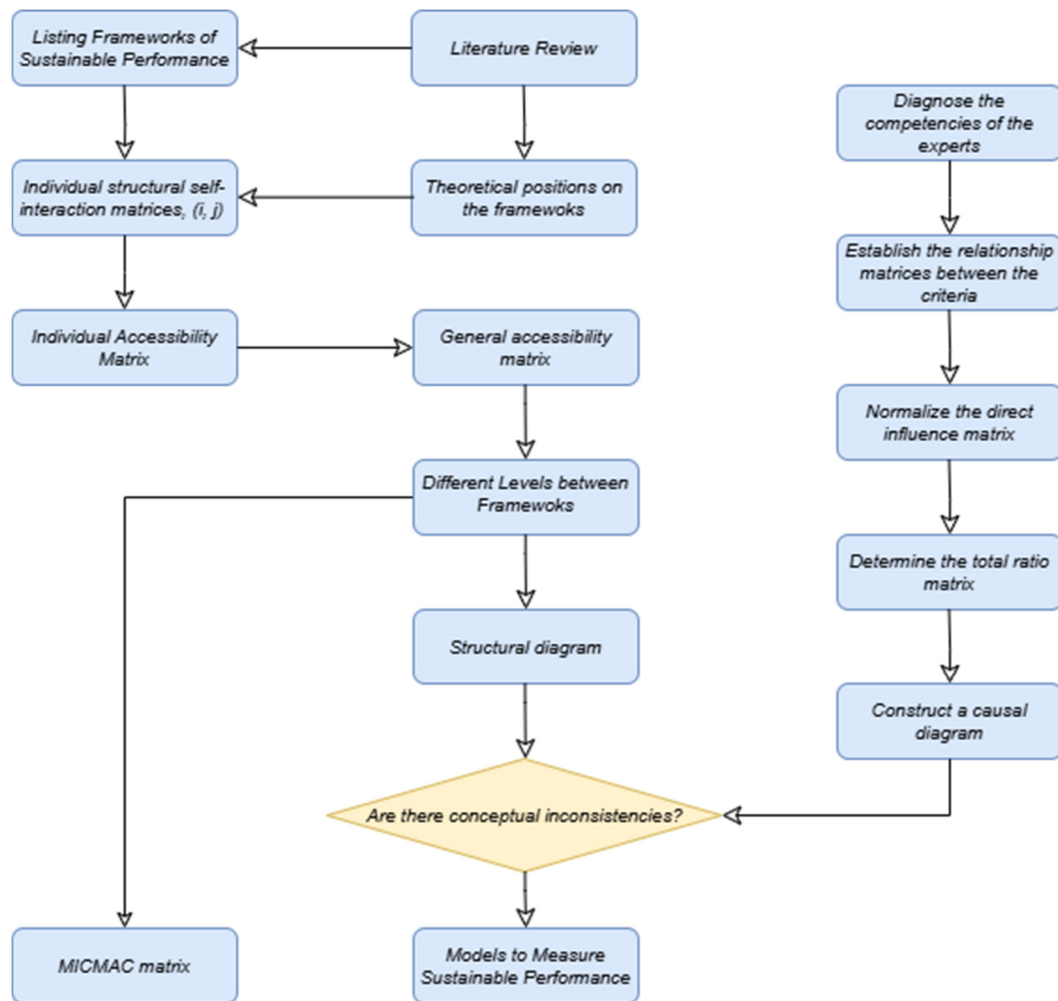


Figure 1. Combined ISM and DEMATEL method

DEMATEL should therefore provide a diagnosis in the form of a theoretical model for assessing the sustainable performance of the *Ricinus communis* L. production system. The steps followed in the study are illustrated below.

Step 1: Diagnose the competencies of the experts according to a rule system for selecting the evaluators who will take part in the study. Consideration should be given to k_c , which is the coefficient of knowledge - training of the experts on the subject in question; and k_a , which is the coefficient of argumentation of the experts. To carry out this step, the procedure proposed by (Pérez-Campaña, 2005) for the selection of the experts who took part in the study, to see figure 2. Based on the evaluation on a scale subdivided between 0 and 1, the self-quantification of k_c , where 0 is the expert's lack of knowledge about the object of study (OS) and 1 is maximum knowledge about the object of study. The sources of argumentation are as follows, to see table 8:

Table 8. Rule for coefficient on sources of argumentation, (k_a)

Sources of argument	High	Medium	Low
Number of theoretical analyses published over OS	0,20	0,15	0,10
Professional experiences on OS	0,20	0,15	0,10
Applied research projects you have participated in on OS	0,15	0,10	0,06
Co-authorship of articles, theses and/or patents on OS	0,15	0,10	0,06
h-index value at the time of the interview	0,15	0,10	0,06
Attribution of intuition skills on OS	0,15	0,10	0,06

The calculation of K_j , which is the expert competence coefficient, is defined by the following equation:

$$K_j = (k_c + k_a) / 2x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (1)$$

In this case, experts with K_j values ≥ 0.75 are accepted to be part of the DEMATEL evaluation team. Pre-selected experts who do not meet this coefficient will be able to present their criteria via an open-ended questionnaire on the criteria under analysis and will be thanked for participating in the study in this way.

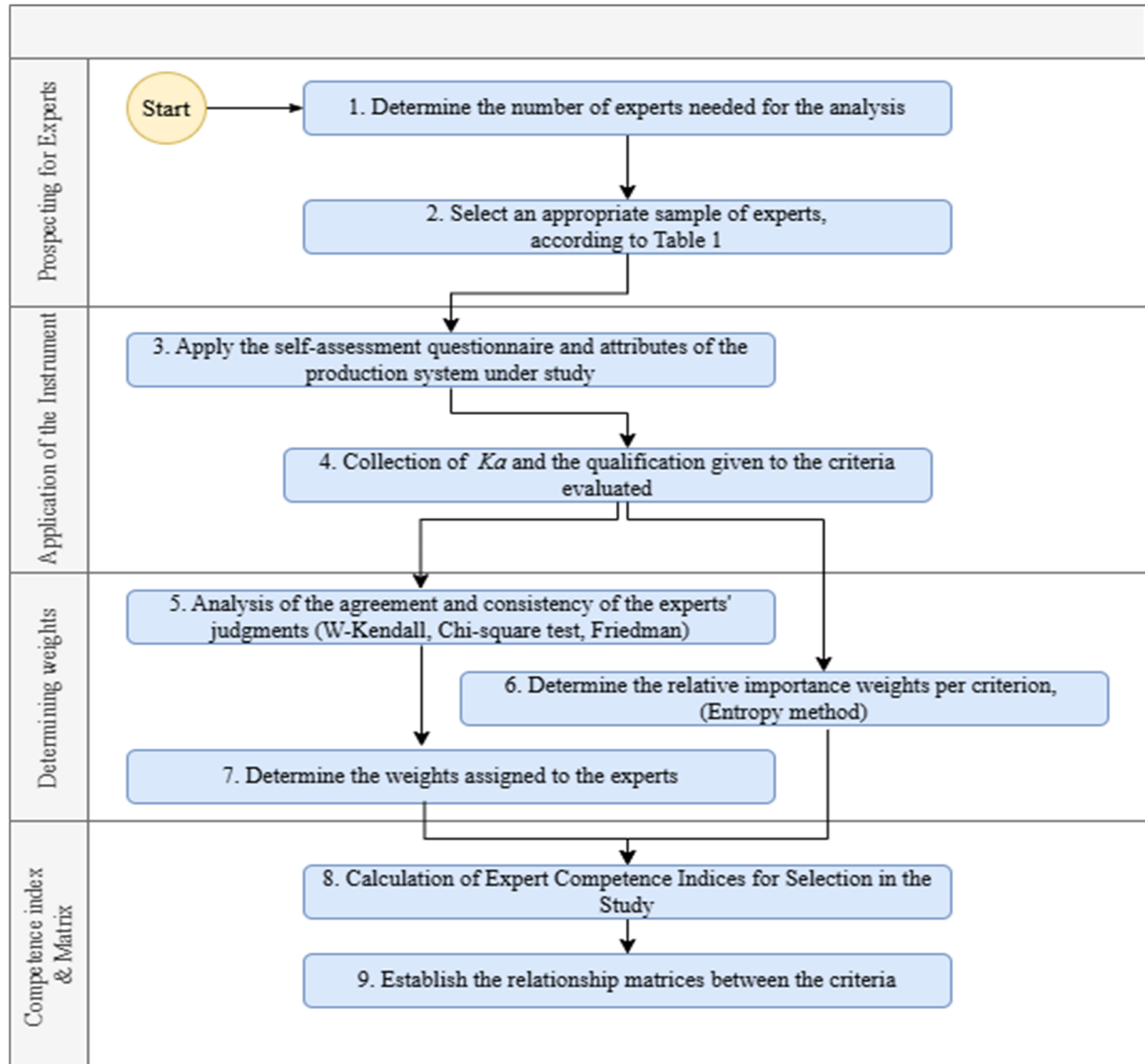


Figure 2. Procedure for selecting relationship matrices

Assigning the weight of the criteria is defined by the following labels:

Weights labels

[0] (no influence)

[1] (very low influence)

[2] (low influence)

[3] (high influence)

[4] (very high influence).

Step 2. Establish the relationship matrices between the criteria, $\{C_1, C_2, C_3, \dots, C_n\}$, where it must be compared by pairs of criteria. This results in under matrices $A_{(i,j)}$. The labels that are assigned per pair of criteria are:

Relationship levels

[0] unrelated

[1] few related

[2] related

[3] high related

[4] highly related

Each criterion must be assigned a weight, which is compared with the pre-established relationship matrix to define the relational value between the criteria:

$$a_{ij} = \frac{\sum_{k=1}^K w_k x_{ij}^k}{\sum_{k=1}^K w_k} \quad (2)$$

Wherein:

w_k : are the importance weights assigned to each criterion,

K : number of experts interviewed who evaluated the criteria,

x_{ij}^k : level of relationship between pairs of criteria,

a_{ij} : relational value between pairs of criteria.

Step 3. Normalize the direct influence matrix by applying the following equation:

$$D = A * S \quad (3)$$

$$S = \frac{1}{\max \sum_{j=1}^n a_{ij}} \quad 1 \leq i \leq n \quad (4)$$

Wherein:

S : normalization factor,

D : matrix of direct relation normalized,

A : matrix of relationships between criteria.

The values of matrix D have a $[0; 1]$.

Step 4. Determine the total ratio matrix that corresponds to the following equation:

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

Wherein:

T : total ratio matrix,

I : identity matrix.

Step 5: Construct a causal diagram using the total relationship matrix. In this case, the sum of the child vectors and columns, r_i and c_j , allows the causal diagram to be drawn up. The sum of $(r_i + c_j)$ is the reflection of the total effects of criteria i on the overall network. For its part, $(r_i - c_j)$ should be reflected like effects or causes, which contributes to the definition of criterion i in the general network.

If $(r_i - c_j)$ is positive the criterion is cause, if $(r_i - c_j)$ is negative the criterion is effect. To establish each factor, the following equations must be met:

$$T = [t_{ij}]_{n \times m}, i, j = 1, 2, 3, \dots, n \quad (6)$$

$$r = \left[\sum_{j=1}^n t_{ij} \right]_{n \times 1} = [r_i]_{n \times 1} \quad (7)$$

$$c = \left[\sum_{i=1}^n t_{ij} \right]_{1 \times n}' = [c_j]_{1 \times n}' \quad (8)$$

According to the DEMATEL procedure, the results would demarcate the causal diagram of the criteria considered in the sustainable performance measurement model. To conclude with the application of the method, an assessment must be made of the inconsistencies in the structural and causal model in relation to the positions of the criteria and/or group of criteria. From this point on, the method provides a result for the strongest relational level between the criteria that characterize sustainable performance, which was cited like object of study.

4. Application of the Combined Method

4.1 Implementation of the Structural Interpretative Instrument

The criteria presented start with the formulation of the framework that were related to the sustainable supply chain and the estimation of the performance of the actors in the chain. The result of this study is a theoretical conceptual consolidation of Sustainable Performance, which is summarized in the following model (see figure 3):

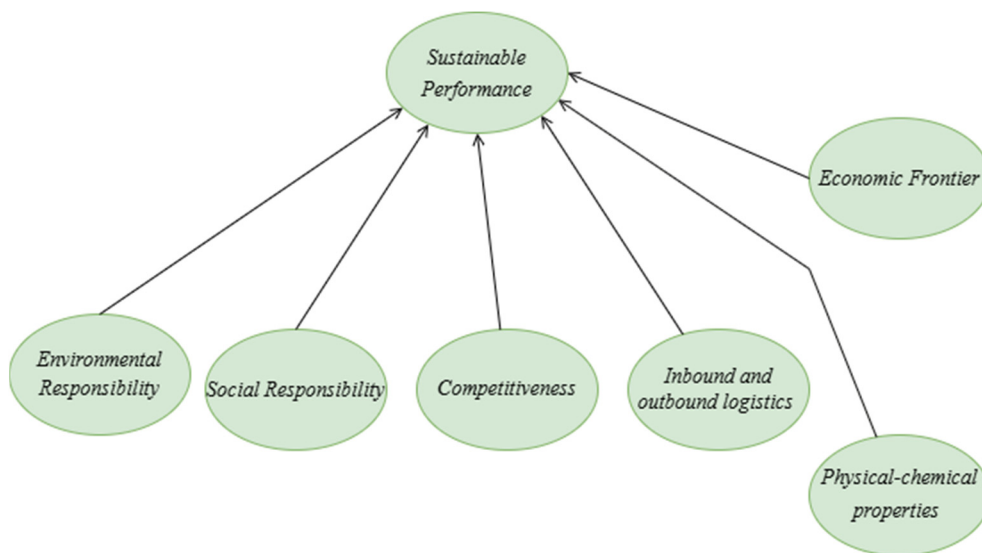


Figure 3. Structural diagram by dependency ratio and driving power

In the structural diagram and MICMAC matrix resulting from the application of ISM, the group of criteria on physical and chemical properties register the highest level of conceptual inconsistency for measuring the sustainable performance of supply chain actors. The present study assumes the premise of regarding this group of criteria, physical - chemical properties derived *Ricinus communis* L. producers, with an observation to evaluation. This decision is based on the search, through the DEMATEL qualitative evaluation method, for the highest degree of parsimony of the other criteria.

4.2 DEMATEL Implementation

The *Ricinus Communis* L. production system highlights the importance of the decision-making process. A matrix of the data collected was constructed (see Appendix 1). 15 specialists were selected with $K_j \geq 0,75$. This makes it possible to calculate the vectors of the criteria that characterize the object of study, (see table 9).

Table 9. DEMATEL results

<i>Criteria</i>	<i>code.</i>	r_i	c_j	(r_i+c_j)	(r_i-c_j)	Trend
Estimated toxicity potential per worker	<i>Sr</i> ₁	35,91	2,91	38,82	33	Cause
Access to workers' means of protection	<i>Sr</i> ₂	-10,91	1,72	-9,19	-12,63	Effect
Regularity of work standards	<i>Sr</i> ₃	-18,2	-6,71	-24,91	-11,49	Effect
Competition with food agriculture	<i>Sr</i> ₄	0	-1	-1	1	Cause
Damage to human health - phytosanitary activities	<i>Sr</i> ₅	-18,63	-4,3	-22,93	-14,33	Effect
Use of pesticides in crop processes	<i>Er</i> ₁	6,33	-10,05	-3,72	16,38	Cause
Prevention of crop waste	<i>Er</i> ₂	-33,07	-1,03	-34,1	-32,04	Effect
Wastewater emissions	<i>Er</i> ₃	54,01	2,15	56,16	51,86	Cause
Terrestrial toxicity generated per functional unit	<i>Er</i> ₄	-1,88	30,02	28,14	-31,9	Effect
Water toxicity generated per functional unit	<i>Er</i> ₅	5,63	-18,74	-13,11	24,37	Cause
Total gCO ₂ -equivalent emissions per functional unit	<i>Er</i> ₆	-1,7	4,98	3,28	-6,68	Effect
Water footprint generated by agro-energy activities	<i>Er</i> ₇	-25,89	-0,11	-26	-25,78	Effect
Total costs per functional unit	<i>Fc</i> ₁	13,49	0,96	14,45	12,53	Cause
Actual transportation costs at harvest	<i>Fc</i> ₂	23,07	2,44	25,51	20,63	Cause
Energy costs per functional unit	<i>Fc</i> ₃	-20,05	-3,29	-23,34	-16,76	Effect
Allocation of investment capital per functional unit	<i>Fc</i> ₄	-6,1	-1,78	-7,88	-4,32	Effect
Profit issued per functional unit	<i>Fc</i> ₅	-0,6	-2,53	-3,13	1,93	Cause
Liabilities per harvest cycle per functional unit	<i>Fc</i> ₆	-3,08	1,15	-1,93	-4,23	Effect
Financial risks and use of insurance per funct. unit	<i>Fc</i> ₇	-45,53	0,13	-45,4	-45,66	Effect
Gross increase in value per functional unit	<i>Fc</i> ₈	2,35	1,57	3,92	0,78	Cause
Inventory maintenance costs per functional unit	<i>Fc</i> ₉	9,85	-9,7	0,15	19,55	Cause
Return on investment per functional unit	<i>Fc</i> ₁₀	2,64	-0,53	2,11	3,17	Cause
Availability of working capital for the harvest	<i>Fc</i> ₁₁	-1,18	27,49	26,31	-28,67	Effect
Purchase prices for castor bean bags	<i>Sk</i> ₁	19,17	-22,09	-2,92	41,26	Cause
Skills in managing plantation diseases and pests	<i>Sk</i> ₂	22,48	-0,78	21,7	23,26	Cause
Skills in managing climatic conditions	<i>Sk</i> ₃	-24,6	0,56	-24,04	-25,16	Effect
Skills in managing soil conditions and nutrients	<i>Sk</i> ₄	-15,1	-1,14	-16,24	-13,96	Effect
Skills in managing consortia in plantations	<i>Sk</i> ₅	-0,36	-1	-1,36	0,64	Cause
Location/allocation of crop support inputs	<i>LS</i> ₁	7,27	1,46	8,73	5,81	Cause
The degree of reliability of production recipients	<i>LS</i> ₂	0,1	-1	-0,9	1,1	Cause
Access to production technologies	<i>LS</i> ₃	17,22	0,01	17,23	17,21	Cause
Access to credit lines to support the harvest	<i>LS</i> ₄	-32,05	2,39	-29,66	-34,44	Effect
Availability of technical advice to support the harvest	<i>LS</i> ₅	-5,9	-8,12	-14,02	2,22	Cause
Net energy ratio kg berries produced*ha ⁻¹	<i>Ps</i> ₁	14,18	1,64	15,82	12,54	Cause
Environmental load ratio per production volume	<i>Ps</i> ₂	19,82	2,26	22,08	17,56	Cause
Net impact reduction per functional unit	<i>Ps</i> ₃	4,47	3,06	7,53	1,41	Cause
Land yield in quantity of biomass	<i>Ps</i> ₄	-15,18	4,82	-10,36	-20	Effect
Economic efficiency per functional unit	<i>Ps</i> ₅	30,59	-7,98	22,61	38,57	Cause
Investment and profit return ratio	<i>Ps</i> ₆	5,9	-5,86	0,04	11,76	Cause
Energy consumption/output per functional unit	<i>Ps</i> ₇	-6,12	1,91	-4,21	-8,03	Effect
Energy consumption/profit per functional unit	<i>Ps</i> ₈	-24,5	-0,75	-25,25	-23,75	Effect
Net present value of the harvest	<i>Ps</i> ₉	-0,66	-1,94	-2,6	1,28	Cause

After calculating the parameter values for each criterion, the causal diagram between them was constructed. The values of (r_i+c_j) and (r_i-c_j) determine the coordinates of the criteria in the diagram, (See figure 4a e 4b).

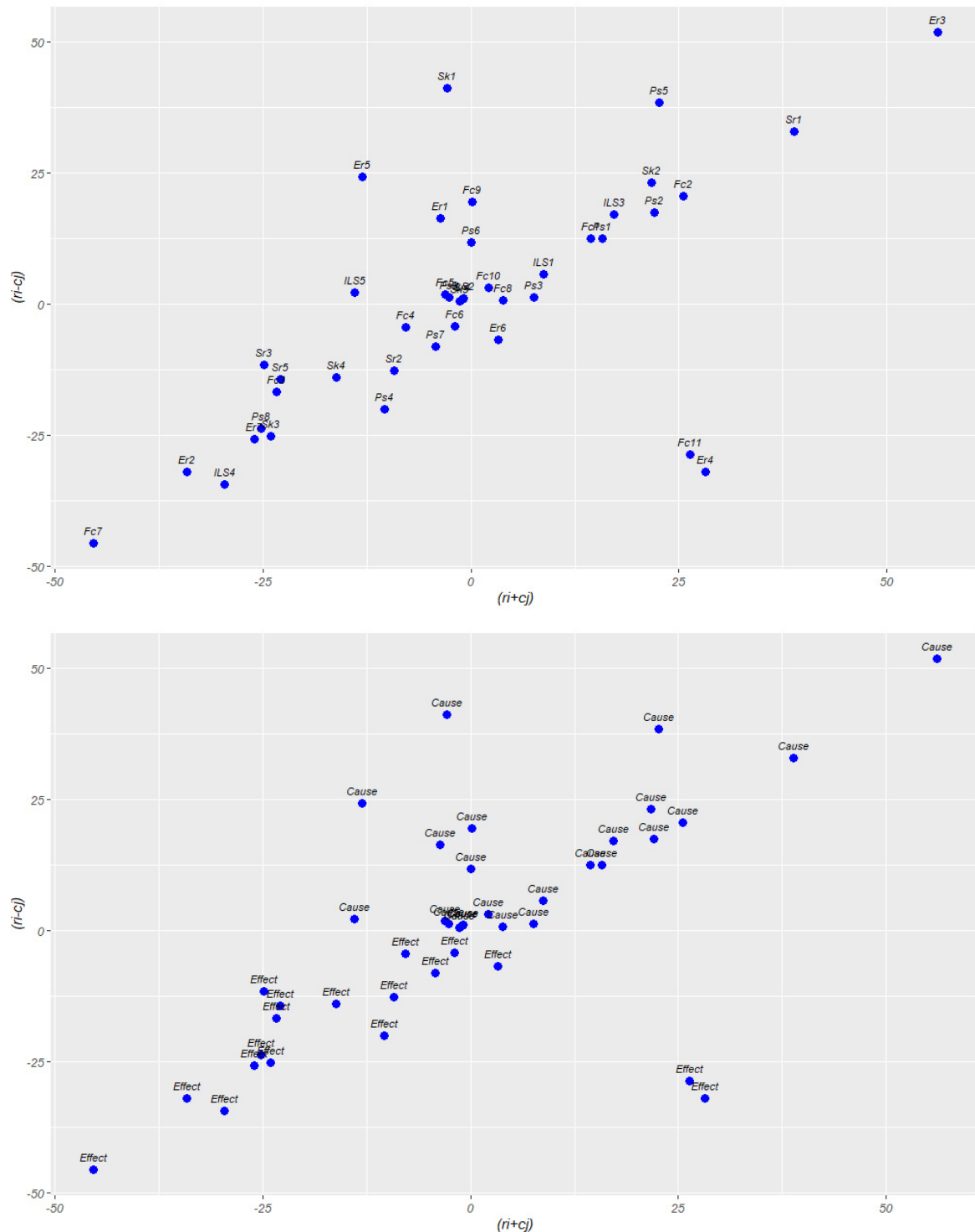


Figure 4a and 4b. Causal - effect diagram of the DEMATEL method

The DEMATEL method enabled the classification of criteria that characterize sustainable performance in the production of *Ricinus Communis* L. The demarcation through the processing of expert criteria is a preliminary diagnosis for this productive sector of oilseed raw materials in the state of Bahia. This productive sector describes a strong interdependence between environmental, economic, and technical-operational criteria in relation to the

sustainable performance of *Ricinus communis* L. producers. This highlights the relationship between the cultural model of this crop and efficiency in agricultural production and resource management, which impacts the sustainability of the productive system. The environmental dimension is an assessment front that brings together indicators describing the environmental impact of this activity on the ecosystem and the risk to human life.

On the other hand, economic indicators are key to attributing sustainability, seen from the territorial plan to the viability of this productive activity and value generation. The economic dimension represents a heterogeneous group of criteria, where items such as total costs per functional unit, actual transportation costs at harvest, profit generated per functional unit, gross increase in value per functional unit, inventory maintenance costs per functional unit, and return on investment per functional unit are causes for the problem discussed in this article. In the case of criteria classified as effects, we can recognize energy costs per functional unit, investment capital allocation per functional unit, liabilities per harvest cycle per functional unit, financial risks and use of insurance per functional unit, and availability of working capital for harvesting. Given the classification framework for economic factors, we can say that the dictates of this dimension are inconclusive. Similarly, the factors that bring together technical knowledge and workforce skills for planting practices. The criteria for skills in managing climatic conditions and soil and nutrient conditions are presented as effect-type, which represents a divergence from the theoretical arguments presented on this dimension in the study.

Based on the results provided by DEMATEL, we can identify some trends that corroborate the answer to the research question about the sustainable performance of *Ricinus communis* L. producers. The criteria evaluated by a multi-criteria analysis of experts recognized P_{s4} (Land yield in terms of biomass quantity) as a key effect of this production system. For the complementary dimensions, not previously characterized, a balance between causal factors and effects is observed. In this case, the indicators show that sustainable performance is built on the internal causes of the production system, and not only on external market factors or aid policies for the cultivation of *Ricinus communis* L.

The DEMATEL method enabled the classification of criteria that characterize sustainable performance in the production of *Ricinus Communis* L. The demarcation through the processing of attributions given by experts is a preliminary diagnosis for this productive sector of oilseed raw materials in the state of Bahia. This productive sector describes a strong interdependence between environmental, economic, and technical-operational criteria in relation to the sustainable performance of *Ricinus communis* L. producers. This highlights the relationship between the cultural model of this crop and efficiency in agricultural production and resource management, which impacts the sustainability of the productive system. The environmental dimension is an assessment front that brings together indicators that describe the causes and impacts corresponding to this productive activity.

The economic indicators of this productive activity represent the economic dimension with a heterogeneous group of criteria, where items such as total costs per functional unit, actual transportation costs at harvest, profit generated per functional unit, gross increase in value per functional unit, inventory maintenance costs per functional unit, and return on investment per functional unit are of the cause type. The criteria classified as effects recognize energy costs per functional unit, investment capital allocation per functional unit, liabilities per harvest cycle per functional unit, financial risks and use of insurance per functional unit, and availability of working capital for harvesting. Given the classification framework for economic factors, there is a lack of complete confirmation regarding their influence on the sustainable performance of *Ricinus communis* L. producers. Similarly, the factors that bring together technical knowledge and workforce skills for planting practices show a difference in the classification of criteria. In this case, the theoretical arguments presented on this dimension in the study are contested by the results of the procedure.

Based on the results provided by DEMATEL, we can identify some trends that corroborate with the research question on the sustainable performance of *Ricinus communis* L. producers. The criteria evaluated by experts using multi-criteria analysis recognized P_{s4} (land yield in terms of biomass quantity) as a key effect of this production system. For the complementary dimensions, not previously characterized, a balance between causal factors and effects is observed. In this case, the indicators show that sustainable performance is built on the internal causes of the production system, and not only on external market factors or aid policies for the cultivation of *Ricinus communis* L.

5. Discussion

Based on these results, it is possible to formulate that Irecê-BA has a productive context characterized by family farming in semi-arid conditions, where water and soil limitations pose additional challenges to castor bean cultivation. Added to this is the strong dependence on input costs and price fluctuations, which accentuates the economic vulnerability of producers. In this scenario, it is essential to incorporate technologies and training actions

to address pests, diseases, and climate variability, in addition to strengthening public policies related to technical assistance, rural credit, and cooperativism. The relational model shows that environmental interventions, such as reducing emissions and controlling pesticide use, can generate not only environmental but also social and financial benefits. In addition, the development of technical skills acts as a leverage factor, capable of reducing negative impacts on costs and productivity. Economic variables, such as prices and transportation, are strongly linked to market dynamics and logistics, with cooperation between producers and the strengthening of alternative associations being strategic for mitigating risks. Finally, it is observed that critical effects, such as financial risks and access to credit, are conditioned by environmental and economic causes, so that appropriate public policies and green financing instruments have the potential to balance and strengthen the sustainability of the castor bean chain in the region.

6. Conclusions

From the development of the study, several conclusive points can be summarized. The first aspect that stands out from the study is an understanding of the dynamic interactions in the *Ricinus communis* L. production system and the relationship to the sustainable performance category. The second conclusive point is related to the theoretical dimensions chosen, which allow us to cover the *Ricinus communis* L. production system and diagnose possible problems related to sustainable performance. The third item is the identification of the region of interdependence between the criteria prospected in the production system and the potential for measuring sustainable management. This last element is geared towards the practicality of the DEMATEL method, which makes it possible to establish a classification system for the criteria derived from the qualitative assessment of the experts. It should be noted that the method facilitated corroboration of the importance of the policies and strategies of responsibility of the actors within the production system of *Ricinus communis* L. This result creates a preliminary basis for considering a strategy for modeling sustainable performance in this type of agro-energy activity. The study recognizes two limitations. The first is the source of data for the implementation of DEMATEL through a group of experts based on self-qualification of the coefficient of competence. The second is the lack of a proposal for using the relational model and classification framework for the criteria that were assessed. In view of these conclusions, it can be stated that the objective of the study was met and the elements suggested have the potential to contribute to future studies.

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Note

Note 1. <https://x.gd/DRmwh> - Questionnaire template used

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Authors contributions

The conceptualization of the research article was realized by A.P-V and J.L. M-R. The methodology was selected by A.P-V with review of J.L. M-R. The validation was developed by A.P-V. The formal analysis, investigation and writing—original draft preparation was responsibility of A.P-V with review of J.L. M-R. The project administration was realized by A.P-V and J.L. M-R.

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Obtained.

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Data sharing statement

No additional data are available.

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