Pesquisa Operacional (2024) 44: e284063 p.1-26
doi: 10.1590/0101-7438.2023.043.00284063

Printed version ISSN 0101-7438 / Online version ISSN 1678-5142
www.scielo.br/pope
ARTICLES

DRIVING ESG COMPLIANCE: THOR-2 ASSESSMENT OF BIODIESEL PRODUCTION CAPACITIES IN THE MIDWEST AND SOUTH OF BRAZIL

Valmiane V. A. Almeida[1*], Carlos Francisco S. Gomes[2], Luis Hernan C. Pinochet[3] and Marcos dos Santos[4]

Received March 1, 24 / Accepted July 20, 24

ABSTRACT. The study employed the THOR-2 method to select a federal unit (UF) in Brazil's Midwest and South regions for investments in biodiesel production, considering ESG criteria. Evaluating six criteria, such as actual production and installed capacity, it was identified that Rio Grande do Sul stood out as the best option, for its established capacity, operational efficiency and growth potential. The ranking of UFs highlighted the importance of multi-criteria-based choices, aiming to balance economic impacts with social and environmental benefits. Thus, the study provided a framework for choosing a UF for biodiesel investments and integrated ESG considerations, contributing to sustainability in the energy sector.

Keywords: THOR-2, biodiesel, sustainability, ESG.

1 INTRODUCTION

Decision-making in complex processes requires methods capable of quantifying uncertainty in alternative rankings and weights, going beyond mere rankings to provide transparent and agile quantitative analyses. The vast land area of oilseed production in the Midwest is pivotal for the biodiesel industry. Besides driving local economic growth, it diversifies the national energy matrix, reducing dependence on fossil fuels. Meanwhile, the South's favorable agricultural climate and crop variety enable more versatile and environmentally responsible production. These regions are crucial in promoting renewable and sustainable energy sources, aligning with ESG

*Corresponding author
[1]Fluminense Federal University (UFF), Niterói, RJ, Brazil – E-mail: valmiane@gmail.com – https://orcid.org/0000-0001-8239-8312
[2]Fluminense Federal University (UFF), Niterói, RJ, Brazil – E-mail: cfsg1@bol.com.br – https://orcid.org/0000-0002-6865-0275
[3]University of São Paulo (FEA-USP), São Paulo, SP, Brazil – E-mail: luis.hernan@usp.br – https://orcid.org/0000-0003-2088-5283
[4]Military Engineering Institute (IME), Rio de Janeiro, RJ, Brazil – E-mail: marcosdossantos@ime.eb.br – https://orcid.org/0000-0003-1533-5535

(Environmental, Social, and Governance) principles. These have become a corporate landscape's sustainability symbol since the 2022 Global Pact (ABIOVE, 2023).

The incorporation of ESG evaluation in investment processes aims for higher returns and lower risk, driving the consideration of these criteria as fundamental in investment strategies (RODRIGUES, 2021). In this context, this article proposes to evaluate and rank the federal units (UFs) in Brazil's South and Midwest regions, seeking to identify opportunities for private investment in the biodiesel production sector. The potential for such investments is significant, with the potential to impact the reduction of greenhouse gas emissions, foster sustainable agricultural practices, and generate jobs in rural areas. This presents a promising opportunity for those interested in contributing to the environmental and socioeconomic sustainability of the region.

The topic's relevance is directly linked to the growing demand for renewable and sustainable energy sources, which is essential to mitigate traditional energy sources' environmental and social impacts (ONU, 2021). Biodiesel production is a viable and promising alternative for diversifying Brazil's energy matrix, reducing greenhouse gas emissions, and promoting local economic development (PESSOA JUNIOR *et al.*, 2020). Moreover, integrating ESG criteria in the investment decision-making process in the biodiesel sector aligns business practices with sustainability principles. It strengthens the resilience of the agricultural and industrial communities involved. Therefore, the careful and structured analysis using the THOR-2 method, applied in the context of biodiesel production, not only fosters the adoption of sustainable practices but also offers a robust model for future initiatives in related sectors.

Biofuel has stood out as a low-cost solution to achieve net zero carbon emissions by 2050 in Brazil. There is a study that reveals that due to the use of bioenergy with carbon capture and storage (BECCS), biofuels play a crucial role in slowing down the phase-out of fossil fuels in the country (POGGIO *et al.*, 2024). This approach takes advantage of Brazil's abundant natural resources and existing knowledge and contributes significantly to reducing greenhouse gas emissions. Furthermore, the flexibility of biofuels allows for the possibility of hybrid strategies, such as the use of ethanol or hydrogen fuel cells in electric powertrains, further increasing the potential for climate mitigation (POGGIO *et al.*, 2024). Therefore, the importance of biofuels is highlighted not only by their economic efficiency, but also by their ability to complement global technological trends, strengthening the resilience and sustainability of the Brazilian energy matrix.

Furthermore, the biofuels sector in Brazil also shows promise in terms of greenhouse gas (GHG) emissions. Using complex networks and input-output analyses, a study reveals that although the agricultural sector is a significant emitter of GHGs in the Brazilian economy, the biofuels sector stands out as the most demanding in relation to GHG emissions embodied in commerce (DE AREA LEÃO PEREIRA *et al.*, 2024). This underlines the critical role of the biofuels industry in addressing environmental challenges, as it requires substantial consideration of GHG emissions in its operations. The conclusions emphasize the importance of biofuels in discussions about mitigating environmental threats from polluting sectors, contributing to the sustainability of the Amazon and in efforts to combat global climate change (DE AREA LEÃO PEREIRA *et al.*, 2024). Therefore, the biofuels sector plays a crucial role in reducing emissions and promoting sustainable development practices for environmental preservation.

The importance of biofuels is also revealed in environmental management and in reducing environmental degradation in the BRICS countries (Brazil, Russia, India, China and South Africa). Using second-generation econometric methodologies, results show that biofuel production has a significant negative relationship with environmental damage caused by waste management, as revealed by the Driscoll-Kraay standard errors (DKSE) approach (GONG & ASLAM , 2024). This implies that an increase in biofuel production is associated with a reduction in environmental degradation in the region. Furthermore, they suggest that although financial sectors face challenges in addressing environmental threats, strict monitoring of financial control measures and provisions relating to environmental issues is necessary to achieve sustainable development (GONG & ASLAM, 2024). Therefore, biofuel production emerges as an effective solution to mitigate environmental damage and promote sustainable development, highlighting the need for political support and a goal-oriented approach supported by the central authorities of the respective countries. Parte inferior do formulário

The article is divided into an introduction and a description of the problem, the theoretical foundation, the methodology, the proposed solution, a discussion of the results, and a conclusion.

2 DESCRIPTION OF PROBLEM

The discussion on sustainable development, incorporating social, environmental, and economic dimensions, is global. In Brazil, public policies have supported the biodiesel sector, notably the program RenovaBio, which is backed by various governmental bodies (BRASIL, 2021). Recognized as a viable substitute for fossil diesel, biodiesel stands as a potential solution for future energy challenges, particularly in developing countries like Brazil (RODRIGUES, 2021).

The concept of sustainability, with a robust history, is broadly defined by the World Commission on Environment and Development (1987), characterizing it as "paths of human progress that meet the needs of the current generation without compromising the ability of future generations to meet their own needs" (BRUNDTLAND, 1987). Goodland and Ledec (1987) elaborate on this vision, conceptualizing sustainable development as "a pattern of social development and structural economic transformations that optimize available benefits in the present without compromising potential benefits in the future." This definition implies sustaining yields from renewable natural systems over time.

Other approaches emphasize the importance of the physical or natural aspect of economic resources in sustainable development. Pearce and Turner (1990) argue that sustainability requires the maintenance over time of aggregate resource stocks, ensuring that the potential to generate well-being does not fall below current levels, raising crucial questions about the measurability of environmental quality. Costanza (1994) highlights the distinction between "growth" and "development," emphasizing that economic growth, as a quantitative increase, is unsustainable indefinitely on a finite planet. In contrast, economic development can be sustainable, which implies improving the quality of life without necessarily increasing resource consumption. He emphasizes that sustainable growth is impossible and advocates that sustainable development should be the primary long-term political goal.

Therefore, the sustainability of natural resources is crucial, and resources and the environment must explicitly guide economic development. A global definition of sustainability underscores the relationship between dynamic human resources, economic systems, and more slowly changing ecological systems, where human life can continue indefinitely, individuals can flourish, and cultures can develop if the effects of human activities remain within limits to avoid the destruction of diversity, complexity, and function of the ecological support system (GOODLAND & LEDEC, 1987; PEARCE & TURNER, 1990; CONSTANZA, 1994).

RenovaBio, established by Law No. 13,546/2017, aims to meet the goals of the 2016 Paris Agreement, promoting the participation of biofuels in the energy matrix and reducing carbon emissions by 2025 (Brazil, 2021). It provides predictability for biofuels' environmental, economic, and social sustainability in the national energy matrix, encouraging adequate production and use, ensuring energy security, and mitigating Greenhouse Gas (GHG) emissions in the transportation sector.

Projections indicate a 7% increase in Brazilian biodiesel production from 2022 (USDA, 2023). The country has 68 authorized biodiesel plants, 32 in the Midwest and 16 in the South. Exploring new feedstocks is essential to expanding biodiesel production and increasing its contribution to the energy matrix (BIODIESELBR, 2023).

Brazil ranks among the top 3 producers and consumers of biodiesel globally, trailing only behind Indonesia and the USA in global production (ABIOVE, 2023). Production in 2022 reached only 62% of installed capacity. With the growth of output and increased biodiesel blending with fossil diesel, there has been a reduction in net diesel imports. However, there is potential to increase biodiesel's share due to biomass availability, ongoing research, and the idle capacity (38%) in production plants.

In this context, the Brazilian agribusiness sector stands out, given its economic relevance and the adverse effects of its activities. It becomes crucial for this sector to adapt to this new corporate phase, becoming highly competitive and effective in environmental protection, maintaining good relationships, and adopting ethical principles (ARRUDA *et al.*, 2022).

These initiatives represent an opportunity to reduce environmental impacts, increase social gains, and ensure fairer and more supportive operations. Additionally, they significantly contribute to sustainable development, aligning with the Agenda 2030. This agenda, in effect since 2015, establishes the 17 Sustainable Development Goals (SDGs) to be achieved by 2030, encompassing everything from ensuring human rights to combating poverty and climate change. Hence, implementing ESG practices in Brazilian agribusiness can generate positive outcomes affecting the entire network of organizations and their profitability and attract investments from individuals and companies recognizing the sector's potential, as indicated by the research (ARRUDA *et al.*, 2022).

The CATWOE analysis can be applied to understand the system's primary components. Developed by Peter Checkland, this technique offers a thorough and detailed insight into a problem, enabling the identification of the involved actors, the understanding of the desired changes, the consideration of underlying worldviews, the identification of the system owners, and the evaluation of the environment in which the situation occurs (CHECKLAND; POULTER, 2010). CATWOE analysis comprises several essential elements for this examination. When applied to the topic at hand, the following components can be identified, as illustrated in Figure 1:

1. **Customer** refers to the individuals, groups, or organizations affected by or benefiting from the situation or system being analyzed.
2. **Actor**: These entities or individuals participating in the system or situation. This can include people, organizations, government institutions, or other relevant stakeholders.
3. **Transformation**: This represents the system's desired change or expected outcomes.
4. **Worldview**: This refers to the beliefs, values, and perspectives that shape how the involved actors view the situation.
5. **Owner**: The system owner is the entity or individual responsible for making decisions and implementing actions to achieve the desired change.
6. **Environment**: This refers to the broader context in which the system exists. It includes social, political, economic, environmental, and cultural factors that may influence the system or situation being analyzed.

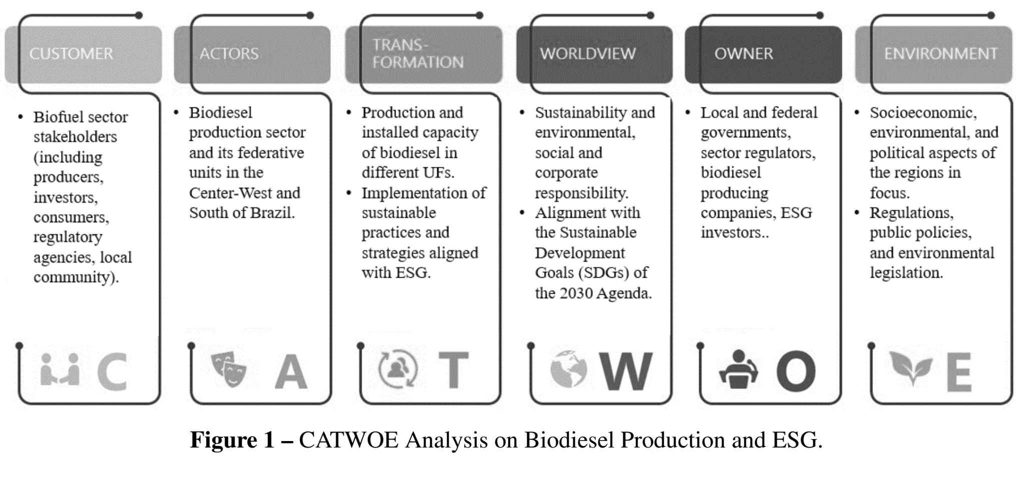

Figure 1 – CATWOE Analysis on Biodiesel Production and ESG.

Building upon the mind map depicted in Figure 2, which outlines the key components associated with ESG considerations in the context of biodiesel production, a closer examination reveals the burgeoning biodiesel industry in Brazil's Midwest and Southern regions. The selected states within these regions emerge as pivotal pillars, playing a significant role in shaping the trajectory of this expanding sector. Understanding and evaluating the installed capacity in these regions is paramount for strategic planning aligned with ESG principles, as it attracts potential investors and contributes directly to the broader sustainability objectives outlined in the agenda 2030.

The “ESG – Environmental, Social, Governance” section is crucial for aligning practices in the biofuels sector with the goals of the 2030 Agenda, promoting sustainable development through environmental, social, and governance criteria (IPBES, 2019). This includes implementing clean technologies in biodiesel production processes and adopting policies that respect social rights and promote transparency in management. ESG not only enhances sector attractiveness for investors committed to sustainable practices but also positively influences Federative Units (UFs) business practices, encouraging the adoption of higher sustainability standards.

The “Number of plants” section impacts regional economies directly through job creation and associated infrastructure and is essential for strategic planning in the energy sector. The number and distribution of biodiesel plants determine the country's total production capacity, directly influencing energy security and market competitiveness. Moreover, increasing the number of plants can indicate sector growth, reflecting investments in new technologies and sustainable practices.

“Production (m^3) of biodiesel from each selected UF” provides a detailed view of each Federative Unit's contribution to national biodiesel production. This allows for the identification of regional trends and variations and facilitates the evaluation of each UF's economic and operational efficiency (IEA, 2021). Understanding these data is crucial for adjusting public policies and business strategies, ensuring that biodiesel production is efficient and sustainable in the long term.

The “Usage rate (%) of each selected UF” reveals critical information about the operational efficiency of production units. Identifying and correcting inefficiencies can lead to more effective use of natural and financial resources, enhancing competitiveness and reducing environmental impacts (IRENA, 2022). This metric is also essential for improving the management of the biodiesel production chain, ensuring that production is optimized sustainably.

The “Installed Capacity of each selected UF” is essential for assessing each region's current and future biodiesel production potential. This installed capacity not only guides the strategic planning of companies and governments but also influences decisions on investment in infrastructure and technology (IPCC, 2018). Monitoring and adjusting installed capacity according to market demands and sustainability goals is essential to ensure balanced and sustainable growth of the biodiesel sector in Brazil.

The “Production of biodiesel” branch focuses on the Midwest and the South of Brazil, highlighting states within these regions. These include Mato Grosso, Goiás, the Federal District in the Midwest, and Rio Grande do Sul, Santa Catarina, and Paraná in the South. These regions are noted for their significant contribution to national biodiesel production due to favorable climatic conditions, developed logistical infrastructure, and strong agricultural base (IPCC, 2018). The concentration of production in these areas drives local economies through job creation and investments and reinforces Brazil's strategic role as a global leader in sustainable biofuel production.

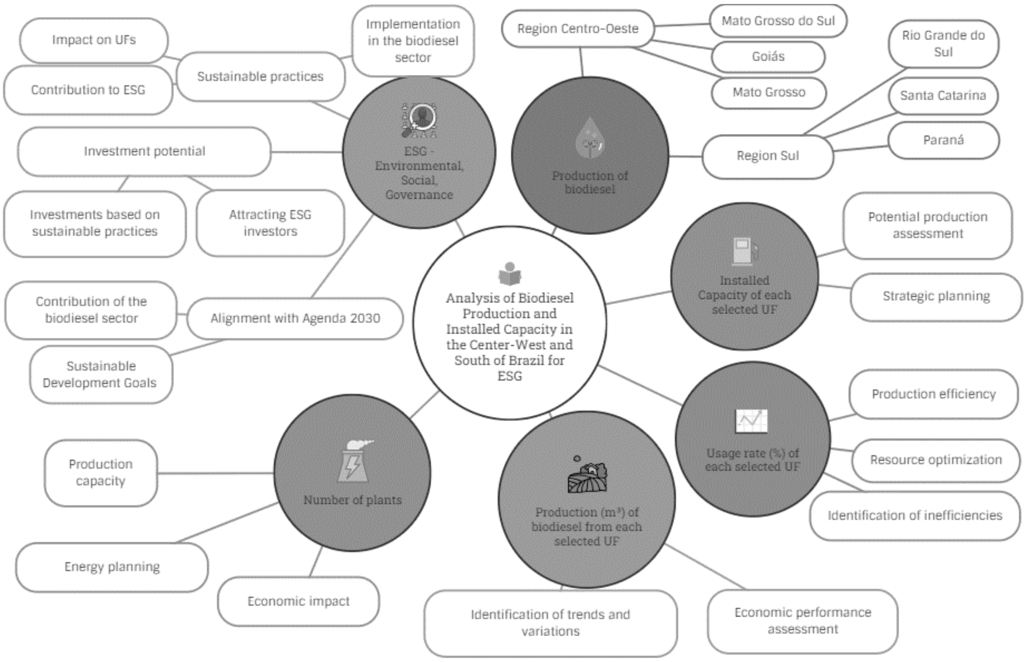

Figure 2 – Mind map on analysis of biodiesel production and installed capacity in the Center-West and South of Brazil for ESG.

The state's thorough analysis of biodiesel production becomes a linchpin in this strategic framework, allowing for identifying trends, optimizing resources, and catalyzing positive developments in environmental, social, and governance realms. This meticulous approach facilitates a comprehensive understanding of the industry's current state, paving the way for informed decision-making and targeted interventions. By delving into the intricacies of each state's contribution to biodiesel production, stakeholders can identify areas of improvement, implement sustainable practices, and foster positive socio-environmental impacts.

Moreover, aligning biodiesel production with ESG considerations is a strategic imperative and a key driver for achieving global development goals. As the international community collectively works towards a more sustainable future, the biodiesel sector, particularly in Brazil's Midwest and Southern regions, is a focal point for positive change. This alignment with global development objectives underscores the industry's potential to contribute significantly to a sustainable energy landscape.

In conclusion, the detailed analysis of biodiesel production, focusing on installed capacity and ESG considerations, provides a roadmap for steering the industry towards sustainability. By leveraging insights derived from this meticulous approach, stakeholders can foster innovation, attract responsible investments, and contribute meaningfully to the overarching goals of environmental preservation, social equity, and robust governance. The biodiesel sector in Brazil's Midwest and Southern regions has the potential to be a beacon of sustainable development, exemplifying how strategic planning and ESG-aligned practices can drive positive change within a critical industry.

3 THEORETICAL FOUNDATION

A bibliographic search was conducted in the Scopus database, utilizing articles from the last five years, focusing on four thematic axes: MCDA (Multiple Criteria Decision Analysis), THOR-2, biodiesel and ESG. The investigation identified 16 documents related to the THOR-2 method, six articles linked to ESG and MCDA, and 21 articles associated with MCDA and biodiesel. However, no article related to the established thematic axis was found. This scenario emphasizes the relevance and existing research gap, highlighting the need to fill this study area.

Figure 3 illustrates the distribution of records by the publication year of articles involving the THOR-2 theme. Scientific production has increased significantly since 2018 and reached its peak in 2021. The observed growth trend suggests the potential for an even greater number of publications.

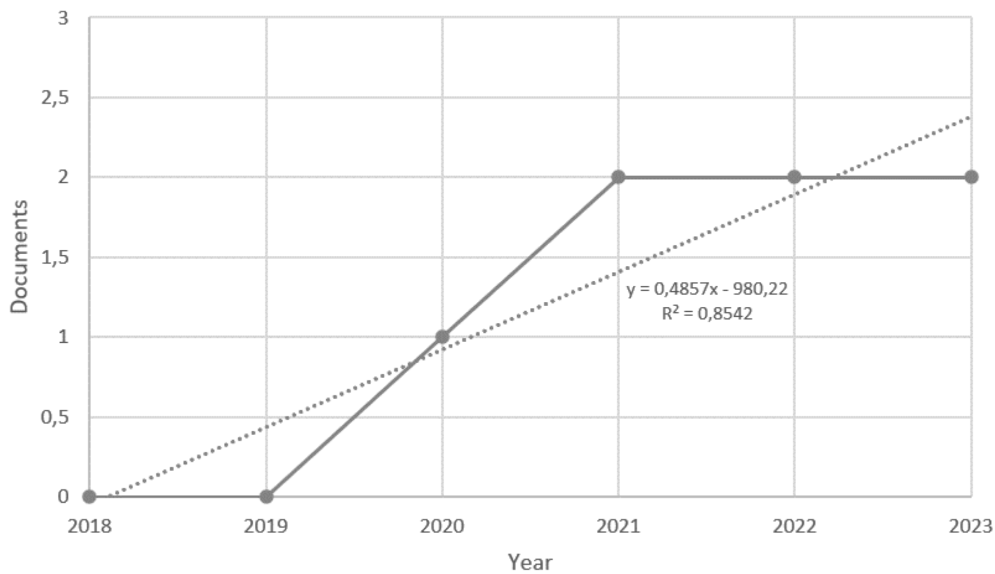

Figure 3 – Distribution of articles by year.

The highlighted article on the discussed topic, "THOR-2 Method: An Efficient Instrument in Situations Where There Is Uncertainty or Lack of Data" (TENÓRIO *et al.*, 2021), advanced the THOR method to THOR-2, introducing refinements in weight assignment and assessment of missing data, maintaining its relevance to prevent exclusion of alternatives or criteria due to data scarcity.

Figure 4 illustrates the collaborative citation network, displaying the interconnection between authors and the frequency of each article's references. The study has been cited 30 times in other research papers, and Litmaps presents a reference map with over 20 relevant articles.

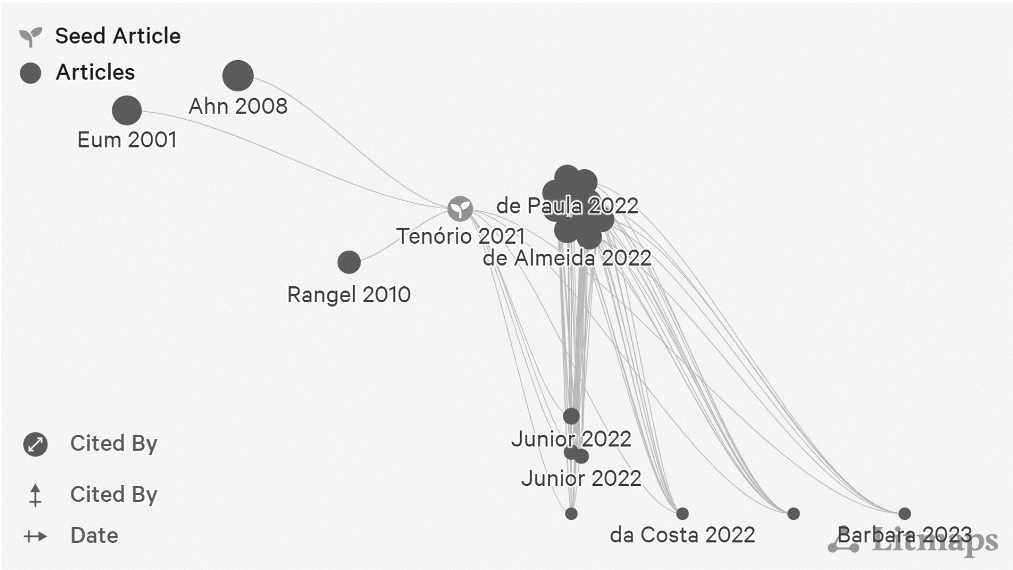

Figure 4 – Network of publications related to the featured article.

The imperative for renewable energy sources has grown in response to environmental challenges and the finite nature of fossil fuels. Biomass is a crucial renewable energy resource, playing a significant role in recent energy production. Given the diverse technologies available for biomass-to-energy conversion, selecting the most suitable option becomes a multicriteria decision-making challenge. Kheybari *et al.* (2019) address this issue by proposing an evaluation framework and identifying key decision-making criteria for the selection of biofuel production technology. Through an online survey, experts ranked criteria based on their significance. The findings underscore air pollution, land use change, and human expertise as the three most critical criteria for selecting optimal biofuel production technology in the specific context of Iran, providing a foundational step in guiding strategic and sustainable decisions in the field.

Paruccini (1994) provides valuable insights that could significantly enhance decision-making processes within the biodiesel production sector, particularly in environmental management. His perspectives are crucial for integrating sustainable practices and refining methodologies considering environmental impacts throughout the biodiesel production lifecycle.

About previous research linked to the chosen method, Costa *et al.* (2020) demonstrated the practical application of the THOR-2 system in selecting the most suitable hospital ship for the Brazilian Navy during the COVID-19 pandemic. This highlighted the versatility of THOR-2 in addressing critical challenges both locally and globally, showcasing its effectiveness in complex decision-making scenarios.

Jardim *et al.* (2020) proposed a Geographic Information System (GIS) tailored for national defense, emphasizing its role in managing crucial geospatial information to bolster the country's security infrastructure. Their comprehensive system includes route tracking and troop access identification, aiming to provide a robust and adaptable platform for strategic geographical information management.

Mofijur *et al.* introduced and applied the PROMETHEE-GAIA method in 2021 to select microalgae strains optimized for aviation fuel production. Their assessment integrated 19 criteria across three crucial aspects: biomass production, lipid quality, and fatty acid methyl ester properties, despite identifying Chlorella sp. NT8a is the most suitable strain, and challenges remain in meeting international jet fuel standards directly from unmodified biofuel. This underscores the need for a comprehensive action plan, including potential revisions to current jet fuel standards and enhancements in biofuel processing from microalgae.

Maêda (2021) applied the SAPEVO-M-NC method to select the most suitable regions in Brazil for cultivating African mahogany of the ivorist's species. The proposed approach offers strategies to mitigate deforestation, promote the commercial planting of tree species and reduce pressure on native forests based on economic and environmental criteria. Anwar (2021) used the Analytical Hierarchical Process (AHP) and the Fuzzy Analytical Hierarchical Process (FAHP) to assign weights to biofuel selection criteria, considering economic, technical, and environmental aspects.

Firouzi *et al.* (2021) focused on prioritizing biomass resources for biofuel production in Guilan province, Iran, using a hybrid Multi-Criteria Decision-Making (MCDM) approach. Techniques such as TOPSIS, ARAS, and WASPAS were employed to assess ten criteria, including technical job creation, preservation of non-renewable energy resources, and environmental impacts of biomass accumulation. Their study identified "municipal solid wastes and sewage," "forest and wood farming wastes," and "livestock and poultry wastes" as significant second-generation biofuel resources, offering valuable insights for sustainable biofuel generation aligned with greenhouse gas mitigation goals in Guilan province.

The TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) evaluates each alternative against a set of criteria, identifying the distance between each alternative and the positive ideal (which maximizes criteria) and the negative ideal (which minimizes the criteria). The best alternative is the one that presents a smallest distance to the positive ideal and the greatest distance to the negative ideal (HWANG & YOON, 1981). The ARAS method (Additive Ratio Assessment) seeks to select the best alternative based on a series of attributes. The final classification of alternatives is made by determining the degree of usefulness of each alternative (ZAVADSKAS & TURSKIS, 2010). The WASPAS (Weighted Aggregate Sum Product Assessment) method applies the weighted aggregate product assessment sum for parametric optimization. It combines the Weighted Sum Model (WSM) and the Weighted Sum Model Product Model (WPM) (ZAVADSKAS *et al.*, 2012).

Esteves *et al.* (2022) proposed a strategy for prioritizing demands in large companies using the Value-Focused Thinking (VFT) approach and the THOR-2 method. Their methodology ranks alternatives based on established criteria, demonstrating its applicability in aligning strategic objectives with operational decisions in corporate settings. Pereira *et al.* (2022) explored improvements in health process management within the Brazilian Navy, employing the THOR-2 and PROMETHEE-SAPEVO-M1 methods to enhance decision-making frameworks and optimize health service delivery.

Santos *et al.* (2022) applied the THOR method to prioritize projects in portfolio management, aligning investments in software development with strategic objectives in technology consulting. Their approach highlights the efficacy of THOR in optimizing resource allocation and achieving business goals.

Cardoso *et al.* (2009) utilized THOR to optimize alternatives for solid waste disposal, demonstrating its versatility in addressing environmental management challenges beyond biodiesel production.

Barbosa de Paula (2022) used the ELECTRE-MOr method to strategize COVID-19 vaccine distribution in remote areas of Brazil, developing a Python computational model to enhance accessibility and efficiency in vaccine planning and distribution. The ELECTRE MOr method is based on the classification of multiple criteria with ordinal weight input, which includes multiple decision makers and distributes alternatives into predefined categories (COSTA *et al.*, 2021).

Drumond (2022) employed the DEMATEL method for multi-criteria analysis in marketing, exploring interrelationships between critical decision criteria to optimize marketing strategies. The DEMATEL (Decision-Making Trial and Evaluation Laboratory) method is a technique for visualizing causal relationship structures complex (GABUS & FONTELA, 1972). Junior *et al.* (2022) applied AHP-TOPSIS-2N to select interns at an IoT startup, showcasing its effectiveness in recruitment decision-making by prioritizing candidates based on multiple criteria. Moreira *et al.* (2022) illustrated the PROMETHEE-SAPEVO-M1 methodology for drone assessment to support public safety, enhancing decision-making processes in emergency response and surveillance operations.

De Almeida (2022) utilized the ELECTRE-MOr method to classify coastal cities as potential naval bases in Brazil, demonstrating its application in strategic planning and infrastructure development. Mellem *et al.* (2022) employed ELECTRE-MOr to enhance training and development practices within Brazilian companies, optimizing the Training and Development (T&D) area to improve workforce capabilities. Costa *et al.* (2021) applied the ELECTRE-MOr method to classify Flying Hospitals in Brazil, underscoring its role in optimizing healthcare logistics and emergency response capabilities during crises such as the COVID-19 pandemic.

De Paula (2022) utilized CRITIC-MOORA-3N for analysis in the oil industry, focusing on AHTS vessels to optimize operational efficiencies and decision-making processes. Drei *et al.* (2023) combined Momentum, THOR-2, and AHP-TOPSIS-2N methods to explore prospective scenarios in post-COVID-19 tourism, highlighting integrated decision-making approaches to adapt to changing global travel trends.

De Feo et al. (2023) applied Multi-Criteria Decision Analysis (MCDA) to assess recycling pathways for used cooking oil (WCO) in sustainable biofuel and industrial product production. Their study compared biodiesel, lubricant, and biosurfactant production options from WCO, emphasizing environmental, economic, and technical factors in decision-making.

Dias *et al.* (2024) applied MCDA to simultaneously evaluate the safety and sustainability attributes of biofuels from early development stages. Their approach facilitates robust evaluation of biofuel options, considering criteria aligned with EU Green Deal objectives for environmental sustainability and pollution reduction.

Kügemann and Polatidis (2024) employed MCDA to assess and rank biofuel-powered buses in Gotland Island's public transportation system. Their study integrated 11 criteria across environmental, social, and economic dimensions, utilizing the weighted summation method guided by the analytic hierarchy process (AHP) to identify optimal sustainable transport solutions.

Each study contributes unique methodologies and insights to enhance decision-making processes across diverse sectors, emphasizing sustainability, efficiency, and strategic alignment with organizational objectives.

The THOR-2 method's application in this study provides a systematic and transparent approach to evaluating biodiesel production alternatives. The inclusion of environmental, social, and governance (ESG) criteria aligns with contemporary sustainability considerations and reflects the growing importance of such factors in investment decisions.

4 METHODOLOGY

The study employed the THOR-2 methodology outlined in five stages, as represented in Figure 5 (Rodrigues et al, 2024). Initially, the study defined the case study, focusing on a specific energy problem in Brazil's central-western and southern regions. In the second stage, the literature review was conducted in the Scopus database, covering four thematic axes between 2018 and 2023. The third stage consisted of modeling the object of analysis using tools such as mind mapping and CATWOE analysis. Subsequently, the THOR-2 method was applied for analysis. Finally, the results were evaluated in the last stage, allowing for the ranking proposed by the chosen method.

THOR-2 ranks discrete alternatives in transitive or non-transitive decision processes, eliminates redundant criteria, and quantifies the imprecision of the decision-making process (TENÓRIO, 2020). An online platform was used to apply the method, available practically through the link http://www.thor-web.com/start?method=2. The first step involves defining the criteria, alternatives, and the number of decision-makers:

- Number of alternatives: 6

  Goiás (GO), Mato Grosso do Sul (MS), Mato Grosso (MT), Paraná (PR), Rio Grande do Sul (RS) e Santa Catarina (SC).

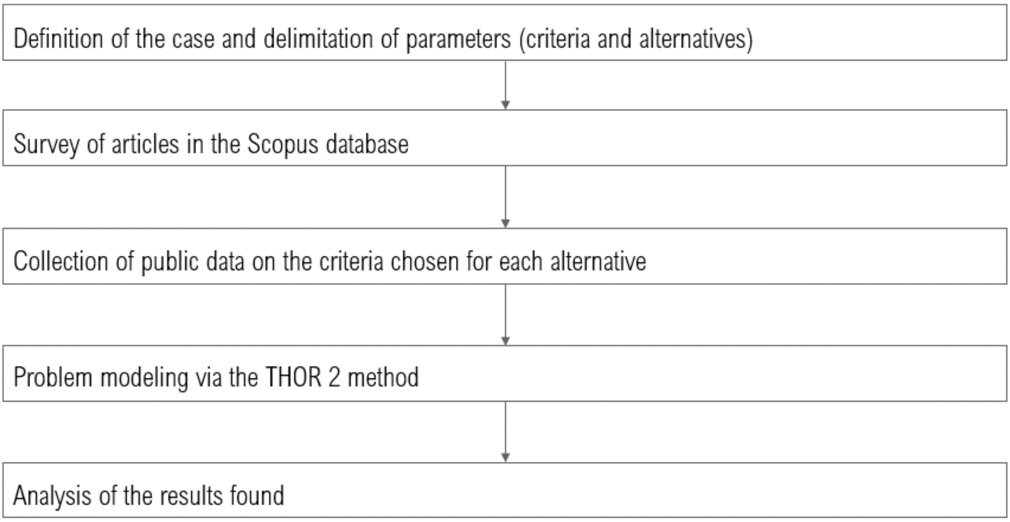

Figure 5 – Research methodology used.

- Number of criteria: 4
  - Production (m^3): actual quantity of biodiesel produced per state. Provides an understanding of the adequate volume generated and evaluates the productive potential of a specific region.
  - Installed capacity (m^3/year): maximum theoretical biodiesel production capacity per state over a year. Offers insights into existing productive capacity and scalability potential.
  - Utilization rate (%): This measures the operational efficiency of the plants, showing how close they are to using their maximum capacity. A high utilization rate may indicate efficient and successful operation.
  - The number of plants: The number of biodiesel plants per state. This number indicates the level of investment and development in the local industry.

The selection of these four criteria—Production (m^3), Installed capacity (m^3/year), Utilization rate (%), and Number of plants—was based on their direct relevance to evaluating the biodiesel industry's operational and economic potential within each state. While governance, environmental, and social factors are crucial for a holistic evaluation of sustainability, the focus on the four selected criteria is primarily on the operational and economic aspects of biodiesel production. This approach provides a clear and direct assessment of the industry's capacity and efficiency, which are fundamental for determining biodiesel production's immediate feasibility and scalability.

- Number of decision-makers: 1

  As indicated in the ABIOVE (2023) report, priority was given to the largest biodiesel-producing states for selecting alternatives. When defining the criteria, crucial elements considered highly relevant to support decision-making were focused on. It was recognized that the advancement of biodiesel production in Brazil should be financially sustainable and offer economic advantages to the country. Quantitative data regarding these criteria were obtained from BiodieselBR (2023), a globally renowned source of biodiesel, and the official ABIOVE 2023 report.

In the next stage, the weights of each criterion were determined according to the decision maker's preferences. Each value was normalized to insert the value of each alternative concerning each criterion. In this case, the decision was not to apply relevance, as all values were obtained from reliable sources. Likewise, Rough Sets Theory (RST) (PAWLAK *et al.*, 1990) was not employed, as there were no redundant criteria to be eliminated. Assigning weights to the criteria in the THOR-2 method is crucial to express the relative importance of each in decision-making, allowing the determination of the relevance of each criterion within the analyzed context.

The preference threshold (p) is a crucial parameter to control the preference between alternatives. Its definition allows evaluation if the score difference between two alternatives is sufficiently significant to consider one superior. Meanwhile, the indifference threshold (q) represents the acceptable deviation to maintain a situation of indifference between two alternatives. A decision matrix was created to represent these parameters in the specific case studied, as shown in Table 1 visually.

Table 1 – Decision matrix for the case under study.

Region	UF	Production (m^3)	Capacity installed (m^3/year)	Usage fee (%)	Number of plants
Midwest		2.553.665	4.808.433	53	32
	GO	964.641	1.963.090	49	9
	MS	367.119	474.500	77	3
	MT	1.221.905	2.370.843	52	20
South		3.182.198	4.885.525	65	16
	PR	1.224.613	1.387.000	88	5
	RS	1.855.787	2.938.250	63	9
	SC	101.798	560.275	18	2
p		100.000	450.000	17	1
q		20.000	100.000	5	1
D		2.000.000	2.000.000	100	100
weights		25	20	35	20

5 SOLUTION OF PROPOSAL

The THOR-2 method allows for the simultaneous analysis of three scenarios, considering two specific criteria. The preference level for alternative a over alternative b by criterion j, considering preference thresholds (p) and indifference thresholds (q), is represented by aPjb, aQjb, and aIjb. Three distinct scenarios (S1, S2, and S3) are considered, ranging from the most stringent to the most flexible. To conduct the analysis, it is essential to employ the equations of preference relations, as shown in Figure 6.

Strong Preference Relations (P):

$$aPb \leftrightarrow g(a) - g(b) > p \tag{1}$$

Weak Preference Relations (Q):

$$aQb \ \leftrightarrow \ q < |g(a) - g(b)| \leq p \tag{2}$$

Relations of Indifference (I):

$$aIb \ \leftrightarrow \ -q \leq |g(a) - g(b)| \leq q \tag{3}$$

Figure 6 – Preferences relations equations.

Equation (1) describes one alternative's strict preference (P) relationship over another. Equation (2) represents a weak preference relationship (Q) of one alternative over another, while equation (3) illustrates the indifference relationship between alternatives (I). In quantifying the alternatives in each of the scenarios (S1, S2, and S3), the equations shown in Figure 7 are used.

$$\begin{aligned}
S1: &\sum_{j=1}^{n} (w_j \mid aP_jb) > \sum_{j=1}^{n} (w_j \mid aQ_jb + aI_jb + aR_jb + bQ_ja + bP_ja) \\
S2: &\sum_{j=1}^{n} (w_j \mid aP_jb + aQ_jb) > \sum_{j=1}^{n} (w_j \mid aI_jb + aR_jb + bQ_ja + bP_ja) \\
S3: &\sum_{j=1}^{n} (w_j \mid aP_jb + aQ_jb + aI_jb) > \sum_{j=1}^{n} (w_j \mid aR_jb + bQ_ja + bP_ja)
\end{aligned}$$

Figure 7 – THOR's scenarios.

In scenario S1, the most rigorous one, alternatives receive scores in situations where equation (1), *a*P*b*, is met. In scenario S2, alternatives are scored when either equation (1) or (2), *a*P*b* or *a*Q*b*, is satisfied. As for scenario S3, it encompasses all equations from Figure 6.

There was a differentiation in assigning weights when calculating scores for the relationship aI_jb and aQ_jb in scenarios S1, S2, and S3. In comparisons involving aI_jb, half the weight of the corresponding criterion is considered, while in cases of aQ_jb, the proportion is established between half the weight of the criterion (aI_jb) and the total weight (aP_jb). This procedure is in Equation (4) (TENÓRIO, 2020).

$$weight_{\ i} * (((a_i - q_i)/(p_i - q_i)) * 0.5 + 0.5) \tag{4}$$

In addition to the mentioned features, there is the advantage of evaluating criterion redundancy through software, using the Rough Set Theory (RST). The algorithm goes through several steps, comparing the original ranking results with the ranking after excluding each criterion, starting from the least important criterion. If the resulting ranking is the same as the original, it is inferred that the excluded criterion is insignificant (TENÓRIO, 2020).

Through RST, it is possible to assess whether a specific criterion significantly impacts the ranking of alternatives or is negligible. The algorithm iterates by comparing the original ranking with new rankings generated after excluding each criterion, starting with the least influential. If the resulting order remains unchanged after excluding a criterion, it suggests that the criterion is irrelevant because its removal does not affect the initial ranking (TENÓRIO, 2020). Irrelevance means the criterion or set of criteria whose exclusion does not alter the original order when all criteria are considered. This reflects similar scores among these criteria, aligning with the weights assigned by the decision maker, indicating their minimal impact on the decision process.

The THOR-2 method, grounded in Preference Modeling, MAUT, and Theories on Imprecise Information, addresses the challenges associated with uncertainty and a lack of data, offering a valuable tool for decision-makers. The use of preference relations, preference thresholds, and indifference thresholds allows for a nuanced analysis, considering both strict and weak preferences and situations of indifference between alternatives.

6 DISCUSSION OF RESULTS

From the decision matrix data, three types of rankings were obtained: S1 (Figure 8), S2 (Figure 9), and S3 (Figure 10). In both S1 and S3, the same ranking of alternatives is observed. However, in S2, there is an alternation in the second and third positions between the PR and MT alternatives. The ranking of other options allows for a more detailed discussion, enabling the adjustment of the relative importance between criteria, weights, relevance, and tolerance limits. This analysis guides the types of investments that can be made in each location, thus promoting the expansion of biodiesel production. According to the criteria established in the study, the resulting ranking was RS $>$ MT $>$ PR $>$ GO $>$ MS $>$ SC.

The analysis shows that the Southern region has the most significant capacity for biodiesel production, with Rio Grande do Sul standing out. The development of the biodiesel industry in RS can be considered strategic for several reasons. As highlighted in the UBRABIO/FIEG report (2022), it is Brazil's largest biodiesel-producing state. The industrialization of this product offers an opportunity to add value to local production, generating jobs and income in the region. Additionally, the National Biodiesel Production and Use Program (PNPB) favors the acquisition of soybeans from family farmers. Considering that RS is home to many farmers in this cate-

S 1

result

GO - 0 0.5 0 0 0 1.0

MS - 0.5 0 0 0 0 0.75

MT - 0.554 0.65 0 0.5 0.5 1.0

PR - 0.6 0.712 0.5 0 0 1.0

RS - 0.526 0.68 0.5 0.65 0 1.0

SC - 0 0 0 0 0 0

Sum

GO = 1.5

MS = 1.25

MT = 3.204

PR = 2.812

RS = 3.356

SC = 0.0

RS > MT > PR > GO > MS > SC - Original.

Figure 8 – S1 ordering for the case studied.

S 2

result

GO - 0 0.5 0 0 0 1.0

MS - 0.5 0 0 0 0 0.75

MT - 0.785 0.65 0 0.5 0 1.0

PR - 0.6 1.0 0.5 0 0 1.0

RS - 0.883 0.68 0.781 0.65 0 1.0

SC - 0 0 0 0 0 0

Sum

GO = 1.5

MS = 1.25

MT = 2.935

PR = 3.1

RS = 3.994

SC = 0.0

RS > PR > MT > GO > MS > SC - Original.

Figure 9 – S2 ordering for the case studied.

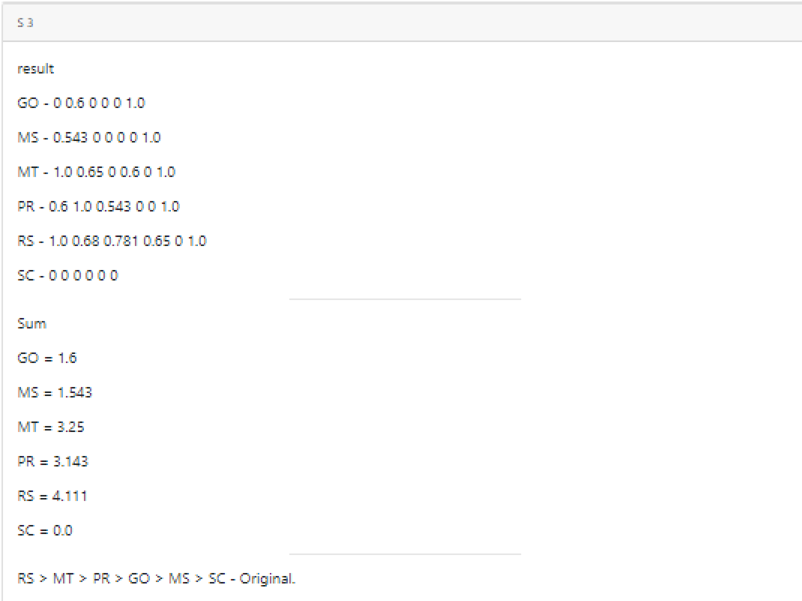

Figure 10 – S3 ordering for the case studied.

gory, a significant local opportunity can contribute to the economic sustainability of these rural properties (DEE/SEPLAG, 2020).

The study's novel contribution lies in its application of the THOR-2 method to the biodiesel production sector, integrating ESG criteria to make informed investment decisions. The research addresses a significant gap in the existing literature, emphasizing the need for sophisticated decision-making tools in the context of sustainable energy development. Including a comprehensive theoretical foundation, extensive literature review, and practical application of the method to real-world scenarios enhances the study's robustness and relevance.

6.1 Sensitivity analysis: checking results obtained with other established methods

In analyzing the results obtained by THOR-2, the MPSI-MARA and SWARA-MOORA-3NAG methods were used based on the data from Table 1. Although the MPSI-MARA and SWARA-MOORA-3NAG methods are relatively new, they are derived from principles grounded in consolidated methodologies. For example, the MPSI-MARA method combines the MPSI weighting method with the MARA ranking method, leveraging the conceptual basis of the PSI technique (Araujo *et al.*, 2023).

The MPSI method was proposed by Gligorić *et al.* (2022). It is based on eliminating some steps from the PSI, making the final weight values a little higher. The PSI method was proposed by Maniya (2010). It is a method of objective approach. It does not require the establishment of a prior relative importance between the criteria, since it is calculated through its algorithm. The alternative ordering part in the MPSI-MARA method refers to the MARA method (GLIGORIĆ *et al.*, 2022).

Similarly, the SWARA-MOORA-3NAG method integrates the SWARA method (KERŠULIENE *et al.*, 2010), for stepwise weight assessment ratio analysis, with the MOORA method (BRAUERS & ZAVADSKAS, 2006), for multi-objective optimization. This integration results in a comprehensive approach that offers computational simplicity, interpretability, and robustness necessary to simultaneously address a variety of selection characteristics, both quantitative and qualitative (PAULA *et al.*, 2022). The term 3NAG refers to the 3 normalizations applied to achieve the final result of the method (HERMOGENES *et al.*, 2022).

The results of the application of the methods were compared in Table 2, where it is observed that the results of THOR-2 are consistent, as when applying the other methods, a similar ranking was obtained, with Rio Grande do Sul (RS) ranking first. Thus, this study stands out for its sensitivity analysis, presenting itself as a significant contribution to the scientific literature. Despite the axiomatically different elaboration, the proposed method reveals results comparable to those of other established methods in the literature.

Table 2 – Comparison between the rankings obtained with the chosen methods.

	1°	2°	3°	4°	5°	6°
THOR-2	RS	MT	PR	GO	MS	SC
SWARA-MOORA-3NAG	RS	PR	GO	MT	MS	SC
MPSI-MARA	RS	PR	MT	GO	SC	MS

7 CONCLUSION

This study successfully applied the THOR-2 methodology to assess biodiesel production alternatives in Brazil, highlighting Rio Grande do Sul as the state with the highest potential in this sector. The rigorous analysis conducted in this work fills a significant gap in the literature by demonstrating the practical application of advanced decision-making tools in sustainable energy development. The consistent results obtained through THOR-2 corroborate its effectiveness in evaluating alternatives under conditions of uncertainty and data scarcity, validating its use as a robust and reliable methodology.

The identification of Rio Grande do Sul as a leader in biodiesel production acknowledges its current capacity and highlights its potential to drive regional economic growth and job creation. This finding is critical for the local economy and aligns with national biodiesel use programs, thus promoting more sustainable and inclusive development.

Furthermore, including environmental, social, and governance criteria in investment decisions underscores this study's commitment to sustainable practices. Integrating these criteria mitigated adverse environmental impacts and promoted responsible social development. This multidimensional approach strengthens the validity of decisions made and serves as a model for future studies aiming to balance economic efficiency with social and environmental responsibility.

The findings of this study provide clear guidelines for strategic investments in expanding biodiesel production, especially in states with higher economic and operational viability identified by the THOR-2 methodology. Moreover, it paves the way for continuous improvement of this methodology, adapting it to different contexts and expanding the application of additional criteria that may influence investment decisions in the future.

In conclusion, this study advanced knowledge of multi-criteria decision-making methods applied to renewable energy and highlighted the importance of environmental and social considerations in formulating sustainable energy policies. As global demand for renewable energies grows, using tools like THOR-2 becomes essential in guiding decisions that maximize economic efficiency and promote sustainable and equitable development.

References

ABIOVE (Associação Brasileira das Indústrias de Óleos Vegetais). 2023. Produção de Biodiesel. Available at: https://abiove.org.br/estatisticas/. Accessed: 29 out. 2023.

Ahn HJ. 2008. Informed Trading in the Index Option Market: The Case of KOSPI 200 Options. *Journal of Futures Markets*, **28**(12): 1118–1146,. Available at: https://doi.org/10.1002/fut.20369.

Anwar M. 2021. Biodiesel feedstocks selection strategies based on economic, technical, and sustainable aspects. *Fuel*, **283**: 119204.

Araujo T, Santos M & Gomes C. 2023. *Aplicativo Python MPSI-MARA*. Anais do Congresso Nacional de Excelência em Gestão.

Arruda C, Braga C, Sardenberg D, Pitta E, Barcellos E, Spitzeck H & GuimarÃes S. 2022. *Inovação: o motor do ESG*. Nova Lima: Fundação Dom Cabral.

Barbara F. 2023. Interactive Internet-Based Tool Proposal for the WASPAS Method: A Contribution for Decision-Making Process. *Procedia Computer Science*, **221**: 200–207,. Available at: https://doi.org/10.1016/j.procs.2023.07.028.

Barbosa De Paula NO; De Araújo Costa IP, Drummond P, Moreira M, Gomes CFS, Dos Santos M & Maêda S. 2022. Strategic support for the distribution of vaccines against Covid-19 to Brazilian remote areas: A multicriteria approach in the light of the ELECTRE-MOr method. *Procedia Computer Science*, **199**: 40–47. Available at: https://doi.org/10.1016/j.procs.2022.01.006.

BiodieselBR. 2023-11-21. As usinas de Biodiesel do Brasil, 2023. Available at: https://www.biodieselbr.com/usinas_brasil.

BRASIL. 2019. Programa Nacional de Produção e Uso do Biodiesel (PNPB). Available at: https://www.gov.br/agricultura/pt-br/assuntos/agricultura-familiar/biodiesel/programa-nacional-de-producao-e-uso-do-biodiesel-pnpb. Accessed: 26 out. 2023.

BRAUERS W & ZAVADSKAS E. 2006. The MOORA method and its application to privatization in a transition economy. *Control and Cybernetics*, **35**: 445–469.

BRUNDTLAND G. 2024. *Our common future; by the world commission on environment and development*. Oxford: Oxford University Press.

CARDOSO R, XAVIER L, GOMES C & ADISSI P. 2009. Uso de SAD no apoio à decisão na destinação de resíduos plásticos e gestão de materiais. *Pesquisa Operacional*, **29**: 67–95,.

CHECKLAND P & POULTER J. 2010. Learning for Action: A Short Definitive Account of Soft Systems Methodology and Its Use for Practitioners. *Teachers, and Students*, .

CONSTANZA R. 1994. *Economia Ecológica: uma agenda de pesquisa. Valorizando a Natureza: uma análise econômica para o desenvolvimento sustentável*. São Paulo: Editora Campus.

COSTA I. 2021. Choosing flying hospitals in the fight against the COVID-19 pandemic: structuring and modeling a complex problem using the VFT and ELECTRE-MOr methods. *IEEE Latin America Transactions*, **19**: 1099–1106.

COSTA I. 2022. Strategy Analysis for project portfolio evaluation in a technology consulting company by the hybrid method THOR. *Procedia Computer Science*, **199**: 134–141. Available at: https://doi.org/10.1016/j.procs.2022.01.017. Accessed: 17 Nov. 2023.

COSTA I, MAÊDA S, TEIXEIRA L, GOMES C, SANTOS D & M. 2020. Choosing a hospital assistance ship to fight the covid-19 pandemic. *Revista De Saúde Pública*, **54**: 79. Available at: https://doi.org/10.11606/s1518-8787.2020054002792. Accessed: 20 Nov. 2023.

COSTA I, SANSEVERINO A, BARCELOS M, BELDERRAIN M, GOMES C & SANTOS M. 2021. Choosing Flying Hospitals in the Fight Against the COVID-19 Pandemic. *Structuring and Modeling a Complex Problem using the VFT and ELECTRE-MOR Methods. 2021 IEEE LATIN AMERICA TRANSACTIONS*, **19**(6).

COSTA I, TENÓRIO F, BARUD N, FÁVERO L, AL-QUDAH A, GOMES C & DOS SANTOS M. 2022. Feasibility of a Hospital Information System for a Military Public Organization in the Light of the Multi-Criteria Analysis, 2022. *Healthcare*, **10**: 2147. Available at: https://doi.org/10.3390/healthcare10112147. Accessed: 09 nov. 2023.

DA COSTA J. 2022. Synthesis of MoO 3 by Pilot-Scale Combustion Reaction and Evaluation in Biodiesel Production from Residual Oil. *International Journal of Energy Research*, **46**(6): 7775–7787. Available at: https://doi.org/10.1002/er.7679.

DE ALMEIDA I, COSTA I, COSTA A, CORRIÇA J, MOREIRA M, GOMES C & DOS SANTOS M. 2022. A multicriteria decision-making approach to classify military bases for the Brazilian Navy. *Procedia Computer Science*, **199**: 79–86. Available at: https://doi.org/10.1016/j.procs.2022.01.198.

DE AREA LEÃO PEREIRA E, DIELE-VIEGAS L & DE SANTANA RIBEIRO L. 2024. GHG emissions in Brazilian Agriculture and livestock sectors and the risk to Amazonia conservation. *The European Physical Journal*, **97**.

DE FEO G. 2023. Assessment of three recycling pathways for waste cooking oil as feedstock in producing biodiesel, biolubricant, and biosurfactant: A multi-criteria decision analysis approach. *Recycling*, **8**: 64,.

DE PAULA N, DOS SANTOS M, GOMES CFS & BALDINI F. 2022. CRITIC-MOORA-3N Application on a Selection of AHTS Ships for Offshore Operations. *Procedia Computer Science*, **214**: 187–194.

DEE/SEPLAG (DEPARTAMENTO DE ECONOMIA E ESTATÍSTICA DA SECRETARIA DO PLANEJAMENTO, ORÇAMENTO E GESTÃO). 2020. A indústria do biodiesel no Rio Grande do Sul e o papel das políticas públicas de incentivo. Available at: https://dee.rs.gov.br/upload/arquivos/202009/30132046-estudo-biocombustiveis.pdf.

DIAS L, CALDEIRA C & SALA S. 2024. Multiple criteria decision analysis to support the design of safe and sustainable chemicals and materials. *The Science of the total environment*, **v. 916**.

DREI S, SILVA B, LIMA J, GOMES C & ANGULO-MEZA L. 2023. An Approach of the Momentum Method for Prospective Scenarios of Brazilian Tourism Post-Covid-19. *Journal Of Futures Studies*, **1**: 1.

DRUMOND P, COSTA I, MOREIRA M, DOS SANTOS M & GOMES C. 2022. Strategy study to prioritize marketing criteria: an approach in the light of the DEMATEL method. *Procedia Computer Science*, **199**: 448–455. Available at: https://doi.org/10.1016/j.procs.2022.01.054.

ESTEVES F, MOREIRA M, COSTA I, JOAQUIM G, GOMES C & DOS SANTOS M. 2022. Demand Prioritization on supply chain by the integration of value-focused thinking approach and THOR-2 method. *Procedia Computer Science*, **214**: 248–256. Available at: http://dx.doi.org/10.1016/j.procs.2022.11.172.

EUM NW ET AL. 2001. An Accurate Evaluation of Routing Density for Symmetrical FPGAs. Available at: https://doi.org/10.1145/368122.368794.

FIROUZI S, ALLAHYARI M, ISAZADEH M, NIKKHAH A, HAUTE V & S. 2021. Hybrid multi-criteria decision-making approach to select appropriate biomass resources for biofuel production. *The Science of the total environment*, **770**: 144449.

GABUS A & FONTELA E. 1972. *World Problems, An Invitation to Further Thought within the Framework of DEMATEL*. Geneva, Suíça: Battelle Geneva Research Centre.

GLIGORIĆ M, GLIGORIĆ Z, LUTOVAC S, NEGOVANOVIĆ M & LANGOVIĆ Z. 2022. Novel Hybrid MPSI–MARA Decision-Making Model for Support System Selection in an Underground Mine. *Systems*, **10**: 248. Available at: https://doi.org/10.3390/systems10060248.

GONG X & ASLAM M. 2024. The role of natural resources, and economic development in evaluating the environmental effects of biofuel and waste energy generation in the group of BRICS. *Applied Energy*, **372**.

GOODLAND R & LEDEC G. 1987. Neoclassical Economics and Principles of Sustainable Development. *Ecological Modeling*, **38**(1-2): 19–46.

HERMOGENES L ET AL. 2022. Proposta do método híbrido swara-moora-3nag e desenvolvimento de uma ferramenta computacional em python. In: *Anais do Simpósio Brasileiro de Pesquisa Operacional*. Campinas, Galoá. Available at: https://proceedings.science/sbpo/sbpo-2022/trabalhos/proposta-do-metodo-hibrido-swara-moora-3nag-e-desenvolvimento-de-uma-ferramenta?lang=pt-br.

HWANG CL & YOON K. 1981. *Multiple attributes decision making methods and applications*. Berlin Heidelberg: Springer.

IEA. 2021. World Energy Outlook 2021. International Energy Agency. Available at: https://www.iea.org/reports/world-energy-outlook-2021.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). 2018. Global Warming of 1.5°C. Summary for Policymakers. Available at: https://www.ipcc.ch/sr15/. Accessed: 10 Jan. 2024.

IRENA AND ILO. 2022. *Renewable energy and jobs: Annual review 2022, International Renewable Energy Agency*. Geneva: Abu Dhabi and International Labour Organization.

JARDIM A, DOS SANTOS M, NETO E, SILVA E & BARROS F. 2020. Integration of the waterfall model with ISO/IEC/IEEE 29148:2018 for the development of military defense system. *IEEE Latin America Transactions*, **18**: 2096–2103. Available at: https://doi.org/10.1109/TLA.2020.9400437. Accessed: 16 Nov. 2023.

JUNIOR C & JARDIM R. 2022. Evaluation of drones for public security: a multicriteria approach by the PROMETHEE-SAPEVO-M1 systematic. *Procedia Computer Science*, **199**: 125–133. Accessed: 12 Nov. 2023.

JUNIOR M. 2022-01-01. Voltammetric Determination of Sulfur in Biodiesel Microemulsion Using a Silver Solid Amalgam Electrode. *Analytical Methods*, **14**(36): 3512–3520,. Available at: https://doi.org/10.1039/d2ay01263d.

JUNIOR S, MOREIRA M & DOS SANTOS M. 2022. Selection of startup interns: an approach based on the AHP-TOPSIS-2N method and the 3DM computational platform. *Procedia Computer Science*, **199**: 984–991. Available at: https://doi.org/10.1016/j.procs.2022.01.124.

KERŠULIENE V, ZAVADSKAS E & TURSKIS Z. 2010. Selection of rational dispute resolution method by applying new step-wise weight assessment ratio analysis (SWARA. *Journal of Business Economics and Management*, **v. 11, n. 2**: 243–258.

KHEYBARI S, MAHDI F & REZAEI J. 2019. Measuring the Importance of Decision-Making Criteria in Biofuel Production Technology Selection. *IEEE Transactions on Engineering Management*, **68**: 483–497.

KÜGEMANN M & POLATIDIS H. 2024. Multi-criteria decision analysis of alternative fuel buses: methodology and case study. *International journal of green energy*, p. 1–21.

LITMAPS. 2022. *Litmaps: Uma plataforma de mapeamento literário (Versão 2.0*. Litmaps Inc. Available at: https://www.litmaps.com.

MANIYA K & BHATT M. 2010. A selection of material using a novel type of decision-making method: Preference selection index method. *Mater. Des*, **31**: 1785–1789.

MAÊDA S, BASILIO M, COSTA I, MOREIRA M, DOS SANTOS M, GOMES CFS, DE ALMEIDA IDP & COSTA AP. 2021. Investments in Times of Pandemics: An Approach by the SAPEVO-M-NC Method. Available at: https://doi.org/10.3233/FAIA210244.

MELLEM P, ARAÚJO I, ARAÚJO A, MOREIRA M, GOMES C, SANTOS D, M C & V J. 2022. Prospective scenarios applied in course portfolio management: An approach in light of the Momentum and ELECTRE-MOr methods. *Procedia Computer Science*, **199**: 48–55. Available at: https://doi.org/10.1016/j.procs.2022.01.007.

MME B. 2021. RenovaBio. Available at: https://www.gov.br/anp/pt-br/assuntos/renovabio. Accessed: 30 out. 2023.

MOFIJUR M, ASHRAFUR S, NGUYEN L, MAHLIA T & NGHIEM L. 2021. Selection of microalgae strains for sustainable production of aviation biofuel. *Bioresource Technology*, p. 126–408.

NEVES M. 2021. *Ferramentas para o futuro do agro: estratégias para posicionar o Brasil como fornecedor mundial sustentável de alimentos*. São Paulo: Editora Gente.

ONU. 2021. Organização das Nações Unidas. Objetivos para o Desenvolvimento Sustentável. Available at: https://www.un.org/sustainabledevelopment/energy/.

PARUCCINI M. 1994. *Applying Multiple Criteria Aid for Decision to Environmental Management*. Dordrecht: Kluwer.

PAULA O, SANTOS M, GOMES C & BALDINI F. 2022. CRITIC-MOORA-3N Application on a Selection of AHTS Ships for Offshore Operations. In: *International Conference on Information Technology and Quantitative Management*.

PAWLAK Z, LECH P & SKOWRON A. 2023. Rough set theory. *KI*, **15**(3): 38–39. Available at: https://doi.org/10.1007/978-3-7908-1776-8_1. Accessed: 29 Nov. 2023.

PEARCE D & TURNER R. 1990. *Economics of Natural Resources and the Environment*. JHU Press.

PESSOA JUNIOR W. 2020. Application of water treatment sludge as a low-cost and eco-friendly catalyst in the biodiesel production via fatty acids esterification: Process optimization. *Energy*, **213**: 118824–118824,.

PLATAFORMA INTERGOVERNAMENTAL SOBRE BIODIVERSIDADE E SERVIÇOS ECOSSISTÊMICOS (IPBES) . 2019. Relatório de Avaliação Global sobre Biodiversidade e Serviços Ecossistêmicos. Available at: https://www.ipbes.net/global-assessment.

POGGIO M. 2024. The role of bioenergy in Brazil's low-carbon future. *Energy and climate change*, **5**.

RANGEL V. 2010. Evaluating the Energy Requirements of Small-Scale Biodiesel Production from Raw Tallow of Tanning Industry. Available at: https://doi.org/10.1115/imece2009-12006.

RODRIGUES A. 2021. Inventário do ciclo de vida da produção de biodiesel utilizando macaúba como fonte de matéria-prima. Available at: http://acervo.ufvjm.edu.br/jspui/handle/1/2662. Accessed: 03 Nov. 2023.

RODRIGUES M, DOS SANTOS M & GOMES C. 2024. Selection of helicopters for offshore service using three multi-criteria decision analysis methods: AHP-TOPSIS-2N, THOR-2 and Gaussian AHP-TOPSIS-2N. *Journal of Control and Decision*, **11**: 1–15.

TENÓRIO F. 2020. *Modelagem multicritério: uma evolução do método thor*. Rio de Janeiro, RJ: IME.

TENÓRIO F. 2021. THOR-2 Method: An Efficient Instrument in Situations Where There Is Uncertainty or Lack of Data. *IEEE Access*, **9**: 161794–161805. Available at: https://ieeexplore.ieee.org/document/9638485.

TENÓRIO F, DOS SANTOS M, GOMES C, ARAUJO J & DE ALMEIDA G. 2021. THOR-2 Method: An Efficient Instrument in Situations Where There Is Uncertainty or Lack of Data. *IEEE Access*, **9**: 161794–161805. Available at: https://ieeexplore.ieee.org/document/9638485. Accessed: 16 Nov. 2023.

TENÓRIO F, SANTOS M, GOMES C & ARAUJO J. 2020. Estratégia para compra de oportunidade de uma fragata para a Marinha do Brasil a partir do método multicritério THOR. *Revista Valore*, **5**: 43–57.

UBRABIO (UNIÃO BRASILEIRA DO BIODIESEL E BIOQUEROSENE). 2022. Goiás se torna 2o produtor de biodiesel do país em 2022. Available at: https://ubrabio.com.br/2023/03/27/

clipping-2a-edicao-goias-se-torna-2o-produtor-de-biodiesel-do-pais-em-2022/. Accessed: 30 out. 2023.

USDA (United States Department of Agriculture. 2023. Biofuels Annual. Available at: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_Brasilia_Brazil_BR2023-0018. Accessed: 15 nov. 2023.

Zavadskas E & Turskis Z. 2010. A new additive ratio assess-ment (ARAS) method in multi-criteria decision making. *Technological and Economic Development of Economy*, **16**(2): 159–172.

Zavadskas E, Turskis Z, Antucheviciene J & Zakarevicius A. 2012. Optimization of weighted aggregated sum product assessment. *Elektronika ir elektrotechnika*, **122**(6): 3–6. Available at: https://doi.org/10.5755/j01.eee.122.6.1810.

How to cite

Almeida VVA, Gomes CFS, Pinochet LHC & Santos M. 2024. Driving ESG compliance: THOR-2 assessment of biodiesel production capacities in the midwest and south of Brazil. *Pesquisa Operacional*, **44**: e284063. doi: 10.1590/0101-7438.2023.043.00284063.