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Quantifying the factors behind the decision to produce second-generation ethanol in Brazil: a Fuzzy-QFD decision-support model.

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Abstract

Second-generation (2G) ethanol is a strategic route for decarbonizing the energy matrix through lignocellulosic residues, yet its consolidation in Brazil remains limited and the corporate decision to produce it is poorly understood in quantitative terms. The literature lacks a systematic framework to assess the relative importance of these factors across different stakeholders. To address this gap, this study develops and applies a Fuzzy Quality Function Deployment (Fuzzy-QFD) decision-support model that quantifies how strongly each factor and barrier is weighed in the decision to produce, or not to produce, 2G ethanol, and how this weighting differs among production-system actors. Nine critical factors and twelve expected-quality groups were derived from two systematic reviews and crossed in a House of Quality; linguistic judgments from 40 stakeholders spanning the Triple Helix (industry, academia, and government) were encoded as triangular fuzzy numbers, adjusted by a competence-based coefficient, aggregated, and defuzzified. The analysis is framed by the Triple Bottom Line and interpreted against the Sustainable Development Goals. Industrial Efficiency ranked first (score 94.9; about 10% relative importance), indicating that 2G ethanol is treated as a commodity whose competitiveness depends on process optimization rather than product properties, while Technology emerged as the structural driver of the model. Although Environmental Sustainability received the highest declared importance, it showed limited operational influence, revealing a gap between sustainability commitments and their translation into decision-making, with implications for SDG 13. The model provides a replicable tool that converts subjective judgments into impact coefficients for each decision actor.

Keywords: Second-generation ethanol; Fuzzy Quality Function Deployment; Multi-criteria decision-making; Triple Bottom Line; Sustainable Development Goals; Triple Helix

1. Introduction

The global transition towards renewable energy matrices constitutes a highly complex environmental system, where strategic decision-making regarding alternative fuels is critical for mitigating climate change and ensuring energy security. Within this systemic context, ethanol serves as a prominent renewable substitute for fossil fuels, characterized by cleaner combustion profiles (Guedes et al. 2021). While first-generation (1G) ethanol, derived from fermentable sugars and starches, is industrially consolidated, its expansion faces structural limitations and complex trade-offs, including competition for arable land and conflicts with food security (Angelidaki et al. 2012; Karagöz et al. 2019). Consequently, the transition to second-generation (2G) ethanol (E2G), produced from lignocellulosic biomass and agricultural residues, has emerged as a strategic decision-analysis challenge. By valorizing residual biomass, E2G aligns directly with circular economy principles and expands agricultural material efficiency; however, its large-scale adoption depends on balancing multiple interrelated factors, including technological maturity, industrial efficiency, economic viability, biomass availability and logistics, environmental performance, regulatory conditions, and market incentives. These factors are often uncertain, interdependent, and perceived differently by stakeholders from industry, academia, and government, making investment and production decisions inherently complex. Consequently, understanding how these factors are prioritized and interact is essential for supporting strategic decisions and requires robust decision-support frameworks capable of systematically integrating multiple perspectives within this socio-technical system (Junqueira et al. 2017; Oliveira et al. 2025).

Despite its systemic sustainability potential, the industrial consolidation of E2G remains hindered by significant techno-economic barriers. The conversion process requires overcoming the natural recalcitrance of lignocellulosic matrices, which necessitates intensive pretreatment, complex enzymatic hydrolysis, and specialized fermentation routes (Bhatia et al. 2020; Rosa

and Garcia 2009). These technical bottlenecks ripple across the economic sphere, inflating operational costs and rendering E2G less competitively viable than 1G ethanol at scale (Bernardi et al. 2023; Ibarra et al. 2019). Furthermore, logistical complexities, such as biomass supply chain constraints and competition for raw materials, exacerbate investment uncertainties (Tavares 2019). The sector is thus characterized by marked heterogeneity, with the pioneering industrial operations being technically feasible but at the same time with limited widespread corporate uptake and poorly understood production decisions in quantitative terms (Junqueira et al. 2017).

The formation of the corporate decision to produce E2G is a complex, multidimensional process intrinsically linked to the global sustainability agenda. Corporate technological and logistical choices dictate long-term economic and environmental impacts, aligning directly with the Sustainable Development Goals (SDGs). Specifically, diagnosing production barriers supports the expansion of renewable energy (SDG 7.2); assessing biomass efficiency promotes responsible consumption and production (SDG 12); quantifying environmental impacts strengthens climate action (SDG 13); and evaluating industrial innovation fosters sustainable infrastructure (SDG 9) (Soccol et al. 2016). But assessing these decisions needs a systemic approach that includes the Triple Bottom Line (TBL) of People, Planet and Profit. Traditional literature tends to overemphasize short-term economic viability treating environmental and social dimensions as secondary or isolated variables (Melo et al. 2020; Mizik 2021; Wicke et al. 2015). This fragmented analytical approach prevents a comprehensive understanding of corporate behavior and obscures the critical trade-offs inherent in the E2G ecosystem.

Brazil offers a privileged setting for this problem. Its sugarcane-energy sector is among the most prominent bioethanol industries in the world (Karp et al., 2021), with a consolidated 1G infrastructure, a national low-carbon-fuel policy (RenovaBio) that monetizes decarbonization through decarbonization credits (CBIOs) (Oliveira & Coelho, 2019), and an installed base of biorefineries with the potential to integrate lignocellulosic routes to improve long-term competitiveness (Junqueira et al., 2017). Yet this maturity coexists with a striking reluctance to scale 2G production, which makes the country an ideal case to ask not whether 2G ethanol is technically feasible (it is) but why, and under which weighting of factors, firms still hesitate to produce it. Answering this question requires moving from descriptive, single-dimension analyses toward an integrated model able to represent the simultaneous influence of technological, economic, social, agricultural, and environmental variables (Wicke et al., 2015; Skrynkovskyy et al., 2018).

A further methodological gap lies in the treatment of expert uncertainty. Elicitation processes in bioenergy decision-making frequently treat subjective judgments as precise values, neglecting the inherent vagueness of human perception (Cadham et al. 2021). Omitting this imprecision reduces analytical robustness and exposes strategic policies and investments to cognitive biases. To address this, Fuzzy Set Theory (Zadeh 1965) provides a mathematical framework to represent linguistic variables and gradual membership, allowing for the quantification of ambiguity in human judgments (Calache et al. 2022). When integrated with Quality Function Deployment (QFD), the Fuzzy QFD methodology translates subjective requirements into measurable technical parameters while preserving and propagating the underlying uncertainty (Junior et al. 2018). This integrated approach is particularly suitable for complex industrial environments like E2G, where decision-makers must weigh interdependent operational barriers against multidimensional quality and sustainability criteria.

The convergence of these two gaps defines the problem addressed here. To date, no integrated quantitative instrument has been proposed to measure which factors are weighed more or less heavily in the decision to produce 2G ethanol in Brazil and how that weighting differs among the actors of the production system. Tools capable of overcoming this fragmentation exist but are rarely applied to the sugarcane-energy sector, which prevents the analysis of trade-offs and

reduces the explanatory power of decision models (Jusakulvijit et al., 2021; Skrynkovskyy et al., 2018; Mohr & Raman, 2013).

Therefore, the central research question of this study is: *How can the impact of factors and barriers influencing the corporate decision to produce second-generation ethanol be quantitatively integrated and prioritized under conditions of uncertainty?* To address this, the study aims to develop and validate a Fuzzy QFD-based decision support model that evaluates and quantifies the impact of E2G production barriers. The model is framed by the TBL and the SDGs, and interpreted through the Triple Helix (TH) of university–industry–government relations. Its contribution is threefold: (i) a systematic inventory of factors, barriers, and expected qualities of 2G ethanol; (ii) a replicable analytical artifact that converts subjective, TBL-oriented judgments into impact coefficients for each actor; and (iii) a method to contrast the empirical perception of stakeholders with the consolidated literature, exposing interpretive noise in the biofuel debate.

The remainder of this paper is organized as follows. Section 2 presents the theoretical background, including second generation ethanol and its systemic bottlenecks, fuzzy sets, quality function deployment, the triple bottom line, sustainable development goals and the triple helix. Section 3 details the materials and methods, comprising the two systematic literature reviews that ground the decision factors, the Fuzzy-QFD mathematical formulation, the competence-based weighting of stakeholders, and the data-collection protocol. The results are presented in Section 4, including the analysis of interpretive noise between literature and industrial practice, the House of Quality matrix and its decision impacts, the clear prioritization of factors, and sample characterization and semantic grouping. Finally, Section 5 draws the conclusions, discusses the limitations of the study, and outlines directions for future research.

2. Theoretical Background

2.1 Second-generation ethanol and systemic bottlenecks

The production of 2G ethanol is distinguished by the use of lignocellulosic biomass, a polymeric matrix of cellulose, hemicellulose, and lignin whose recalcitrance protects fermentable sugars from enzymatic and chemical access (Firsty et al., 2023; Pu et al., 2015). Overcoming this recalcitrance requires intensive pretreatment and hydrolysis steps that dominate production cost, and the fermentation of pentoses remains a bottleneck for full sugar utilization (Rosa & Garcia, 2009; Bhatia et al., 2020). Two technological routes coexist: the biochemical route (pretreatment, hydrolysis, fermentation, and distillation) and the thermochemical route (gasification and catalytic synthesis); each with distinct costs, maturity, and scale requirements (Rosa & Garcia, 2009). These technical conditions translate directly into economic risk, so that the decision to produce 2G ethanol is inseparable from technology, workforce, logistics, policy, and sustainability considerations (Junqueira et al., 2017).

The biochemical route concentrates most research and development because of its higher yield potential and milder chemistry: pretreatment (steam explosion, hydrothermal, dilute-acid, organosolv, or AFEX) exposes the cellulose; enzymatic hydrolysis releases fermentable sugars; and integrated configurations (SHF, SSF, SSCF, and CBP) seek to reduce cost by combining steps (Rosa & Garcia, 2009; Robak & Balcerek, 2018). The high cost of cellulolytic enzymes and the difficulty of standardizing pentose-fermenting strains remain the principal economic bottlenecks (Al-Zuhair et al., 2013). The thermochemical route, based on gasification and Fischer-Tropsch or methanol-mediated synthesis, is less dependent on biotechnology but demands large scale and gas cleaning, and direct ethanol synthesis still lacks commercial selectivity (Rosa & Garcia, 2009). These technical realities directly constrain the economic viability of E2G, creating a heterogeneous industrial landscape where decision-making requires

balancing operational efficiency against market competitiveness, this is exactly what makes the produce/not-produce decision a multi-criteria problem.

2.2 Fuzzy sets and QFD modeling

To overcome the limitations of deterministic multi-criteria evaluation in complex systems, this study employs Fuzzy Set Theory. A fuzzy set A in a universe of discourse X is defined by a membership function $\mu_A(x): X \rightarrow [0,1]$, which quantifies the degree to which an element x belongs to the set (Zadeh 1965; Köseoğlu et al. 2024). This formalization allows gradual membership, capturing the nuances and subjectivities of human reasoning. To ensure mathematical consistency, fuzzy numbers utilized in this study must satisfy the properties of normality and convexity, typically represented via triangular or trapezoidal membership functions (Calache 2022).

Operations such as union, intersection, and complementation extend classical Boolean logic. The union ($A \cup B$) is defined by the maximum of the membership grades, while the intersection ($A \cap B$) is defined by the minimum, enabling the aggregation of imprecise information (Côrtes et al. 2021). The conversion of crisp inputs into fuzzy grades (fuzzification) enables the application of algebraic operations, culminating in defuzzification to translate aggregated fuzzy outputs back into actionable crisp values. The centroid method, widely employed for its stability, calculates the center of gravity under the output membership curve (Ren et al. 2025):

$$COA = \frac{\int x\mu(x)dx}{\int \mu(x)dx} \tag{1}$$

Quality Function Deployment (QFD) structurally translates subjective "Whats" (client/stakeholder requirements) into measurable "Hows" (technical parameters) via the House of Quality (HOQ) matrix (Chadly et al. 2024). The classical QFD prioritization assigns numerical relationship grades r_{ij} between the i-th requirement and the j-th technical characteristic. However, the classical approach fails to capture the inherent vagueness of these relationships. The Fuzzy QFD methodology mitigates this by substituting crisp values with fuzzy numbers (Junior et al. 2018). For each technical characteristic j, the fuzzy weight $\widetilde{W}_j$ is obtained through the fuzzy aggregation of the relationships $\tilde{R}_{ij}$ and the requirements' importance $\tilde{T}_i$ (Yazdani et al. 2017):

$$\widetilde{W}_j = \oplus_{i=1}^{m}[\tilde{T}_i \otimes \tilde{R}_{ij}] \tag{2}$$

By applying this model to the E2G industry, the method correlates critical operational factors (e.g., enzymatic costs, logistics) with expected production qualities, explicitly quantifying the systemic trade-offs between short-term economic barriers and long-term TBL sustainability goals.

2.3 TBL, SDGs, and the Triple Helix

Elkington's (1997) Triple Bottom Line proposes that organizational performance be measured across three interdependent dimensions: economic (Profit), environmental (Planet), and social (People), rather than just financial results. It implements the three-pillar concept of sustainability, in which the economy, environment, and society are treated as coequal and mutually constraining domains (Purvis et al., 2019). A defining property of the TBL is the incommensurability of its accounts: economic value, expressed in monetary units; environmental value, expressed in biophysical terms; and social value, expressed in distributional terms, cannot be collapsed into a single figure without contestable weighting

choices (Glac, 2015). This incommensurability underpins the distinction between weak sustainability, which allows for substitution among the three types of capital, and strong sustainability, which views natural capital as only partially substitutable (Purvis et al., 2019). It also underpins a common criticism of applied TBL: when the three accounts are reported side by side but not confronted, the framework can document sustainability without changing decisions, decoupling disclosure from operational behavior (Nica et al., 2025; Sabino et al., 2024). In lignocellulosic ethanol, these tensions are evident; gains from residue valorization and decarbonization (Planet) must be weighed against conversion costs and productivity (Profit), as well as the effects on labor qualification and regional development (People). In this study, the TBL provides the framework of value dimensions along which the production decision is contested and along which its criteria are organized.

If the TBL supplies the internal dimensions of value, the 2030 Agenda supplies the external, globally comparable language that translates those dimensions into policy-relevant targets. Unlike the broad discourse of sustainability, the Agenda unfolds each of its seventeen goals into concrete targets and quantifiable indicators, rendering the framework at once normative and operational (measurable, comparable across contexts, and consequently parameterizable in this study), since it is through this indicator-based structure that the selection of the sustainability-relevant decision factors is made. The E2G parameters map directly onto SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), SDG 9 (industry, innovation, and infrastructure), SDG 12 (responsible consumption and production), and SDG 13 (climate action). Framing the factor rankings against these goals converts a firm-level, context-specific decision into a diagnostic instrument that identifies where intervention has the highest potential impact on each target and enables comparison across geographies and production models. This subordination of the analysis to the SDGs also yields the study's most policy-relevant reading: the sector's alignment is pragmatic and paradoxical, actively advancing SDG 8, 9, and 12 through efficiency, biotechnology, and qualified labor, and resolving the historical food-versus-fuel tension in favor of SDG 7, while simultaneously placing SDG 13 at risk because environmental value remains discursive rather than operational. The model therefore turns the SDGs from an aspirational backdrop into a measurable axis of the decision.

However, operationalizing these measurable targets does not occur in an institutional vacuum. The consolidation of a lignocellulosic route is an innovation-system process that unfolds through the coordinated dynamics of university, industry, and government (the Triple Helix) (Etzkowitz & Leydesdorff, 2000; Etzkowitz, 2003). In this model, innovation in knowledge-based economies emerges from the recursive interaction among these three institutional spheres rather than from any of them in isolation: the university generates and transfers knowledge, industry deploys it at commercial scale, and government provides regulation and incentives, with hybrid organizations arising at their intersections (Leydesdorff & Meyer, 2003; Cai & Amaral, 2021; Leydesdorff & Smith, 2021). Understood as an analytical framework for innovation policy, the Triple Helix treats these overlaps (rather than linear technology transfer) as the locus where emerging technologies such as second-generation ethanol are matured (Ranga & Etzkowitz, 2013).

The relevance of this framework to the evaluation of the E2G production decision follows from the multidimensional nature of the problem. The factors that condition whether a firm produces second-generation ethanol span the technological, economic, agricultural, social, and regulatory domains at once, and this interdependence has repeatedly frustrated attempts to represent the decision through any single lens (Wicke et al., 2015; Julio et al., 2017; Skrynkovskyy et al., 2018; Jusakulvijit et al., 2021). No single category of actor holds adequate competence over all of these domains (Mohr & Raman, 2013; Rafiaani et al., 2018); rather, each sphere reasons from the knowledge situated in its own field of practice. Universities and research institutes are best positioned to appraise technological maturity, conversion routes, and workforce

qualification (Junqueira et al., 2017; Uyan et al., 2020; Pinhas et al., 2025); government and regulatory bodies command the information and authority to weigh public policy, incentives, and compliance (Dick et al., 2018; Nogueira et al., 2017); and firms are the locus of judgment on economic viability, cost structures, and the operational feasibility of logistical and technological routes (Melo et al., 2020; Junqueira et al., 2017). A valid and systemic assessment of the decision therefore cannot rest on a single viewpoint; it must bring together the complementary, domain-specific competences of the three helices, so that each dimension of the problem is evaluated by the actors closest to it in practice (Cai & Amaral, 2021; Ranga & Etzkowitz, 2013). The Triple Helix thus provides the conceptual basis for characterizing the E2G decision through the integrated perspectives of academia, government, and industry, each contributing to the dimensions it is best equipped to evaluate (Jusakulvijit et al., 2021).

3. Materials and Methods

3.1 Research design and systematic framework

This study adopts an applied, mixed-methods research design structured around a prescriptive-normative axiomatic approach (Bertrand and Fransoo 2002). The core objective is to construct a quantitative decision support artifact that maps the asymmetric relationships between expected production qualities (Whats) and the systemic barriers and decision factors (Hows) in the E2G industry. To ensure empirical grounding and operational validity, the research flow integrates two Scalable Systematic Literature Reviews (SSLRs) that feed directly into the Fuzzy QFD modeling.

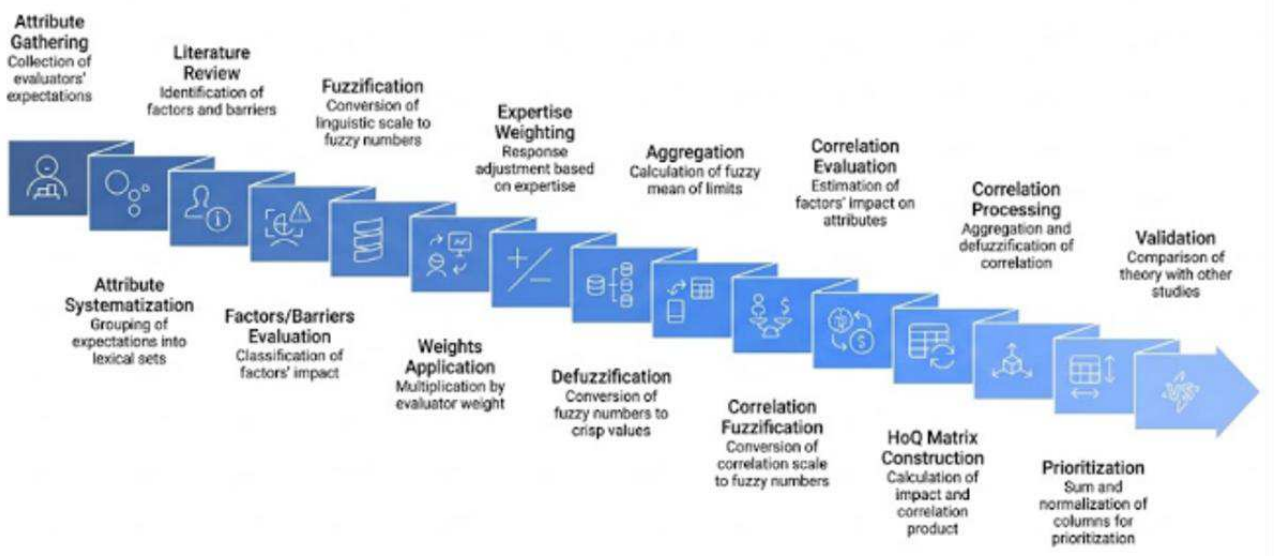


Fig. 1 Analytical process flow of the Fuzzy-QFD prioritization and decision-making model

The inventory of decision factors was grounded in two scalable systematic literature reviews (SSLRs) conducted by the authors on the Web of Science and Scopus databases, both feeding directly into the Fuzzy-QFD modeling. The first SSLR mapped the state of the art on multi-criteria decision-making (MCDM) applied to bioenergy over the 2014–2024 window, using a Boolean strategy that combined ethanol-based descriptors with decision-making variables; successive title, abstract, and full-text screening reduced the corpus to 36 strictly relevant peer-reviewed articles, which were then mapped bibliometrically with VOSviewer by journal, author, country, and institution. The second SSLR was experimentally oriented, restricted to the last quinquennium (2020–2024) and filtered for Design of Experiments (DOE) methodologies

to capture contemporary technological bottlenecks; from a synthesis of 51 selected articles, critical factors and barriers were extracted through content analysis.
The decision-making review organized the field into recurrent thematic categories (supply-chain assessment and plant location; sustainability and environmental impact; economic analysis and feasibility; public policy and development strategies; technology and production-process assessment; social acceptability; risk management; and efficiency and performance) and found that the most-used techniques were mixed-integer linear programming, the Analytic Hierarchy Process, and the Delphi method, while multi-area, integrated decision models remained rare and the economic factor, though frequent, was not predominant. Complementarily, the DOE review showed that experimental research concentrates on pre-treatment, sugar conversion, by-products, integrated production, product quality, and feedstock, with Brazil emerging as the leading hub, thereby anchoring the technological and biomass-related factors of the model.

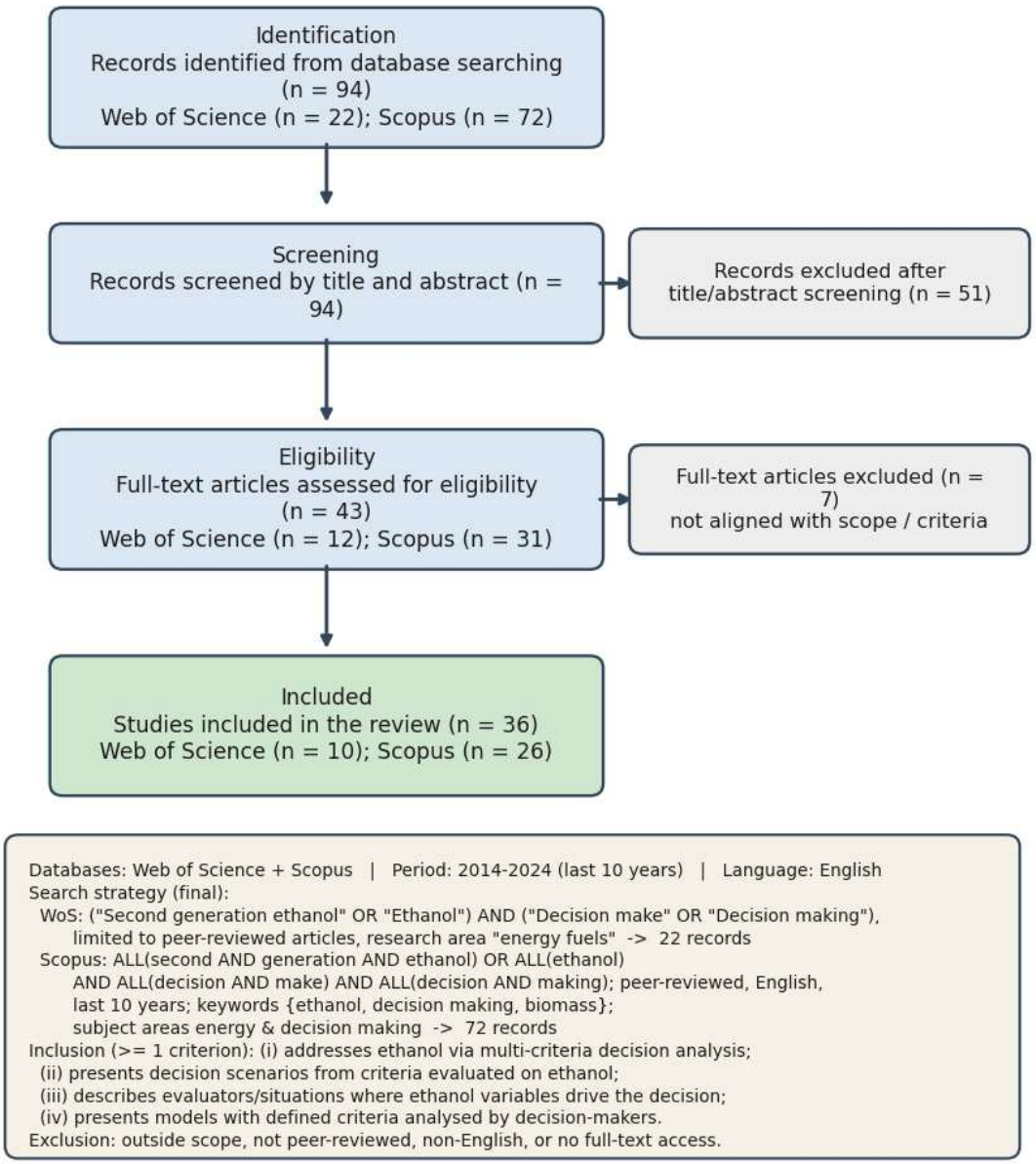


Fig. 2 PRISMA flow of the systematic review on multi-criteria decision-making applied to bioethanol production (SSLR 1)

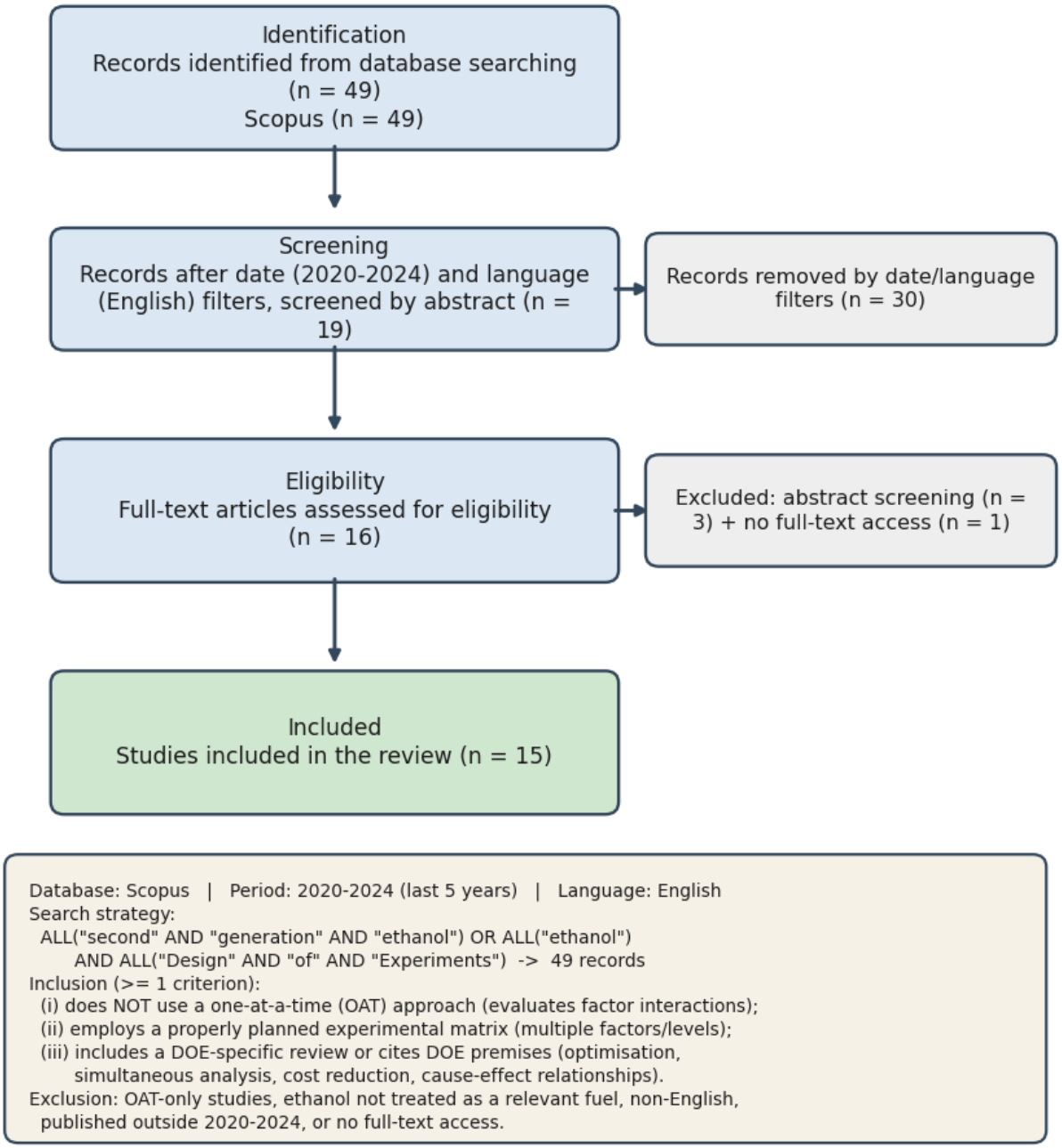


Fig. 3 PRISMA flow of the systematic review on Design of Experiments (DOE) applied to bioethanol production (SSLR 2)

The two reviews culminated in the set of independent variables of the model. The integrated systematic reviews (2014–2024) revealed that existing literature on bioethanol decision-making is structurally fragmented. While multi-criteria techniques are widely applied, they predominantly isolate binary TBL dimensions (e.g., economic vs. environmental), failing to capture the total systemic complexity of the E2G production chain. By cross-referencing the macroscopic decision-making review with the experimental DOE review (2020–2024), the study identified a convergent set of critical elements. These were systematically categorized into nine macro-areas of impact, representing the primary barriers and enablers (Hows) that govern the feasibility of E2G production:

- Technology: Encompasses biotechnological innovations, equipment, and conversion routes. Its presence increases yield and lowers costs; its absence blocks scalability (Uyan et al. 2020; Prado et al. 2023).
- Labor: Relates to human capital qualification and availability. Deficits create operational bottlenecks and elevate implementation costs (Jusakulvijit et al. 2021).
- Supply Chain: Covers biomass availability, cost, and logistics. Due to the volume and perishability of raw materials, infrastructure directly alters competitiveness (Corsano et al. 2014; Wicke et al. 2015).
- Public Policies: Includes regulations and incentives. Instability or absence of clear frameworks can render otherwise profitable projects unviable (Dick et al. 2018; Nogueira et al. 2017).
- Environmental Sustainability: Relates to impact minimization and circularity. Negligence creates legal and public acceptance barriers (Hilst et al. 2018; Lucia et al. 2019).
- Plant Location: Proximity to biomass sources and markets. Poor selection exponentially increases logistical costs (De Laporte and Ripplinger 2019).
- Centralized Production: Integration of steps in a single hub. Generates economies of scale but concentrates logistical and social risks (Bressanin et al. 2021).
- Food vs. Ethanol Competition: The trade-off for land and inputs. Impacts food security and social legitimacy, conditioning policies (Jusakulvijit et al. 2021).
- Energy vs. Ethanol (Biomass utilization): Refers to using residues for energy generation. Improves systemic efficiency but requires complex technological-regulatory arrangements (Mutran 2020; Nogueira et al. 2017).

3.2 Fuzzy QFD modeling and mathematical formulation

The proposed model adapts the traditional HOQ by embedding fuzzy set theory to handle the epistemic uncertainty inherent in expert elicitation. Standard QFD calculates technical priorities w_j via the weighted sum of relationship degrees r_{ij} and importance ratings I_i. However, in the complex E2G sector, crisp evaluations fail to capture the ambiguity of technological and market risks. Therefore, evaluations are captured via linguistic variables and converted into triangular fuzzy numbers (TFNs), defined by the triplet (l, m, u). This triplet represents the lower bound, peak, and upper bound of the membership function $\mu_{\tilde{A}}(x)$, respectively (Calache 2022; Junior et al. 2018). For a TFN $\tilde{A} = (l, m, u)$, the membership function is expressed as:

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x \leq l \text{ or } x \geq u \\ \dfrac{x-l}{m-l}, & l < x \leq m \\ \dfrac{u-x}{u-m}, & m < x < u \end{cases} \tag{3}$$

The variables were assessed using two distinct linguistic scales, algebraically aligned over a continuous discourse universe [0, 7]. The absolute importance of barriers/factors (Whats) was rated on a 7-point Likert scale (from "Not Relevant" to "Extremely Relevant"), mapped as $\tilde{T}_i$. The correlation between factors and expected qualities (Hows) was rated on a 3-point scale (Low, Medium, High Contribution), mapped as $\tilde{R}_{ij}$. Tables 1 and 2 detail the fuzzy sets underlying the 7-point and 3-point linguistic scales, respectively.

Table 1 Fuzzy linguistic scale for the relevance of factors and barriers

Category	Description	TFN Limits (l,m,u)
NR	Not Relevant	(0, 0, 1)
SR	Slightly Relevant	(0, 1, 2)
LR	Lightly Relevant	(1, 2, 3)
MR	Moderately Relevant	(2, 3, 4)
RE	Relevant	(3, 4, 5)
VR	Very Relevant	(4, 5, 6)
ER	Extremely Relevant	(5, 6, 7)

Table 2 Fuzzy linguistic scale for the correlation between quality attributes and factors

Category	Linguistic Variable	TFN (l,m,u)
HC	High Contribution	(5, 6, 7)
MC	Medium Contribution	(3, 4, 5)
LC	Low Contribution	(1, 2, 3)

The triangular fuzzy numbers associated with the two linguistic scales are depicted in Figs. 4 and 5, respectively.

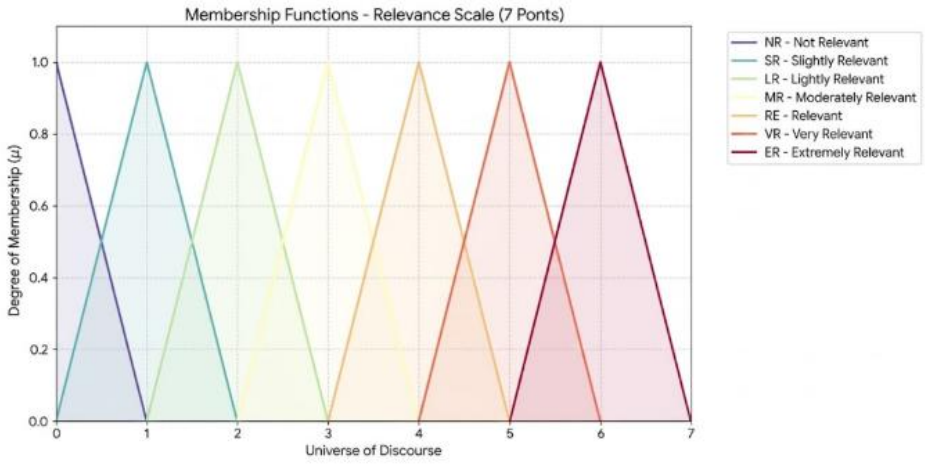


Fig. 4 Triangular Fuzzy Numbers (TFN) membership functions representing the 7-point linguistic scale used for evaluating the relevance of decision-making factors

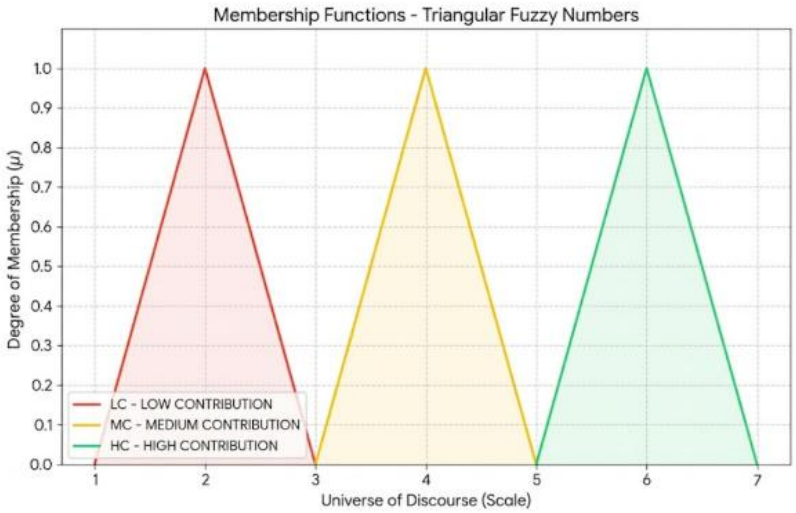


Fig. 5 Triangular Fuzzy Numbers (TFN) membership functions representing the 3-point linguistic scale used for assessing the correlation between quality attributes and decision-making factors

To prevent structural bias from experts evaluating variables outside their operational domain, each crisp evaluation $\tilde{E}_{ij}$ is adjusted by an association coefficient $a_{ij} \in [0,1]$. This coefficient reflects the proximity between the evaluator's institutional expertise (e.g., enzyme developer vs. logistics manager) and the specific factor evaluated. The adjusted fuzzy evaluation $\tilde{R}_{ij}$ is computed via standard fuzzy multiplication:

$$\tilde{R}_{ij} = \tilde{E}_{ij} \otimes a_{ij} \tag{4}$$

Where $\otimes$ denotes the fuzzy multiplication operator. For two TFNs $\tilde{A} = (l_1, m_1, u_1)$ and $\tilde{B} = (l_2, m_2, u_2)$, multiplication and addition are governed by the extension principle:

$$\begin{aligned} \tilde{A} \otimes \tilde{B} &\approx (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \\ \tilde{A} \oplus \tilde{B} &= (l_1 + l_2, m_1 + m_2, u_1 + u_2) \end{aligned} \tag{5}$$

The collective fuzzy opinion $\widetilde{W}_j$ for each factor j across k experts is aggregated via the fuzzy arithmetic mean, combining the importance $\tilde{T}_i$ and the adjusted relationship $\tilde{R}_{ij}$ (Yazdani et al. 2017):

$$\widetilde{W}_j = \frac{1}{k} \bigoplus_{i=1}^{k} \left(\tilde{T}_i \otimes \tilde{R}_{ij}\right) \tag{6}$$

To convert the aggregated fuzzy weights back into actionable crisp values and calculate the final priority vector, the centroid method (Center of Area - COA) is applied (Ren et al. 2025). For a resulting TFN $\widetilde{W}_j = (l, m, u)$, the crisp value x_j^* is:

$$x_j^* = \frac{l + 2m + u}{4} \tag{7}$$

Finally, the crisp weights are normalized relative to the sum of all evaluated factors, yielding the relative priority weight P_j for each production barrier/attribute within the HOQ matrix:

$$P_j = \frac{x_j^*}{\sum_{j=1}^{n} x_j^*} \tag{8}$$

3.3 Defining evaluator weights on QFD model

A central element of the proposed framework is the application of multiplier weights (association coefficients) to the Fuzzy numbers. These weights ensure that the subjective perceptions are quantitatively integrated with the actual evaluative capacity and expertise of each stakeholder within the E2G sector.

The coefficients were not assigned arbitrarily. Building on the two systematic reviews, each of the nine factors was classified by its frequency and emphasis in the literature for each type of

organization, and the factors were then compared for their relative importance to each actor. On this basis, a relevance scale from 0.1 to 1.0 was established, in which higher values correspond to factors repeatedly reported as critical to that organization's performance or strategic decision, and every attribution was documented together with the sources that supported it. The resulting scheme was validated with the respondents of the data-collection phase, ensuring transparency and replicability. For example, ethanol producing plants received the maximum weight (a = 1.0) for Technology, Workforce, Environmental Sustainability, Plant Location, Food-versus-fuel, and Biomass-for-energy (dimensions that form the operational core of their CAPEX and OPEX) whereas Supply Chain and Public Policy received an intermediate weight (a = 0.5) because, although influential, they are largely exogenous to the firm's control; equipment suppliers, conversely, prioritized Technology (a = 1.0) but received marginal weight (a = 0.1) for Plant Location and Biomass, reflecting their focus on engineering performance rather than biomass logistics. This competence-based weighting ensures that the aggregated fuzzy opinions reflect genuine operational expertise rather than generalized perceptions.
The analyses are detailed below:

- *E2G Producers*: Received maximum weights (1.0) for technology, labor, sustainability, location, food vs. fuel competition, and biomass, as these dimensions directly dictate CAPEX, OPEX, productivity, and compliance (Rosa & Garcia, 2009; Sharma et al., 2020; Silva et al., 2018). Supply chain and public policies received intermediate weights (0.5) because, although influential, they are largely exogenous variables (Bryngemark & Söderholm, 2021; Usmani et al., 2021).
- *Input Suppliers*: Prioritize technology and biomass (1.0), along with supply chain logistics, to guarantee product performance and follow market expansion trends (Mafakheri & Nasiri, 2013; Touhami et al., 2024).
- *Equipment Suppliers & Technical Support*: Focus predominantly on technology and specialized labor (1.0), respectively. These attributes represent their core value propositions, whereas factors like plant location or biomass availability have a marginal impact on their specific evaluative capacity (Nachum & Schmid, 2013; Eras-Almeida & Egido-Aguilera, 2019; Nunes et al., 2020).
- *R&D Institutions*: Evaluate technology, biomass, and food competition with maximum relevance (1.0) due to their institutional mandate to generate knowledge, assess emerging conversion routes, and provide sustainable innovations (Hall & Bagchi-Sen, 2006; Viikari et al., 2012; Chowdhury et al., 2025).
- *General Services*: As their activities (e.g., cleaning, basic infrastructure) are measured by standard service indicators rather than E2G-specific technical parameters, they exhibit limited evaluative capacity over the sector's specific bottlenecks, justifying a uniform minimum weight (0.1) across all dimensions (Machado et al., 2020; Trento et al., 2022).

The resulting association coefficients applied to the evaluations are detailed in next table.

Table 3 Association coefficients assigned by stakeholder area of expertise

Company Type	Technology	Labor	Supply Chain	Public Policies	Env. Sustainability	Plant Location	Food vs. Fuel Competition	Biomass for Energy
E2G Producing Company	1.0	1.0	0.5	0.5	1.0	1.0	1.0	1.0
Input Supply Company	1.0	0.5	1.0	0.5	0.5	0.5	0.5	1.0
Equipment Supply Company	1.0	0.5	0.1	0.5	0.5	0.1	0.1	0.1

Technical Support Company	0.5	1.0	0.1	0.1	0.5	0.1	0.1	0.1
R&D Institution	1.0	0.5	0.1	0.1	0.5	0.1	1.0	1.0
General Services Company	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

3.4 Data collection protocol and expert elicitation

The artifact was validated via a structured electronic survey instrument designed to measure latent variables and quantify the systemic impact of the identified barriers. The survey was divided into three operational blocks: (i) respondent profiling for association coefficient assignment; (ii) Likert-scale valuation of barriers and mapping of semantic quality groups; and (iii) assessment of theoretical convergence to identify dissonances between literature and empirical practice.

Recognizing that the consolidation of the E2G sector depends on the TH dynamic the sampling strategy targeted a transversal cohort across these three spheres. Institutional contacts were extracted from the Brazilian Petroleum and Gas Institute (IBP), the National Agency of Petroleum, Natural Gas and Biofuels (ANP), and the NovaCana database. Targeted entities included UNICA (Industry), CTC (Technology), ORPLANA (Producers), and CEISE Br. Simultaneously, 112 Brazilian public higher education institutions with traditions in Engineering and Agrarian Sciences were contacted, alongside 56 regional professional councils (CRQ, CRBio, CREA). This net cast resulted in 123 industry contacts, 112 academic contacts, and 56 regulatory contacts, totaling 291 institutional outreach points.

A persistent challenge in eliciting expert opinions from industrial binaries is the historically low engagement rate in extensive academic surveys. To overcome this cognitive load barrier without compromising methodological robustness, an active engagement hybrid strategy was deployed. Rather than sending blank surveys, pre-filled minutas (drafts) were generated for each industrial participant via Institutional Discourse Analysis (Bardin 1977).

This pre-filling was not based on arbitrary keyword frequency but on a four-vector analytical matrix applied to the companies' public reports, ESG summaries, and equity stories:

- *Terminological Recurrence***:** Semantic field mapping of operational terms.
- *Information Hierarchy*: Gradient weighting based on textual location (e.g., high weight for CEO letters/risk matrices; low weight for footnotes).
- *Discursive Centrality***:** Evaluation of whether the factor is framed as a proprietary competitive differentiator or a basic operational requirement.
- *Value Materiality***:** Correlation of the factor with direct financial performance (EBITDA) or market advantages (e.g., decarbonization credits - CBios).

Proposed fuzzy values were pre-assigned in the survey based on this lexical-topographical mapping. Synchronous video-assisted interviews were offered to validate or adjust the pre-filled data. Thus, when an expert validated the draft, the data represented a convergence between secondary institutional evidence and primary expert ratification. By the cut-off date (July 2025), this protocol yielded exactly 40 fully validated responses, providing the primary dataset for the Fuzzy QFD matrix.

The dependent variables of the model (the qualities expected from the E2G product and its production process - the “Whats”) were obtained through the elicitation and consolidated by a structured content-analysis protocol. First, all responses were transcribed verbatim, preserving the exact terms used by the evaluators. Second, an exploratory reading of the full corpus identified recurrent lexical patterns, and every term describing a relevant quality or attribute was highlighted. Coding then followed a criterion of semantic uniqueness: synonyms and conceptually equivalent terms were initially kept separate for detailed appraisal. In the semantic-analysis stage proper, terms were grouped into preliminary categories according to

conceptual and functional proximity, combining traditional qualitative content analysis with interpretive inference and considering both explicit meanings and implicit contexts.
The preliminary categories were then submitted to internal validation through cross-comparison between terms, ensuring consistency and cohesion; whenever conceptual divergences appeared, the associated terms were revised, regrouped, or used to create new categories. This process consolidated the responses into twelve lexical categories: Physico-chemical Properties, Quality and Standardization, Industrial Efficiency, Agronomic Innovation and Biotechnology, Environmental Sustainability, Sustainability (general sense), Logistics and Value Chain, Strategy and Competitiveness, Management and Governance, Regulatory Compliance, Human Capital and Culture, and Resilience and Compatibility. Each consolidated axis was documented together with its constituent synonyms, allowing its subsequent integration (as the rows of the House of Quality) with the quantitative analysis.
The third block of the survey was designed to detect interpretive noise, that is, the dissonance between the consolidated scientific literature and the pragmatic perception of the sector's practitioners. From the two systematic reviews, ten affirmations were extracted, each expressing a proposition about second-generation ethanol that is widely established and recurrently endorsed in the literature, for instance, statements concerning the integral (economic, social, and environmental) nature of sustainability, the valorization of by-products and the circular-economy rationale, the readiness of conversion technologies, the alignment of production with national strategic objectives, risk management under uncertainty, and the multidimensional character of the production decision. Rather than eliciting the importance of factors, this block asked respondents to express their level of agreement with each statement, so that the instrument measures how far propositions already consolidated in theory are internalized in industrial practice.
To preserve methodological consistency with the rest of the model, the level of agreement was captured on a seven-point Likert concordance scale, ranging from "do not agree" to "fully agree," and each degree was mapped onto the same triangular-fuzzy-number parameterization used throughout the study. The judgments were aggregated across respondents by the fuzzy arithmetic mean and defuzzified by the centroid method (Equation 6), yielding a crisp concordance value for each statement. Because these statements are already established in the literature, the resulting concordance values function as a diagnostic reference (A high value indicates that a consolidated proposition is fully internalized on the plant floor, whereas a lower value signals a gap between theoretical consensus and empirical practice). Read against the factor prioritization obtained from the House of Quality, this block therefore allows the analysis to locate where the literature and the stakeholders converge and where interpretive noise persists.
In short, the digital questionnaire was designed using Microsoft Forms and structured into three progressive sections to capture both explicit evaluations and latent variables within the E2G sector.

- *Part I:* Respondent Profiling (Questions 1–3) This section gathered demographic and institutional data to determine the respondent's association coefficient.
    - Respondents classified their organization into one of six categories: Ethanol Producer, Input Supplier, R&D Institution, Equipment Supplier, Technical Support, or General Services.
    - It also captured the company's core product/service and geographical location.
- *Part II*: Quality Elicitation and Fuzzy Valuation (Questions 4–15) This core section operationalized the QFD matrix inputs.
    - Open Elicitation (Q4–Q5): Evaluators were asked an open-ended question to spontaneously elicit process and product qualities: "List the expected qualities for a good fuel and for a good production process of this fuel."

    - Absolute Relevance (Q6): Respondents evaluated the nine literature-derived factors (Technology, Labor, Supply Chain, etc.) on a 7-point Fuzzy Likert scale (from Not Relevant to Extremely Relevant), answering: "Which factors does your company consider most relevant when considering second-generation ethanol production?"
    - Relational Matrix (Q7–Q15): For each of the nine factors, respondents cross-referenced their self-elicited qualities using a 3-point Fuzzy scale (High, Medium, or Low Correlation).
- *Part III*: Literature Validation and Theoretical Propositions (Questions 16–25) The final section aimed to measure the alignment between empirical industry perception and theoretical literature. Respondents used a 7-point scale (1 = Totally False / Disagree, 7 = Totally True / Agree) to evaluate ten specific statements derived from the systematic review. Key propositions included:
    - Q16 (Centralization): "Ethanol production should be centralized (meaning raw material cultivation, processing, and manufacturing must occur geographically close or integrated within the same industrial plant) to optimize resources, reduce logistical costs, and increase operational efficiency."
    - Q18 (Triple Bottom Line): "The sustainability of ethanol production must simultaneously consider social aspects (e.g., job creation, working conditions), economic aspects (financial viability, market competitiveness), and environmental aspects (GHG reduction, responsible use of natural resources)."
    - Q19 (Strategic vs. Economic Value): "Second-generation ethanol production presents advantages such as the use of agricultural residues and the reduction of environmental impacts. In a general context, these advantages can be considered more relevant than the immediate economic conditions of production."
    - Q24 (Technology Maturity): "Second-generation ethanol production technologies have not reached full maturity yet."
    - Q25 (Economic Preference): "There is a preference for the economic dimension of sustainability when considering ethanol production; that is, the profit obtained considered more important than the social conditions and environmental impacts involved."

4. Results

4.1 Sample characterization and semantic grouping

The final validated dataset comprised 40 responses representing the operational triad of the TH: 9 universities/R&D institutes, 15 ethanol producing plants, 10 input suppliers, 2 equipment suppliers, 2 technical support firms, and 2 general service companies.

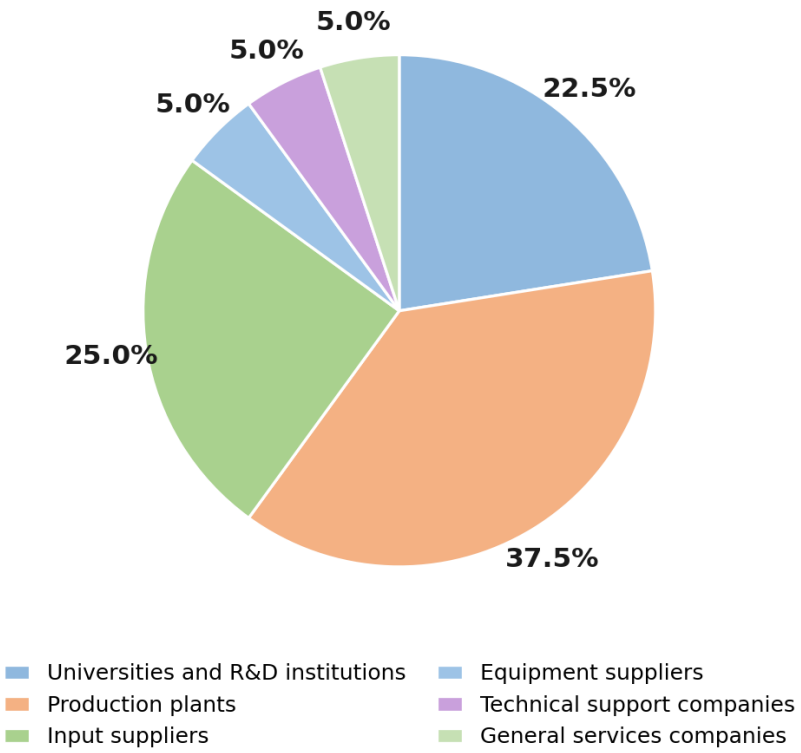


Fig. 6 Composition of the sample group by stakeholder category (%)

The open-ended elicitation of the qualities expected from second-generation ethanol and its production process returned a broad and heterogeneous set of attributes that consolidated into twelve semantic groups. These groups express the multidimensional expectations of the sugarcane-energy sector and constitute the "Whats" that are subsequently crossed with the decision factors in the HoQ. They distribute across five analytical dimension: the intrinsic properties of the product, the production frontier, the sustainability and continuity of the business, the market and value flow, and the organizational–institutional base.

At the level of the product itself, two groups emerged. *Physico-chemical Properties* aggregate purity, octane rating, fluidity, chemical stability, calorific value, and controlled ignition, while *Quality and Standardization* express the demand for traceability, chemical metrology, impurity control, and technical compliance. At the production frontier, *Industrial Efficiency* consolidates conversion yield, low corrosivity, engine compatibility, maintenance, and the operational excellence associated with Industry 4.0, whereas *Agronomic Innovation and Biotechnology* aggregate genetic improvement, edaphoclimatic adaptation, phytosanitation, mechanization aptitude, and the pursuit of lower production costs.

The sustainability and continuity of the business were captured by two further groups: *Environmental Sustainability*, encompassing decarbonization, low carbon intensity, decarbonization credits (CBIOs), water security, circularity, and vinasse valorization; and *Sustainability in a general sense*, encompassing institutional solidity, financial stability, and the flexibility and resilience of the productive matrix. The market and value-flow dimension comprised *Logistics and Value Chain* (logistical intelligence, vertical integration, infrastructure, and synchronization of the harvest window) and *Strategy and Competitiveness* (market access, margin management, cost reduction, and national energy security).

Finally, the organizational and institutional base was represented by four groups: *Management and Governance* (administrative transparency, corporate and cooperative governance, and price formation); *Regulatory Compliance* (ANP conformity, RenovaBio certification, and metrological inspection); *Resilience and Compatibility* (climatic dynamics, seasonal and

phenological resilience, and production flexibility); and *Human Capital and Culture* (humanized and specialized management, technical training, 5S practices, and social responsibility). Taken together, the twelve groups show that the sector's notion of quality extends well beyond the physico-chemical specification of the fuel to encompass process efficiency, sustainability, market positioning, and organizational capability.

4.2 Fuzzy aggregation and crisp prioritization of barriers

Experts evaluated the absolute importance of the 9 barriers/factors using a 7-point Likert scale, parameterized via TFNs over the continuous discourse universe [0, 7]. The arithmetic mean of the fuzzy boundaries (l, m, u) was calculated across the 40 experts to synthesize the collective perception. The centroid defuzzification method was then applied to derive the global crisp values.

Table 4 Defuzzified (crisp) values representing stakeholder evaluations of E2G production factors

Factor / Barrier	E2G Producers	Input Suppliers	R&D Institution	Equipment Suppliers	Technical Support	General Services	Global Crisp [illegible]
Environmental Sustainability	5.733	5.100	5.667	3.000	5.500	4.000	5.325
Technology	5.600	5.000	5.444	4.500	6.000	4.000	5.300
Supply Chain	5.200	6.000	4.667	5.000	5.500	5.000	5.275
Public Policies	4.933	5.500	4.444	1.125	6.000	5.000	4.831
Energy vs. Ethanol	5.200	4.025	4.806	3.500	4.000	0.625	4.444
Labor	4.000	3.400	3.889	2.500	3.500	3.000	3.675
Plant Location	3.200	2.800	4.222	5.000	4.000	2.625	3.431
Centralized Production	2.350	2.150	3.139	3.000	2.000	1.125	2.431
Food vs. Ethanol	0.567	0.850	4.222	2.125	1.125	0.625	1.569

The global crisp prioritization revealed a "strategic triad" at the apex of the ranking: Environmental Sustainability (5.325), Technology (5.300), and Supply Chain (5.275). The arithmetic proximity among these three areas suggests that experts no longer interpret them as isolated variables, but rather as an indivisible operational nucleus where logistical efficiency and technological innovation are the vectors that enable environmental compliance.

Conversely, the "Food vs. Ethanol" dilemma ranked last (1.569), classified between "Slightly" and "Slightly Relevant." This evidences that stakeholders consider the food-fuel conflict an outdated or external narrative with no direct operational impact on E2G feasibility. Public Policies (4.831) maintained high relevance, recognized as the structural framework for business stability, though subordinated to internal productive urgency.

In the subsequent phase, respondents evaluated the correlation between the elicited Quality Attributes (Semantic Groups) and the E2G production factors/barriers using the 3-point Fuzzy scale defined in the methodology. This step establishes the strength of the relationship between the operational bottlenecks and the desired outcomes of the bioethanol plant. The qualitative evaluations were converted into TFN and aggregated using the fuzzy arithmetic mean. Crucially, each element was multiplied by the respective association coefficient to ensure that the correlation weight reflected the specific technical expertise of the stakeholder group evaluating it. Following the weighted aggregation, the results were defuzzified into crisp values using the centroid technique. This process generated a relational matrix for each stakeholder segment. The next table presents an excerpt of these segment-specific crisp values, illustrating how different actors within the Triple Helix evaluate the impact of variables like Technology or Labor on specific semantic qualities such as Industrial Efficiency. These segment-specific matrices were subsequently synthesized into a single, global relational matrix. This global aggregation forms the central relationship matrix of the House of Quality, allowing for the calculation of the absolute and relative importance of each quality attribute regarding the E2G

production decision.

Table 5 Excerpt of defuzzified (crisp) relational values by stakeholder segment (input for the global QFD matrix)

Stakeholder Segment	Semantic Quality Group	Food vs. Ethanol	Supply Chain	Energy vs. Ethanol	Plant Location	Labor	Public Policies	Centralized Production	Env. Sustainability	Technology
E2G Producers	Industrial Efficiency	2.00	2.88	5.50	2.75	4.50	2.00	3.50	5.25	5.75
E2G Producers	Agronomic Innovation	2.00	3.00	3.44	4.29	4.00	1.86	2.00	5.43	5.43
Input Suppliers	Quality & Standardization	1.00	6.00	4.00	1.25	1.25	2.00	1.50	1.00	4.00
Input Suppliers	Strategy & Competitiveness	1.00	6.00	4.00	1.00	1.00	3.00	1.00	2.00	4.00
R&D Institutions	Compliance & Regulation	6.00	0.60	2.00	0.60	1.00	0.60	0.20	3.00	6.00
R&D Institutions	Environmental Sustainability	4.29	0.40	4.29	0.37	1.57	0.40	0.37	3.00	5.29

In this final analytical stage, the crisp values derived from the Triangular Fuzzy Numbers were integrated into the QFD matrix. This parametrization enabled the conversion of linguistic evaluations into objective numerical magnitudes, properly accounting for the inherent imprecision of expert judgments.

To determine the final impact of each factor, the absolute weight of each element was calculated. This was achieved by multiplying the degree of importance assigned to a specific factor by its corresponding correlation value with the expected quality, and then summing these products to obtain the effective contribution of each element to the decision-making process. Subsequently, the relative participation of each quality attribute within the global decision framework was established. This measure was obtained by dividing the individual absolute weight by the sum of the absolute weights of all factors, resulting in an impact percentage. This index proportionally expresses the influence of each dimension, highlighting which variables exert the most or least relevance in determining production viability.

To facilitate visual interpretation of the QFD matrix, a color-coded correlation threshold was applied based on the crisp values:

- Green (High Correlation): Values ≥ 3.5, representing critical strategic associations.
- Yellow (Medium Correlation): Values between 2.0 and 3.4, indicating moderate influence.
- Red (Low Correlation): Values < 2.0, highlighting weak or negligible relationships.

	Weight	Human Capital	Compliance & Reg.	Ind. Efficiency	Strategy & Comp.	Mgmt. & Gov.	Agron. Innovation	Logistics & Value	Physicochem. Prop.	Quality & Stds.	Resilience & Comp.	Sustain. (General)	Env. Sustain. (Tech)
Technology	5.30	4.93	3.00	4.55	3.32	2.47	5.05	3.16	3.80	4.28	4.00	3.62	3.47
Environmental sustainability	5.33	2.32	3.00	3.12	2.47	1.94	2.69	1.94	1.60	2.12	1.81	2.89	2.62
Supply chain	5.28	2.12	1.87	2.08	2.03	2.00	2.50	2.16	1.50	2.13	2.00	2.05	1.47
Public policies	4.83	1.15	1.44	1.41	1.45	1.43	0.92	1.05	0.82	1.29	1.56	1.42	1.20
Energy vs. Ethanol	4.44	2.30	2.06	3.34	2.72	2.05	3.29	2.08	1.80	2.28	2.15	3.63	2.44
Workforce	3.67	3.75	2.07	3.47	2.45	1.47	2.59	1.95	1.97	1.87	1.56	2.49	2.00
Location	3.43	1.40	1.07	0.96	1.05	0.98	1.64	2.00	0.41	0.90	0.86	1.17	1.13
Centralized production	2.43	0.97	1.01	1.27	0.90	1.30	0.88	1.40	0.43	0.83	1.16	0.99	1.02
Food vs. Ethanol	1.57	1.97	1.84	1.56	1.86	1.39	1.36	1.78	1.16	1.18	2.68	1.93	1.64
Abs. Importance		89.5	74.5	94.9	78.3	64.1	92.8	73.0	60.0	75.4	74.2	87.0	73.0
Rel. Importance (%)		9.6%	8.0%	10.1%	8.4%	6.8%	9.9%	7.8%	6.4%	8.1%	7.9%	9.3%	7.8%

Fig. 7 Global House of Quality (QFD) relational matrix for second-generation ethanol (E2G) production

The application of the HoQ structure successfully recognized conceptually evident correlations widely consolidated in the literature, such as the positive association between Labor and Human Capital (Bento & Thomaz, 2021; Baccarin, 2023), and Supply Chain with Logistics (Jusakulvijit et al., 2021). This internal consistency validates the robustness of the adopted Fuzzy-QFD model. However, adjusting the actors' opinions through the relational matrix revealed profound strategic paradigm shifts in the bioenergy sector.

In the weighted global ranking, Industrial Efficiency emerged in the first position with a score of 94.9 (approximately 10% of the relative importance). This highlights that operational performance is the absolute core of the decision-making context (Jusakulvijit et al., 2021; Berzina et al., 2023). This contrasts sharply with unweighted preliminary analyses where Physicochemical Properties appeared dominant. The inversion indicates that decision-makers perceive the intrinsic quality of the biofuel as a fully consolidated and standardized commodity (Nageswara-Rao & Soneji, 2018). Meeting quality standards is merely an entry barrier, not an optimization goal (Melo et al., 2020, 2022). For E2G, the strategic dilemma is no longer what to produce, but how to produce it efficiently to overcome its inherent conversion deficits compared to first-generation ethanol (Pereira et al., 2021).

Corroborating the focus on efficiency, Technology stood out as the most critical vector in the entire decision matrix, positively influencing almost all expected qualities. Technology is not perceived as mere operational support, but as the structural core for survival and expansion (Carvalho et al., 2018; Melo et al., 2022). The highest correlation in the entire matrix occurred between Technology and Agronomic & Biotech Innovation. This indicates that future E2G competitiveness relies less on conventional thermochemical infrastructure and heavily on advanced genetic improvement, precision agriculture, and biological conversion routes (Perlatti et al., 2014; Brito et al., 2024).

The rise of Human Capital and Culture in the relational ranking highlights that technological modernization demands a highly qualified workforce. The sugarcane sector has evidently

surpassed the era of seeking exclusively low-cost manual labor, shifting its focus toward retaining professionals capable of operating complex Industry 4.0 systems (Bento & Thomaz, 2021; Gilio et al., 2019).

Although companies almost unanimously assigned high absolute importance to Environmental Sustainability, its correlation with other operational factors was surprisingly weak (Karita et al., 2021; Silva et al., 2019). This finding suggests two implications: first, sustainability may currently perform a legitimizing function without substantially altering core investment choices; second, the sector may lack the technical and operational integration mechanisms necessary to convert environmental goals into actionable performance metrics. (Araújo et al., 2020; Silvestre et al., 2016).

The analysis demonstrates the sector's detachment from traditional territorial dilemmas. The Food vs. Fuel debate, along with Plant Location and Centralized Production, ranked as secondary or negligible concerns (Jusakulvijit et al., 2021; Rosa & Garcia, 2009). The low reliance on Public Policies further indicates a maturing industry seeking operational autonomy through internal energy efficiency rather than external subsidies (Lisbinski et al., 2026).

Ultimately, the E2G decision-making process is profoundly multi-causal. The pragmatic alignment of these factors directly impacts the UN Sustainable Development Goals (SDGs). The focus on industrial efficiency and biotechnological dominance strongly drives SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production), while the demand for Industry 4.0 qualifications supports SDG 8 (Decent Work and Economic Growth). However, the weak operational correlation of environmental metrics raises a critical alert regarding SDG 13 (Climate Action), emphasizing that future integrated models must actively bind technological capacity with concrete sustainability accountability to ensure effective structural changes.

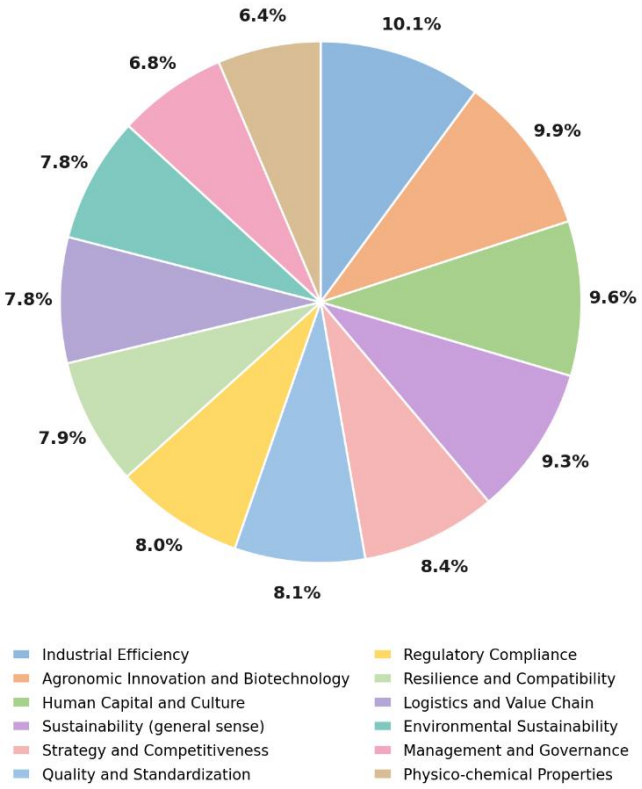


Fig. 8 Relative importance (%) of the expected quality attributes in the decision-making process for second-generation ethanol (E2G) production, derived from the Fuzzy-QFD matrix

4.3 Interpretive noise between literature and stakeholder perception

To evaluate the alignment between the consolidated scientific literature and the pragmatic reality of the production floor, 11 research participants voluntarily evaluated 10 theoretical affirmations derived from the systematic reviews. The affirmations were evaluated using a 7-point fuzzy concordance scale, and the aggregated crisp concordance values were calculated.

Table 6 Level of agreement with literature propositions (defuzzified crisp values)

#	Theoretical Proposition from Systematic Review	Crisp Value
3	Ethanol production sustainability must consider social, economic, and environmental aspects simultaneously.	**5.556**
7	By-products (e.g., fertilizers, xylanol) must be considered valuable elements, contributing to economic/environmental sustainability.	**5.556**
6	Technologies and production routes must align with the specific needs of the producing country (e.g., job creation, rural economy).	**5.333**
8	Risk management and mitigation strategies are essential to minimize the impact of uncertainty in investment projects.	**5.222**
4	E2G production advantages (e.g., waste utilization) can be considered more relevant than immediate economic conditions.	**5.000**
2	Experimental planning (DOE) is fundamental to validate more effective production routes and improve raw material cultivation.	**4.659**
1	Ethanol production should be centralized (cultivation, processing, and manufacturing integrated) to optimize operational efficiency.	**4.625**
5	The decision to produce E2G must include multiple factors; considering more factors increases the satisfaction with the final decision.	**4.556**
9	Second-generation ethanol production technologies have not yet reached full maturity.	**4.556**
10	There is a preference for the economic dimension of sustainability; profit is considered more important than social/environmental impacts.	**4.111**

Affirmations regarding integral sustainability (Affirmation 3; Crisp = 5.556) and the valuation of subproducts/circular economy (Affirmation 7; Crisp = 5.556) presented elevated crisp values, indicating strong alignment with literature and minimal interpretive noise. This reinforces the HoQ findings: the concept of the biorefinery is consistently perceived and prioritized, validating that E2G feasibility is understood as dependent on the technological capacity to add value to the total biomass.

However, affirmations involving national strategic alignment (Affirmation 6; Crisp = 5.333), risk management (Affirmation 8; Crisp = 5.222), and the comparative advantages of 2G ethanol (Affirmation 4; Crisp = 5.000) presented moderate crisp values. This indicates that while the empirical perception recognizes the relevance of these concepts for macroeconomic strategy, internalization is not fully consolidated. The moderation in Affirmation 4 particularly highlights that while the environmental potential of E2G is recognized, the theoretical advantages still encounter practical operational bottlenecks, aligning with the HOQ finding that Industrial Efficiency is the primary structural barrier.

The most significant dissonance emerged in the affirmations regarding technological maturity (Affirmation 9; Crisp = 4.556) and the prioritization of the economic dimension over social/environmental ones (Affirmation 10; Crisp = 4.111). The low score on technological maturity reveals skepticism regarding the readiness of 2G technologies. This paradoxically justifies why Industrial Efficiency was the top priority in the HOQ: if the technology is not perceived as fully mature and is less efficient than 1G, the decision to produce E2G remains heavily constrained.

The low score on economic prioritization reflects a rejection of the premise that profit supersedes environmental/social goals. However, this outwardly contradicts the HOQ matrix, which demonstrably shows economic/efficiency factors as the primary structural drivers. This paradox highlights a sector struggling to translate conceptual sustainability into concrete productive efficiency. The empirical data suggests a scenario where sustainability is an "non-negotiable discourse" but operational decisions remain anchored in productive efficiency, exposing a critical gap between theoretical literature and industrial practice.

5. Conclusions

This study developed and applied a quantitative decision-support artifact, grounded in Fuzzy QFD methodology, to systematically evaluate and prioritize the complex web of barriers and enablers shaping the Brazilian E2G) industry. By operationalizing the TBL through the integrated lens of the TH and mapping expert judgments against Sustainable Development Goals (SDGs), the research overcomes the fragmentation inherent in traditional multi-criteria bioenergy analyses. The application of competence-based fuzzy weighting and the construction of the HOQ matrix revealed a highly structured, non-linear socio-technical ecosystem where discursive priorities diverge significantly from operational drivers.

The empirical findings demonstrate that the Brazilian E2G sector is governed by a pragmatic paradox. While environmental sustainability holds the highest isolated discursive value among stakeholders, it exhibits weak operational correlation within the decision matrix, functioning primarily as an institutional legitimizing mechanism rather than a structural driver of investment. Conversely, Industrial Efficiency and Technology emerged as the absolute core priorities. Decision-makers perceive E2G as a standardized commodity; thus, competitive advantage is not sought through the alteration of final physical-chemical fuel specifications, but through the relentless optimization of the conversion process. The highest systemic correlation was observed between Technology and Agronomic Innovation/Biotechnology, asserting that the future feasibility of E2G is heavily dependent on biological conversion routes, genetic improvement, and advanced biorefinery concepts, rather than thermos-chemical infrastructure expansion. Furthermore, the ascension of Human Capital and Culture as a critical mediator highlights a sector transitioning toward Industry 4.0 paradigms, requiring highly specialized labor to operate complex systems. The historic "Food vs. Ethanol" dilemma was effectively relegated to an outdated narrative, demonstrating a maturing sectoral vision focused on internal technological efficiency over external territorial disputes.

Theoretically, this study advances the operationalization of socio-technical systems theory in the bioenergy domain. It empirically proves that corporate decision-making in complex industrial ecosystems is not monocausal but emerges from the dense, non-linear interaction of multiple vectors where operational efficiency acts as the primary mediating variable. By embedding the TH perspective into the Fuzzy QFD matrix, the framework bridges the gap between abstract sustainability paradigms (SDGs 7, 9, 12, 13) and technical decision matrices. It also confirms the applicability of fuzzy logic in capturing the epistemic uncertainty of heterogeneous expert panels, translating imprecise subjective judgments into actionable, quantified trade-offs without losing analytical robustness.

Practically, the resulting HoQ offers industry stakeholders and policymakers a prioritized, evidence-based roadmap. The clear prioritization of Technology and Industrial Efficiency provides empirical support for directing R&D investments toward biotechnological conversion routes rather than exclusively toward logistical scale-ups. The observed dissonance highlights the need for greater alignment between environmental discourse and operational practice, since, without robust mechanisms for translating environmental goals into actionable metrics, sustainability commitments may have limited influence on corporate decisions. The proposed competence-based weighting mechanism also serves as a practical tool for policy design, ensuring that regulatory frameworks are calibrated to incentivize the specific operational bottlenecks that genuinely hinder E2G competitiveness against first-generation ethanol.

Despite the methodological rigor, this study has inherent limitations. First, the final validated dataset, while robust in representing the Brazilian TH, remains geographically concentrated in the Center-South region. This edaphoclimatic bias may limit the generalizability of the findings to other Brazilian biomes or international contexts with distinct biomass profiles and regulatory frameworks. Second, the theoretical dissonance analysis suffered sample attrition (n=11 in the

final concordance phase), which, while sufficient for identifying operational trends, reduces the statistical power required for broader inferential generalization.
Future research should expand the sample to include international stakeholders, enabling cross-country comparative analyses to test the universality of the "efficiency-over-sustainability" paradox. Additionally, integrating predictive machine learning algorithms into the Fuzzy QFD matrix could allow for dynamic, real-time reassessment of barrier impacts as new technological breakthroughs emerge or as regulatory landscapes shift. Applying structural equation modeling (SEM) or instrumental variable approaches in future elicitations could help isolate the exact causal effects of specific TH interactions (e.g., university-industry vs. government-industry) on the actual adoption rate of E2G technologies. Finally, expanding the semantic mapping of expected qualities to include real-time market volatility indicators and climate adaptation metrics would further refine the robustness of the decision-support artifact.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

This article derives from a master's dissertation that was originally written in Portuguese. During the preparation of this manuscript, the authors used Claude (OPUS 4.8 - Anthropic) to translate the source text from Portuguese into English and to assist with language editing. Generative artificial intelligence was not used to conceive the study, to collect, generate, or analyze research data, or to produce scientific content: the decision-support model, the Fuzzy-QFD computations, the two systematic literature reviews, the interpretation of the results, and the conclusions are entirely the work of the authors. After using this tool, the authors reviewed and edited the content as needed, verified its accuracy, and take full responsibility for the content of the publication.

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