Innovation capacity of Brazilian wineries: an integrated approach using the fuzzy Delphi and random forest methods

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Abstract.

The innovation capacity of organizations, particularly in the competitive Brazilian wine industry, plays a pivotal role in their performance and competitiveness. This study aimed to identify and validate metrics for assessing the innovation capacity of Brazilian wineries through a two-stage research process. Initially, a systematic literature review was conducted using Scopus and Web of Science databases. This phase was followed by a quantitative analysis involving 44 Brazilian winery managers, utilizing the Fuzzy Delphi and random forest methods to validate and prioritize the dimensions and indicators of innovation capacity. Out of 88 potential indicators spanning eight dimensions, 50 were confirmed as validated through the Fuzzy Delphi method, as their defuzzified values exceeded the predetermined cutoff threshold. Research and development, product and service innovation, and sustainability and environmental initiatives emerged as the most critical dimensions, collectively representing over half of the innovation capacity in the wineries. Additional significant, albeit less dominant, dimensions included customer feedback and relationships, emphasizing the importance of consumer engagement, and process efficiency, highlighting the significance of operational effectiveness. While not as prominently, employee engagement and training, strategic collaboration, and market adaptation and diversification were identified as essential for sustained innovation. This research provides strategic metrics to enhance the competitiveness and sustainability of Brazilian wineries.

Keywords: innovation, competitiveness, sustainability, research and development, viticulture.

1. INTRODUCTION

The concept of innovation has evolved to encompass elements from all stages of the knowledge production chain, promoted as an essential tool for addressing national challenges. This perspective on innovation, bolstered by policies that extend beyond economic viewpoints, emphasizes its significance [1]. Innovation capacity (IC) has risen to prominence for its role in decision-making and strategy implementation, markedly influencing organizational performance [2]. Research conducted by Kamal et al. [3] suggests that IC is vital for harnessing the relationship between radical innovation and performance, highlighting the critical role of IC in facilitating radical innovation. Furthermore, IC is instrumental in sustainable growth as it enables the integration of various organizational components and their linkage to outcomes in product, process, market, and organizational innovations [4–6].

At the organizational level, IC is shaped by strategy, leadership, structure, systems, and culture [7]. It signifies an organization's capability to develop new or enhanced products and knowledge [8]. Thus, evaluating IC is crucial, given the uncertain and complex nature of innovation processes, which necessitates accurate measurement methods to ensure alignment with innovation goals [9]. Studies have developed methods to evaluate IC in industrial clusters, small and medium-sized enterprises (SMEs), and the role of IC in promoting sustainability [10–13].

Nevertheless, metrics specific to certain contexts, such as the winery sector in emerging economies such as Brazil, are limited [14]. However, while the concept of IC has been explored in various industrial contexts, there remains a notable gap in metrics tailored for sector-specific challenges, particularly for industries in emerging economies. The Brazilian wine sector exemplifies this need, as it faces unique barriers related to climate adaptation, resource sustainability, and regional market dynamics that are not fully addressed by existing IC frameworks [15].

As of 2023, Brazil ranks as the 15th largest wine producer globally, with the southernmost state of Rio Grande do Sul accounting for approximately 62.41% of the country's production. This demonstrates its established dominance in the vitiviniculture sector, supported by favorable climatic conditions and advanced production techniques [18,19]. While the southern region leads in production, the southeastern and northeastern regions of Brazil are becoming increasingly prominent, showcasing significant potential for growth.

The southeastern region, particularly in states such as São Paulo and Minas Gerais, has demonstrated potential through the adoption of innovative logistical practices, including postponement strategies that enhance production efficiency and responsiveness to market demands [20,21]. Meanwhile, the northeastern region, characterized by its unique terroir and the capability to produce high-quality wines under tropical conditions, offers opportunities for expanding Brazil's wine diversity and competitiveness in niche markets [22]. These developments underscore the increasing diversification of Brazil's wine production landscape, contributing to its growing prominence on the global stage. The industry faces challenges related to climate change, sustainability, and domestic and international competition [23].

This study explores how to evaluate the innovation capacity of Brazilian wineries to identify and validate metrics for IC assessment, uncover the best practices, challenges, and innovations within the sector [24]. Few studies have focused on IC in the winery context, highlighting the significance of this research [25]. This study is also socially relevant as it supports family farming-based companies, creates employment, and enhances rural product value, contributing to the economic and social resilience of wine-producing areas [26–28]. Furthermore, it enriches the literature on innovation management by offering empirical and theoretical insights into winery innovation dynamics [14,29].

2. THEORETICAL FOUNDATION

2.1. The wine industry and innovation capacity

The wine industry is a significant agricultural sector, contributing to the economy and sustainability, with the global wine market's revenue projected to reach approximately 175.9 billion dollars by 2024 [21,31]. In Brazil, the wine industry is mainly concentrated in the southern region, representing about 73% of the nation's planted area and producing around 951,000 tons of grapes in 2021 [17]. Innovation in wineries transcends internal efforts, stemming from collaborations with stakeholders [31].

Innovation is a multidimensional concept that has been explored through various theoretical frameworks. For instance, Schumpeter (1947) [32] defines innovation as conducting activities in a novel way, while Garcia and Calantone (2002) [33] emphasize that innovation is not solely about the product itself but also about the social context that enables its commercialization. Similarly, Crossan and Apaydim (2010) [34] argue that innovation encompasses how a product is delivered, marketed, and produced. These perspectives provide distinct yet complementary insights into the concept of innovation.

When considering open innovation—defined as the internal and external use of knowledge to accelerate the innovation process [35]—the Triple Helix Model, proposed by Leydesdorff and Etzkowitz [36], emerges as a key theoretical framework. This model highlights the interactions between universities, industries, and governments as central drivers of innovation. It posits that innovation does not result solely from linear processes within a single organization but instead emerges from dynamic, collaborative networks that integrate knowledge creation, technological advancements, and political support.

In the context of wineries, the Triple Helix Model is particularly relevant, as partnerships with research institutions foster technological advancements in viticulture and oenology, thereby enhancing innovation capacity and competitive advantage. Innovation capacity, a critical factor for improving organizational performance [37], is influenced not only by technological progress but also by the ability to adapt to market demands and customer expectations. Engaging in innovative practices and collaborating with complementary entities strengthen wineries' value propositions by addressing technological, environmental, and market challenges [38,39].

Furthermore, the ability to innovate relies on an organization's internal competencies and its capacity to overcome inherent limitations. This includes the development of new products or services, as well as fostering customer readiness to adopt these innovations [40]. The Triple Helix Model also underscores the importance of government policies in establishing an environment conducive to innovation, which is crucial for the growth, sustainability, and global competitiveness of wineries. By applying this model to assess innovation processes, a holistic perspective emerges—aligning organizational practices with systemic drivers of innovation and emphasizing the strategic significance of cross-sector collaboration.

Karagiannis and Metaxas [41] noted the importance of government support and collaboration between wineries and research institutions, including tax incentives, research and development funding, and training programs. Measuring innovation performance in the wine industry is challenging due to its unique attributes, which often result in expensive data collection and analysis [24]. Nevertheless, addressing these challenges is essential, as innovation significantly impacts marketing, sustainability, and product and service offerings [42-44]. It is key to fulfilling consumer demands, achieving competitiveness and sustainability, and ensuring wineries' development and survival, as positive innovation capacity positively influences business performance [41,45-47].

2.2. Dimensions and Indicators of Innovation Capacity

Innovation in the wine industry can be effectively assessed through a structured approach that includes specific dimensions and their corresponding indicators. These dimensions encompass key aspects of innovation, such as Research and Development, Strategic Collaboration, Employee Training and Engagement, Process Efficiency, Product and Service Innovation, Sustainability and Environmental Initiatives and Customer Feedback and Relationship. Each of these dimensions is essential for measuring innovation capacity and reflects the unique challenges and opportunities within the wine industry. This framework of dimensions and indicators provides a comprehensive approach to assessing innovation capacity tailored to the wine industry.

3. MATERIAL AND METHODS

This section outlines the methods and criteria employed to analyze the innovation capacity dimensions of Brazilian wineries. The qualitative and quantitative study is based on a systematic literature review and a scale assessing the importance of various dimensions and indicators according to winery specialists [48-50]. The data collection and analysis were conducted in two stages, as depicted in Figure 1.

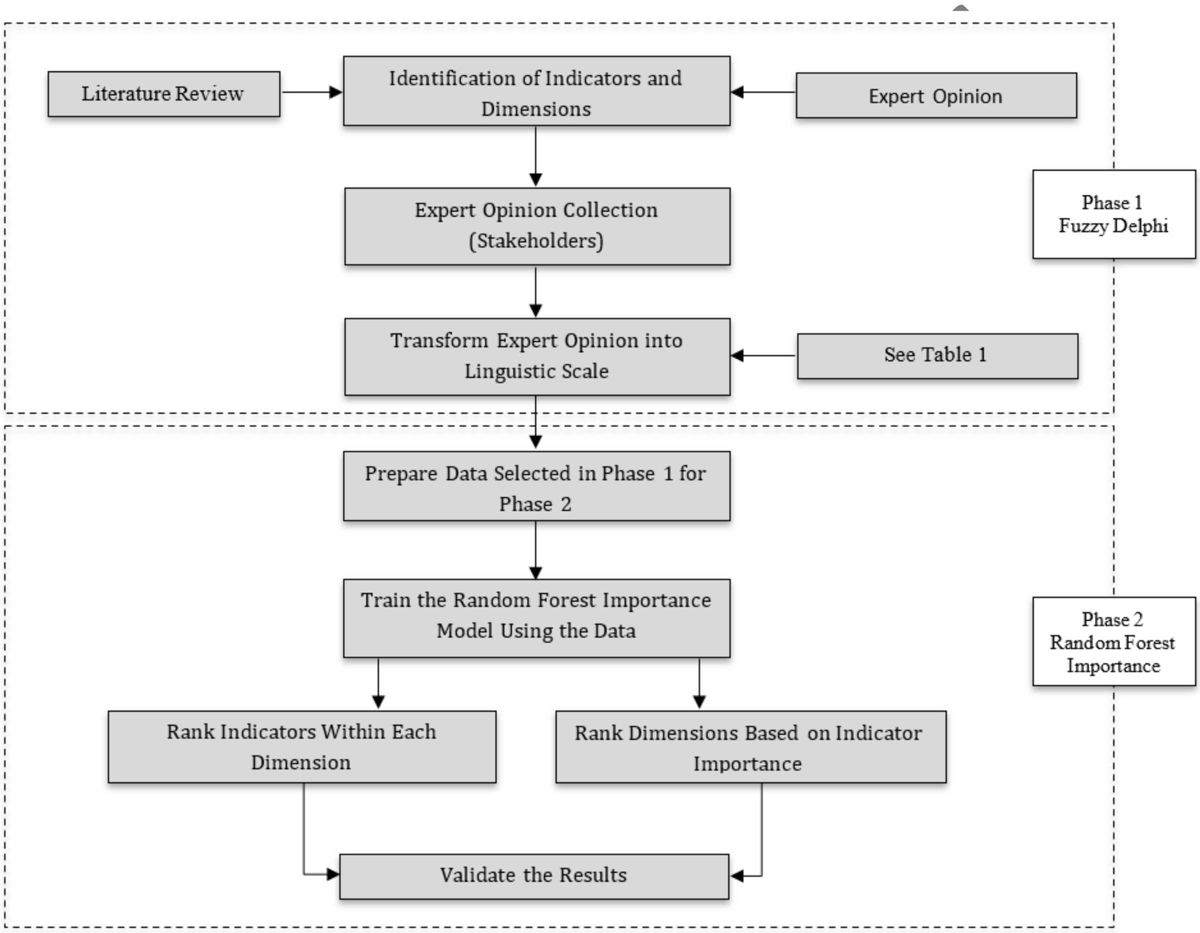


Figure 1. Proposed framework based on Fuzzy Delphi and Random Forest Importance.

The initial stage commenced with a systematic literature review utilizing the Scopus and Web of Science databases, employing the search strings: ((“Innovation capacity” OR “Innovation capability”) AND (“SME*” OR “small* business*” OR “medium company*” OR “small and medium enterprise*” OR “medium business*” OR “small company*”)).This review yielded 3,222 articles, from which 193 were chosen based on their classification in the Q1 and Q2 quartiles, denoting the top 50% of most cited articles from high-impact journals according to the Scimago rankings. Subsequently, 67 articles focusing on small and medium enterprises were selected for further analysis.

This process identified key dimensions and innovation capacity indicators pertinent to wineries, establishing a solid theoretical foundation. Analysis of these articles revealed 88 indicators across nine dimensions: research and development (R&D) with 16 indicators, strategic collaborations (SC) with 6 indicators, employee training and engagement (ETE) with 8 indicators, process efficiency (PE) with 16 indicators, product/service innovation (P/SI) with 16 indicators, sustainability and environmental initiatives (SEI) with 9 indicators, market adaptation and diversification (MAD) with 6 indicators, and customer feedback and relationship (CFR) with 11 indicators.

The first step's second stage was the validation of these indicators and dimensions using the Fuzzy Delphi method, informed by responses from 44 experts comprising winery managers. Data were collected via in-person and online questionnaires through Google Forms, ensuring participant anonymity to protect privacy. The study adhered to ethical standards, providing a consent form outlining the research objectives and the voluntary nature of participation. An ethical approval certificate was obtained from the Research Ethics Committee (CAAE no. 53139921.0.0000.5346).

3.1 Validation of Indicators Using the Fuzzy Delphi Method

As previously mentioned, to validate the indicators within their respective dimensions, responses from 44 experts were utilized, employing the Fuzzy Delphi method for analysis. The Fuzzy Delphi method is a technique derived from the traditional Delphi method, first developed by Dalkey & Helmer (1963) [51], which has been used to gather information through a systematic feedback process from experts [52].

The Delphi technique is a methodology used to achieve consensus among experts, applied in contexts where specialized knowledge and collective opinion are relevant for decision-making [53]. It should be noted that since its creation, the method's intent is to help establish a consensus among different opinions—in this case, those of winery experts—to define the most accurate decision within a group (dimensions) as decision-makers [54,55].

Ishikawa et al. (1993) [56] proposed the Fuzzy Delphi method to address the uncertainty present in data collection based on human opinion, utilizing Max and Min values. This method resulted in improvements regarding the number of iterations required by the traditional Delphi method, as well as savings in time and costs. Since its development, the method has been used to define and validate innovation capacity indicators through expert feedback, identifying and prioritizing the most relevant indicators for measuring innovation in different organizational contexts [57].

To apply the Fuzzy Delphi method, specific calculations are required, involving the manipulation of data obtained through the systematic collection of information from experts. These calculations are inherent to the process of aggregating opinions and modeling the uncertainty associated with the subjective evaluations of the experts [58]. Based on the research of Singh & Sarkar (2020) [59] and Mabrouk (2021) [60], the Fuzzy Delphi method includes the following phases:

1. *Development of indicators*: Initially, 88 indicators were identified from the literature, subdivided into 9 dimensions.
2. *Data collection and expert judgments*: The experts, characterized by winery managers, were tasked with evaluating the importance of the indicators related to their respective dimensions. Each respondent used the linguistic scale presented in Table 1.

Table 1. Linguistic terms and corresponding triangular Fuzzy numbers for the five-point Likert scale

Linguistic Variable	Value	Corresponding Triangular Fuzzy Numbers
Extremely unimportant	1	(0.1, 0.1, 0.3)
Unimportant	2	(0.1, 0.3, 0.5)
Indifferent	3	(0.3, 0.5, 0.7)
Important	4	(0.5, 0.7, 0.9)
Extremely Important	5	(0.7, 0.9, 0.9)

Source: Singh & Sarkar (2020)

After collecting the experts' judgments, the linguistic variables are converted into triangular Fuzzy numbers $\widetilde{a_{ij}} = \left(a_{ij}, b_{ij}, c_{ij}\right)$ for $i = 1, 2, \dots, n$ & $j = 1, 2, 3, \dots m$, where: $\widetilde{a_{ij}}$ represents the importance of the i-th indicador do j-th expert, n indicates the number of indicators, and mmm denotes the number of experts.

The Fuzzy weights of the barriers ($\tilde{a}_{\_j}$) are described as follows:

$$\tilde{a}_{\_j} = \left(a_j = \{a_{ij}\}; b_j = \left(\Pi_i^n\, b_{ij}\right)^{\frac{1}{n}};\ c_j = max\{c_{ij}\}\right). \quad (1)$$

Next, defuzzification is performed using the center of gravity method proposed by Hsu et al. (2010) [61].

$$D_i = \frac{a_j + b_j + c_j}{3}, j = 1, 2, 3, \dots, n. \quad (2)$$

To determine the cutoff point, the threshold was established by comparing the weight of the indicator with the threshold $\tilde{\alpha}$, where the weight of $\tilde{\alpha}$ is calculated by averaging the weights of all the indicators $\tilde{\alpha}_j$. This procedure follows the methodology adopted by Bouzon et al. (2016) [62], where the inclusion and exclusion principles are as follows: if $\tilde{\alpha}_j \geq \tilde{\alpha}$ the indicator j is included, and if $\tilde{\alpha}_j < \tilde{\alpha}$ the indicator *j* is excluded.

It is important to note that $\tilde{\alpha}_j$ and $\tilde{\alpha}$ are combined Fuzzy sets, and therefore it is necessary to transform them into crisp values to make comparisons (equation 3).

$$x_{ij} = \frac{[(u_{ij} - l_{ij}) + (m_{ij} - l_{ij})]}{3} + l_{ij} \quad (3)$$

The method presented is appropriate for the data, as it allows for the validation of indicators to compose the model and assess the innovation capacity of Brazilian wineries. This method has proven effective in several studies in the field of innovation, which used the technique to define and validate performance indicators [63-65].

It is worth noting that this method was implemented using a Python algorithm developed by the authors. The result is in the Appendix (supplementary material). Following the validation, the second phase began (Tabela 4), applying the Random Forest Importance (RFI) technique to generate importance weights for the dimensions and indicators.

3.2 Ranking of Dimensions Using the Random Forest Importance (RFI) Technique

To create the ranking of dimensions based on the indicators validated by the Fuzzy Delphi method, a Machine Learning algorithm was developed in Python, specifically using the Random Forest Importance (RFI) technique [66]. This technique aims to provide accurate and reliable predictions while robustly calculating the importance of the dimensions. The use of the RFI technique to calculate the degree of importance of dimensions has proven extremely effective in various research areas and practical applications [67-69]. The technique is valued for its ability to provide an interpretable degree of importance for dimensions, which is highly relevant for data-driven analysis and decision-making.

Based on the research of Li (2021) [70] and Mizumoto (2023) [71], the RFI technique follows these procedures: To construct the decision tree, bootstrapping (sampling with replacement) is required, where each tree is trained on a random subset of the training data; node splitting is then applied, where the best split point for each node is selected to minimize impurities [Gini impurity (Equation 4) and impurity reduction (Equation 5)].

$$Gini(t) = 1 - \sum_{i=1}^{D} p_i^2 \quad (4)$$

where:

t: decision tree node containing a subset of winery experts;

D: total number of dimensions;

$\boldsymbol{p_i}$: proportion of indicators belonging to dimension *i* in node *t*.

$$\Delta I_t = I(t_{parent}) - p_L I(t_L) - p_R I(t_R) \quad (5)$$

meaning:

ΔI_t: Impurity reduction at node *t*;

I(t): Impurity of node t (calculated by Gini);

t_{parent}: Parent node before the split;

t_L: Left child node after the split;

t_R: Right child node after the split;

p_L: Proportion of indicators going to the left child node t_L;

p_R: Proportion of indicators going to the right child node t_R.

The importance of the indicators is calculated by the average impurity reduction, while the importance by dimension is given by the sum of the indicator importance:

$$Import(Ind)_j = \frac{1}{N_{tree}} - \sum_{i=1}^{N_{tree}} \left(\sum_{t \in T_j} \Delta I_t * p_t \right); \quad (6)$$

$$Import(Dim)_k = \sum_{j \in Dim_k} \quad Import(Ind)_j; \tag{7}$$

where:

N_{tree}: the number of decisions trees;

T_j: sets of nodes in tree j;

p_t: proportion of samples that pass-through node t.

Both the importance of the indicators (Equation 8) and the importance of the dimensions (Equation 9) will be evaluated in relation to the total, that is, the relative importance:

$$Import(Ind)_j\% = \frac{Import(Ind)_j}{\sum \quad Import(Ind)_k}\ ; \tag{8}$$

$$Import(Dim)_m\% = \frac{Import(Dim)_m}{\sum \quad Import(Dim)_n}; \tag{9}$$

where $\boldsymbol{j}$ is the indicator, $\boldsymbol{k}$ is the number of indicators, $\boldsymbol{m}$ is the dimension, and $\boldsymbol{n}$ is the number of dimensions.

To ensure the reliability and generalizability of the Random Forest Model in evaluating innovation indicators, a cross-validation process was implemented using 5-fold cross-validation. This method, as noted in the literature [72], mitigates overfitting and assesses performance by dividing the dataset into $\boldsymbol{k}$ folds, iteratively training on $\boldsymbol{k-1}$ folds, and testing on the remaining one. For each fold, $\boldsymbol{i}$, the accuracy was computed as follows:

$$Accuracy_i = \frac{Correct\ Predictions\ in\ Fold_i}{Total\ Predictions\ in\ Fold_i}; \tag{10}$$

The mean accuracy and standard deviation were calculated to assess the overall predictive performance of the model.

$$Mean\ Accuracy = \frac{\sum_{i=1}^{k} \quad Accuracy_i}{k}; \text{ and} \tag{11}$$

$$Standard\ Deviation = \sqrt{\frac{\sum_{i=1}^{k} (Accuracy_i - Mean\ Accuracy)^2}{k-1}}. \quad (11)$$

where *k* represents the number of folds.

For a detailed explanation of the data analysis methods, including specific formulas, steps, and their application in this study, please refer to the supplementary material provided in the Appendix. This material encompasses Python algorithms used for implementing the Fuzzy Delphi and Random Forest Importance methods, as well as additional results and sensitivity analyses.

4. RESULTS

4.1 Identification of Dimensions and Innovation Capacity Indicators

Table 2, summarizes the dimensions and indicators along with supporting literature:

Table 2. Dimensions and Key Indicators of Innovation Capacity in the Wine Industry

Dimension	Description of Dimension	Key Indicators	Supporting Authors
Research and Development	Research and Development refers to the deliberate efforts of an organization to create new or improved products	Number of R&D projects, partnerships, R&D budget %	Engelmann (2024) [73]; Doloreux & Lord-Tarte (2013) [74]; Alonso & Bressan (2014) [75]
Strategic Collaboration	Ability to form partnerships that enhance innovation and competitiveness	Number of partnerships, partnership satisfaction	Alonso & Bressan (2016) [75]; Corvello et al. (2023) [76]; Presenza et al. (2017) [77]
Employee Training and Engagement	Organizational structure and culture that foster employee participation and motivation	Training hours, promotion rates, job satisfaction	Deci & Ryan (2000) [78]; Rampa & Agogué (2021) [79]; Sánchez-García et al. (2023) [80]
Process Efficiency	Focuses on optimizing processes to reduce	Production cycle time, waste rate, energy efficiency	Alonso & Bressan (2014) [75]; Awogbemi et al. (2022) [81];

	waste and improve resource utilization		
Product and Service Innovation	Creation of new products or enhancement of existing offerings	Number of new products, revenue from new products	Batistella et al. (2023) [82]; Castro et al. (2024) [83]
Sustainability and Environmental Initiatives	Adoption of eco-friendly practices to reduce environmental impact	Renewable energy use, emissions reduction, sustainable practices investment	Alonso & Bressan (2014) [75]; Kelley et al. (2022) [84]; Montalvo-Falcón et al. (2023) [85]
Market Adaptation and Diversification	Expansion into new markets and adaptation to changing consumer demands.	Number of new markets, revenue diversity, wine tourism	Alonso et al. (2023) [86]; Masset & Weisskopt (2024) [87]
Customer Feedback and Relationship	Importance of engaging with customers to inform innovation and foster loyalty	Customer satisfaction, retention rate, number of interactions	Mastroberardino et al. (2022) [88]; Cholez et al. (2023) [89];

The detailed presentation of the validated dimensions and indicators establishes both a theoretical and a practical foundation for subsequent analysis. This analysis focuses on the validation and prioritization of these elements through the use of the Fuzzy Delphi and Random Forest methods.

4.2. Data collection and analysis

In this stage, 44 managers/experts contributed to the validation and prioritization of indicators and dimensions, as outlined in Table 3.

Table 3. Absolute and relative frequencies of sociodemographic variables (n = 44).

Variables	Categories	n	%
State	Rio Grande do Sul (RS)	20	45,4
	Santa Catarina (SC)	8	18.2
	Paraná (PR)	8	18.2
	Sergipe (SE)	8	18.2
Level of education	Graduate education	3	6.8
	Higher education	36	81.8
	High school education	5	11.4

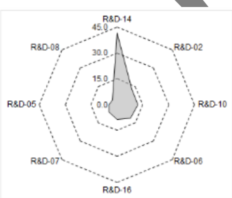
Age range (years)	18-35	12	27.3
	36-55	28	63.6
	> 55	4	9.1
Time in the role (years)	≤ 5	24	54.5
	6-10	11	25.0
	> 10	9	20.5

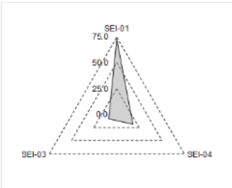
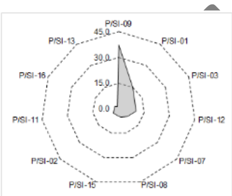
4.3. Validation and ranking of the dimensions and indicators using the Fuzzy Delphi method and Random Forest Importance

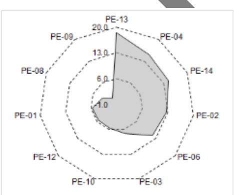
Stage 1 commenced with the Fuzzy Delphi method to evaluate the relevance of each indicator for measuring innovation capacity in wineries. This assessment led to the exclusion of 38 indicators from various dimensions due to experts' evaluations: 8 from R&D, 3 from SC), 4 from ETE, 5 from PE, 5 from P/SI, 6 from SEI, 3 from MAD, and 4 from CFR. Consequently, 50 indicators were retained for further analysis in Stage 2, focusing on this capacity.

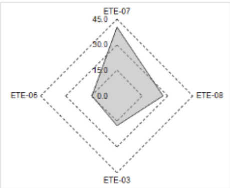
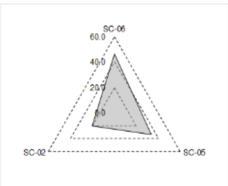
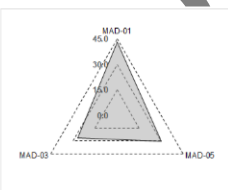
Details on the elimination of indicators using the Fuzzy Delphi technique can be found in the supplementary material. The validated indicators were then ranked according to the dimensions they belong to, with importance weights assigned using the random forest importance method. The results are depicted in Table 4 and Figure 2.

Table 4. Relative importance of dimensions and indicators using the Random Forest Importance Method (Cross-Validation Process).

Dimension	Indicator	Degree of importance (%)		Accuracy	
		Dimension	Indicator	Mean	SD
Research and Development		22.63		0.97	0.174
	14 - Success rate of R&D projects, measured by the number of successfully completed projects relative to the total number of projects initiated		41.51		
	02 - Number of R&D projects executed internally		12.33		
	10 - Number of tests and experiments conducted to validate new ideas or prototypes		12.33		

Dimension	Indicator	Degree of importance (%)		Accuracy	
		Dimension	Indicator	Mean	SD
	06 - Monetary value allocated to internal R&D activities during the year		10.91		
	16 - Number of low-cost innovations implemented (frugal innovations)		8.48		
	07 - Number of funding programs or grants obtained for R&D projects		6.36		
	05 - Number of new products launched		4.55		
	08 - Percentage of the R&D budget in relation to the company's total budget		3.53		
Sustainability and Environmental Initiatives		15.52		0.93	0.177
	01 - Total energy consumption from renewable sources		72.77		
	04 - Percentage of total waste generated that is recycled or reused		18.33		
	03 - Total water consumption per unit of product produced		8.90		
Product and Service Innovation		15.35		0.69	0,175
	09 - Success rate of new products or services based on market acceptance		38,27		
	01 - Number of new services launched		15.50		
	03 - Revenue generated from new products or services		10.81		
	12 - Number of ongoing innovation projects		10.65		
	07 - Cost of developing new products or services		7.28		
	08 - Development time from conception to launch		5.37		
	15 - Number of products or services that meet new consumer needs		4.21		
	02 - Number of significantly improved products or services		3.90		
	16 - Environmental impact of new products or services (sustainability)		2.67		

Dimension	Indicator	Degree of importance (%)		Accuracy	
		Dimension	Indicator	Mean	SD
	13 - Customer feedback on innovations (satisfaction and acceptance)		1.33		
Customer Feedback and Relationship		14.61		0.86	0.240
	06 - Percentage of complaints resolved during the first interaction with the customer		58.44		
	10 - Total number of customer interactions on social media platforms, including comments, likes, and shares		12.48		
	07 - Measure reflecting the likelihood of customers recommending the winery to others		10.66		
	05 - Total number of complaints received within a specific period		6.56		
	11 - Average time the company takes to respond to customer requests, measured in hours or days		4.33		
	04 - Percentage of customers who continue doing business with the winery year after year		3.92		
	09 - Percentage of potential customers (leads) that become buyers		3.61		
Process Efficiency		13.75		0.54	0.145
	13 - Number of customer complaints related to product quality		18.45		
	04 - Number of defects or reworks per batch		15.17		
	14 - Percentage of production orders completed without incidents		14.54		
	02 - Production cost per unit		12.75		
	06 - Raw material waste rate		11.80		
	03 - Rate of production capacity utilization		7.11		
	10 - Employee satisfaction index with operational processes		5.73		
	12 - On-time delivery rate		5.44		
	01 - Average production cycle time		4.64		

Dimension	Indicator	Degree of importance (%)		Accuracy	
		Dimension	Indicator	Mean	SD
	08 - Response time to failures or breakdowns		3.33		
	09 - Maintenance cost as a percentage of production cost		1.04		
Employee Training and Engagement		12.26		0.48	0.108
	07 - Percentage of employees participating in engagement activities organized by the company		40.36		
	08 - Frequency and results of performance evaluations that include feedback from peers and supervisors		27.53		
	03 - Percentage of employees who remain with the company for a specified period		17.59		
	06 - Frequency of unexcused absences from work		14.52		
Strategic Collaborations		4.28		0.39	0.145
	06 - Measure of the geographical reach of partnerships, including local, national, and international partners		46.25		
	05 - Analysis of revenue growth directly attributable to established partnerships		33.49		
	02 - Indicators of innovations or process/product improvements introduced in the winery		20.26		
Market Adaptation and Diversification		1.60		0.39	0.194
	01 - Number of new geographic markets or consumer segments reached		43.07		
	05 - Amount invested in research activities to better understand consumer needs and preferences		30.07		
	03 - Total number of different product types or product lines offered by the winery		26.86		

Analysis of Table 4, as depicted in Figure 2, reveals that the R&D dimension holds the highest significance (22.63%), followed by SEI (15.52%). Conversely, the dimensions deemed least important by experts are SC (4.28%) and MAD (1.60%). The overall mean accuracy of the model is 0.66, with a standard deviation (sd) of 0.173, indicating moderate predictive performance with reasonable consistency across folds in the cross-validation process. A comparative analysis of accuracy between Rio Grande do Sul and other Brazilian states (SC, PR, and SE) was conducted. The mean accuracy for RS was 0.67 (sd = 0.154), compared to 0.64 (sd = 0.172) for the other states.

A t-test revealed no significant differences ($p > 0.05$), indicating that both groups have statistically similar accuracies. This demonstrates equivalent sensitivity in evaluating the stability of the rankings, reinforcing the robustness and applicability of the proposed framework across different regional contexts. It is important to recognize the overlap between certain indicators across different dimensions. For example, Indicator 5 from the R&D dimension and Indicator 1 from the Product and Service Innovation dimension both assess aspects related to the development of new products or services.

Nonetheless, these overlaps were retained based on recommendations from the systematic literature review, ensuring that the dimensions and indicators comprehensively captured the multifaceted nature of innovation capacity. Notably, these indicators were confirmed during the fuzzy Delphi phase, further validating their relevance within the framework. It is also worth noting that within the R&D dimension, this indicator ranked in position 7 (8.48 degree of importance), while in the Product and Service Innovation dimension, it ranked in position 2 (15.09 degree of importance).

This distinction highlights the perceived greater significance of the indicator for Product and Service Innovation compared to R&D, an observation that should be taken into account when analyzing data and discussing the findings. Such nuances underscore the need for careful interpretation of overlapping indicators to better understand their relative importance within different dimensions and their contribution to the overall framework.

These nuances emphasize the need for a meticulous analysis of the data and findings. Figure 2 illustrates the performance evaluation of the dimensions in assessing innovation capacity, providing a visual representation of their respective roles within the framework.

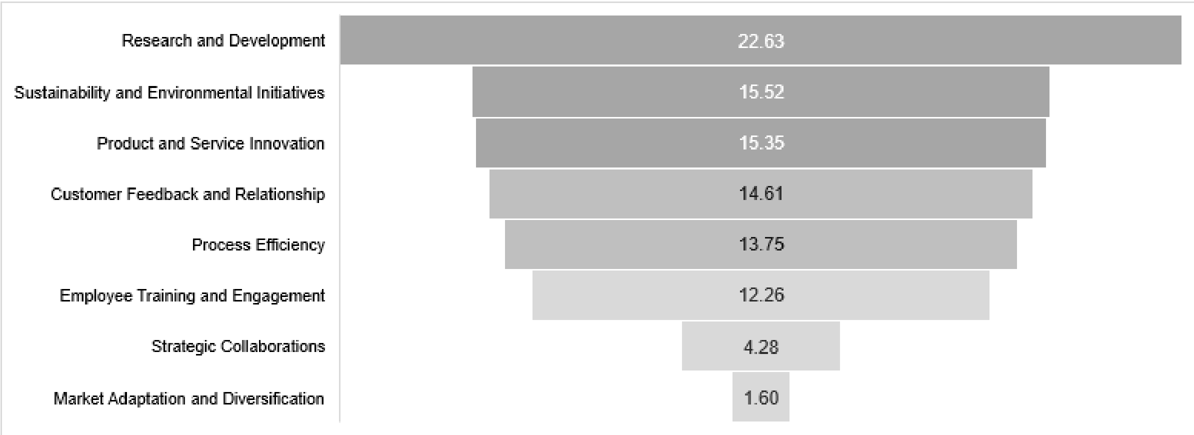


Figure 2. Ranking of the dimensions according to their degree of importance.

5. DISCUSSION

The discussion of the results underscores the significance of each dimension in evaluating the innovation capacity of Brazilian wineries. Furthermore, R&D is identified as the most critical factor, accounting for 22.63% of the overall importance. R&D enhances innovation by developing new products, grape varieties, and advanced winemaking techniques. Indicators of R&D capacity include the number of projects, collaborations with research institutions, and budget allocations, which are central to improving product quality and production efficiency, crucial for maintaining competitiveness in the wine sector [73-75,90,91].

Sustainability and environmental initiatives represent 15.35% of the innovation capacity, highlighting the importance of eco-innovation in the industry. Wineries investing in sustainable practices, such as using renewable energy and reducing emissions, appeal to environmentally conscious consumers, thereby enhancing their market image and consumer loyalty. The significance of sustainability in influencing purchasing decisions has already been reported in the literature, making SEI a key factor in innovation [75,88,92].

Product and service innovation accounts for 15.52% importance, emphasizing the adoption of new technologies and procedures to enhance wine quality and production processes, meeting consumer demands and maintaining market differentiation [83,85,93]. As for CFR and PE, they collectively contribute 28.36% to the innovation capacity; CFR constituting 14.61%, highlights the role of strong customer relationships and feedback in guiding innovation and building brand loyalty, with digital tools and wine tourism as strategies for improving customer interactions [88,89,94,95]. PE, constituting 13.75% of the innovation capacity, focuses on operational efficiency through waste reduction and energy efficiency, contributing to sustainability and cost reduction [75,80,96,97].

While EEF, SC, and MAD are considered less critical, with a combined importance of 18.14%, they are essential for sustaining innovation. Hence, EEF boosts employee productivity and creativity [79,98,99], SC enables partnerships that provide new knowledge and markets, and MAD allows for the diversification of offerings and reduces market dependence, ensuring resilience [76,100]. Overall, this study highlights the interconnectedness of these dimensions in driving the innovation capacity of Brazilian wineries, providing a comprehensive framework for assessing and improving their competitive position in the market.

The integration of emerging technologies, such as artificial intelligence (AI), presents transformative opportunities to enhance wineries' capacity for innovation. AI-driven tools can optimize viticulture processes by analyzing soil conditions, predicting climate impacts, and automating harvest schedules, thereby increasing efficiency and sustainability. For example, predictive analytics can identify optimal planting and harvesting times, reducing waste and improving yield quality. Additionally, AI-powered marketing tools enable wineries to adapt their product offerings based on consumer preferences, leveraging big data to refine strategies and expand market reach.

Beyond operational improvements, these technologies also promote innovation in product development and customer engagement. For instance, machine learning algorithms can analyze global wine trends to identify market gaps, inspiring the creation of unique blends that meet emerging consumer demands. Virtual and augmented reality technologies can enhance wine tourism experiences by providing interactive vineyard tours or immersive narratives about the winemaking process. By adopting these technologies, wineries not only increase their competitive edge but also strengthen their ability to innovate in a rapidly evolving industry landscape.

5.1 Limitations, Potential Biases in the Methodology, and Future Directions

This study validates metrics for assessing the innovation capacity of Brazilian wineries, emphasizing their relevance for competitiveness and sustainability. Using the Fuzzy Delphi and Random Forest methods, 8 dimensions and 50 key indicators were prioritized, with *R&D*, *Sustainability*, and *Product and Service Innovation* identified as the most influential. Secondary dimensions, such as *Customer Feedback* and *Process Efficiency*, also play significant roles in enhancing operations and fostering customer-centric innovation.

While comprehensive, the study acknowledges certain limitations. First, the regional focus on Rio Grande do Sul may limit the direct applicability of the findings to other regions with differing characteristics. Second, challenges arose during data collection, particularly with managers whose primary focus lies on operational management, potentially constraining the depth of responses. Additionally, despite the robustness of the methodology, potential biases exist, notably the reliance on expert judgments, which may introduce variations influenced by individual experiences and perceptions.

Nevertheless, the findings present a versatile framework that can be adapted to other agricultural and beverage industries, particularly in emerging markets that face similar sustainability and competitiveness challenges. Aligned with global trends, such as sustainable practices, consumer-driven innovation, and digital transformation, this research offers valuable insights to advance innovation strategies across diverse contexts worldwide.

Future research should aim to address these limitations by expanding the scope to include other regions and incorporating a broader range of stakeholders to refine the understanding of innovation dynamics in the wine sector. Employing alternative methods, such as Fuzzy AHP, CRITIC, Shannon Entropy, or Fuzzy DEMATEL, could complement the analysis by assigning importance weights and establishing relationships among dimensions and indicators, thereby providing deeper insights into critical innovation factors.

Furthermore, advanced statistical techniques, such as Principal Component Analysis (PCA) or Factor Analysis, could be applied to validate the proposed dimensions and group indicators. However, these methods would require a larger sample size, enabling broader generalization and applicability of the results to other sectors. Expanding research in this direction would contribute significantly to the evolving discourse on innovation capacity and its role in organizational competitiveness and sustainability.

6. FINAL CONSIDERATIONS

The research aimed to identify and validate metrics for assessing the innovation capacity of Brazilian wineries. It developed a comprehensive framework that includes multiple dimensions vital for the competitiveness and sustainability of the sector. Key dimensions identified were R&D, sustainability and environmental initiatives, and product and service innovation. These dimensions play a crucial role in enhancing product quality and operational efficiency.

Investment in R&D enables wineries to innovate in viticulture and winemaking, leading to new grape varieties, wine types, and more efficient production processes. Consequently, this supports product diversification and differentiation, establishing a unique market identity and boosting competitiveness. Sustainability initiatives, such as using renewable energy and recycling, appeal to environmentally conscious consumers, allowing wineries to enhance their public image and attract eco-friendly customers. Incorporating product and service innovation with sustainable practices helps wineries stay competitive and contribute to environmental protection.

Furthermore, our findings also highlight the significance of intermediate dimensions, such as customer feedback and relationships and process efficiency, in driving customer-centric innovation and maintaining operational efficiency. These dimensions facilitate continuous improvement through customer insights, which are essential for retaining loyalty, adapting to evolving consumer preferences, and ensuring cost-efficient production processes. Although receiving less emphasis, dimensions such as employee engagement and training, strategic collaborations, and market adaptation and diversification are equally critical for fostering a robust innovation ecosystem. Neglecting these aspects could compromise wineries' resilience and adaptability to dynamic market conditions.

The methodologies employed in this study—specifically the Fuzzy Delphi and Random Forest Importance techniques—demonstrate significant relevance in assessing innovation capacity. By combining expert validation with machine learning-based prioritization, these methods provide a rigorous and adaptable framework for identifying and evaluating key innovation indicators. Their flexibility enables application across sectors and regions, offering valuable insights into strategic innovation practices beyond the wine industry.

This methodological approach ensures both rigor and practical applicability, contributing to the development of actionable metrics that guide decision-makers in enhancing organizational competitiveness and sustainability. Moreover, these techniques validate dimensions and indicators tailored to the wine industry, establishing a solid foundation for future research. Managers can leverage these insights to refine innovation strategies and enhance competitive performance, while policymakers can utilize the findings to inform innovation policies and foster sustainable development across industries.

Future research should incorporate longitudinal analyses to evaluate the long-term sustainability of innovations. Additionally, exploring the role of emerging technologies, such as artificial intelligence and the Internet of Things (IoT), in driving innovation within the wine sector is recommended. While this study focuses on Rio Grande do Sul, future investigations should extend to other Brazilian states and emerging viticulture regions worldwide to achieve a more comprehensive understanding of innovation challenges and opportunities in the global wine industry.

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SUPPLEMENTARY MATERIAL (APPENDIX)

Table 1. Selection of Innovation Capacity Indicators Using the Fuzzy Delphi Technique.

Dimension	Values		
Indicator	Fuzzy Weight	Defuzzification	Decision
1 - Research and Development			
Decision Value		0.593	
1 - Total number of employees dedicated exclusively to R&D	(0.10, 0.60, 0.90)	0.534	Excludes
2 - Number of R&D projects executed internally	(0.30, 0,74, 0,90)	0.648	Includes
3 - Percentage of R&D activities conducted through external sources in relation to total R&D activities	(0,10, 0,56, 0,90)	0.520	Excludes
4 - Number of R&D projects conducted in collaboration with other companies	(0,10, 0,56, 0,90)	0.553	Excludes
5 - Number of new products launched	(0,30, 0,56, 0,90)	0.634	Includes
6 - Monetary value allocated to financing internal R&D activities during the year	(0,30, 0,56, 0,90)	0.648	Includes
7 - Number of funding programs or grants obtained for R&D projects	(0,30, 0,56, 0,90)	0.647	Includes
8 - Percentage that the R&D budget represents in relation to the company's total budget	(0,30, 0,56, 0,90)	0.644	Includes
9 - Number of prototypes developed for market testing	(0,10, 0,56, 0,90)	0.546	Excludes
10 - Number of tests and experiments conducted to validate new ideas or prototypes	(0,30, 0,56, 0,90)	0.639	Includes
11 - Number of market studies conducted to guide R&D activities	(0,10, 0,56, 0,90)	0.572	Excludes
12 - Monthly frequency of systematic brainstorming sessions or other idea generation techniques	(0,10, 0,56, 0,90)	0.523	Excludes
13 - Number of analyses conducted to understand the technological and competitive environment	(0,10, 0,56, 0,90)	0.558	Excludes
14 - R&D project success rate, measured by the number of successfully completed projects in relation to the total number of projects initiated	(0,30, 0,56, 0,90)	0.640	Includes
15 - Number of patents or intellectual property registrations applied for	(0,10, 0,56, 0,90)	0.558	Excludes
16 - Number of low-cost innovations implemented (frugal innovations)	(0,30, 0,56, 0,90)	0.626	Includes
2 - Strategic Collaborations			
Decision Value		0.610	
1 - Number of formal partnerships the winery maintains with other companies, research institutions, distributors, or local producers	(0.10, 0.75, 0.90)	0.583	Excludes
2 - Indicators of innovations or process/product improvements introduced in the winery	(0.30, 0.75, 0.90)	0.651	Includes
3 - Level of satisfaction of the winery with each of its strategic partners, usually through surveys or direct feedback	(0.10, 0.74, 0.90)	0.580	Excludes
4 - Average duration in months that strategic partnerships are maintained	(0.10, 0.67, 0.90)	0.556	Excludes
5 - Analysis of revenue growth directly attributable to established partnerships	(0.30, 0.69, 0.90)	0.632	Includes
6 - Measure of the geographical reach of partnerships, including local, national, and international partners	(0.30, 0.77, 0.90)	0.656	Includes
3 - Employee Training and Engagement			

Decision Value		0.560	
1 - Number of employees participating in training programs relative to the total number of employees	(0.10, 0.62, 0.90)	0.539	Excludes
2 - Results of employee satisfaction surveys conducted periodically	(0.10, 0.58, 0.90)	0.528	Excludes
3 - Percentage of employees who remain with the company for a specified period	(0.10, 0.68, 0.90)	0.560	Includes
4 - Annual average hours of training per employee	(0.10, 0.59, 0.90)	0.531	Excludes
5 - Proportion of employees who received a promotion in the last year	(0.10, 0.46, 0.90)	0.485	Excludes
6 - Frequency of unexcused absences from work	(0.30, 0.73, 0.90)	0.642	Includes
7 - Percentage of employees participating in engagement activities organized by the company	(0.30, 0.70, 0.90)	0.635	Includes
8 - Frequency and results of performance evaluations that include feedback from peers and supervisors	(0.10, 0.68, 0.90)	0.560	Includes
5 - Process Efficiency			
Decision Value		0.640	
1 - Average production cycle time	(0.3, 0.73, 0.90)	0.645	Includes
2 - Production cost per unit	(0.3, 0.81, 0.90)	0.670	Includes
3 - Rate of production capacity utilization	(0.3, 0.77, 0.90)	0.657	Includes
4 - Number of defects or reworks per batch	(0.3, 0.75, 0.90)	0.650	Includes
5 - Energy efficiency in production	(0.1, 0.73, 0.90)	0.578	Excludes
6 - Raw material waste rate	(0.3, 0.78, 0.90)	0.661	Includes
7 - Percentage of automated processes	(0.1, 0.65, 0.90)	0.551	Excludes
8 - Response time to failures or breakdowns	(0.3, 0.74, 0.90)	0.648	Includes
9 - Maintenance cost as a percentage of production cost	(0.3, 0.77, 0.90)	0.657	Includes
10 - Employee satisfaction index with operational processes	(0.3, 0.72, 0.90)	0.640	Includes
11 - Number of process improvements implemented per year	(0.3, 0.70, 0.90)	0.632	Excludes
12 - On-time delivery rate	(0.5, 0.83, 0.90)	0.742	Includes
13 - Number of customer complaints related to product quality	(0.5, 0.82, 0.90)	0.739	Includes
14 - Percentage of production orders completed without incidents	(0.3, 0.76, 0.90)	0.653	Includes
15 - Average time for production line changeover or equipment adjustment	(0.1, 0.66, 0.90)	0.553	Excludes
16 - Efficiency in the use of water and other critical inputs	(0.1, 0.71, 0.90)	0.571	Excludes
6 - Product/Service Innovation			
Decision Value		0.633	
1 - Number of new services launched	(0.30, 0.73, 0.90)	0.645	Includes
2 - Number of significantly improved products or services	(0.30, 0.75, 0.90)	0.651	Includes
3 - Revenue generated from new products or services	(0.30, 0.77, 0.90)	0.657	Includes
4 - Percentage of revenue from products or services launched in the last 3 years	(0.10, 0.70, 0.90)	0.568	Excludes
5 - Number of disruptive innovations introduced to the market	(0.30, 0.67, 0.90)	0.624	Excludes
6 - Number of patents or intellectual property registrations obtained	(0.10, 0.64, 0.90)	0.548	Excludes
7 - Cost of developing new products or services	(0.30, 0.75, 0.90)	0.650	Includes
8 - Development time from conception to launch	(0.30, 0.71, 0.90)	0.636	Includes
9 - Success rate of new products or services based on market acceptance	(0.30, 0.77, 0.90)	0.656	Includes

10 - Number of strategic partnerships focused on product/service innovation	(0.30, 0.69, 0.90)	0.628	Excludes
11 - Total investment in research and development activities	(0.30, 0.72, 0.90)	0.641	Includes
12 - Number of ongoing innovation projects	(0.30, 0.71, 0.90)	0.636	Includes
13 - Customer feedback on innovations (satisfaction and acceptance)	(0.30, 0.79, 0.90)	0.664	Includes
14 - Adoption rate of emerging technologies in production processes	(0.10, 0.64, 0.90)	0.546	Excludes
15 - Number of products or services that meet new consumer needs	(0.50, 0.78, 0.90)	0.728	Includes
16 - Environmental impact of new products or services (sustainability)	(0.30, 0.74, 0.90)	0.648	Includes
7 - Sustainability and Environmental Initiatives			
Decision Value		0.567	
1 - Total energy consumption from renewable sources	(0.10, 0.72, 0.90)	0.572	Includes
2 - Amount of greenhouse gas (GHG) emissions reduction compared to previous periods	(0.10, 0.68, 0.90)	0.559	Excludes
3 - Total water consumption per unit of product produced	(0.30, 0.76, 0.90)	0.653	Includes
4 - Percentage of total waste generated that is recycled or reused	(0.10, 0.74, 0.90)	0.578	Includes
5 - Total number of ecological or sustainability certifications acquired, such as ISO 14001, LEED certification (Leadership in Energy and Environmental Design), etc.	(0.10, 0.64, 0.90)	0.547	Excludes
6 - Value invested in technologies or practices that promote sustainability	(0.10, 0.68, 0.90)	0.561	Excludes
7 - Total initiatives conducted in partnership with environmental NGOs or other entities for environmental conservation	(0.10, 0.63, 0.90)	0.542	Excludes
8 - Life cycle assessment of new products to determine their environmental impact	(0.10, 0.68, 0.90)	0.559	Excludes
9 - Number of training hours provided to employees on sustainable practices	(0.10, 0.59, 0.90)	0.530	Excludes
8 - Market Adaptation and Diversification			
Decision Value		0.640	
1 - Number of new geographic markets or consumer segments reached	(0.30, 0.75, 0.90)	0.648	Includes
2 - Proportion of total revenue coming from recently launched products or new markets	(0.30, 0.70, 0.90)	0.633	Excludes
3 - Total number of different product types or product lines offered by the winery	(0.30, 0.76, 0.90)	0.652	Includes
4 - Average time between identifying a new market trend and introducing a corresponding product or service	(0.30, 0.70, 0.90)	0.634	Excludes
5 - Amount invested in research activities to better understand consumer needs and preferences	(0.30, 0.72, 0.90)	0.641	Includes
6 - Proportion of revenue from sales outside the domestic market	(0.30, 0.69, 0.90)	0.630	Excludes
9 - Customer Feedback and Relationship			
Decision Value		0.656	
1 - Average customer satisfaction score received through regular surveys	(0.30, 0.76, 0.90)	0.654	Excludes
2 - Percentage of customer feedback responded to within a specified timeframe	(0.30, 0.77, 0.90)	0.655	Excludes
3 - Monthly number of customer interactions per period	(0.30, 0.76, 0.90)	0.652	Excludes

	4 - Percentage of customers who continue doing business with the winery year after year	(0.50, 0.83, 0.90)	0.744	Includes
	5 - Total number of complaints received within a specific period	(0.30, 0.77, 0.90)	0.658	Includes
	6 - Percentage of complaints resolved during the first interaction with the customer	(0.30, 0.79, 0.90)	0.664	Includes
	7 - Measure reflecting the likelihood of customers recommending the winery to others	(0.50, 0.86, 0.90)	0.753	Includes
	8 - Count of loyalty programs offered and the number of active customers in those programs	(0.10, 0.69, 0.90)	0.562	Excludes
	9 - Percentage of potential customers (leads) that become buyers	(0.30, 0.77, 0.90)	0.658	Includes
	10 - Total number of customer interactions on social media platforms, including comments, likes, and shares	(0.10, 0.68, 0.90)	0.560	Includes
	11 - Average time the company takes to respond to customer requests, measured in hours or days	(0.30, 0.77, 0.90)	0.658	Includes

Glossary of Technical Terms Used in Data Analysis

Fuzzy Delphi Method
A refinement of the traditional Delphi method that incorporates fuzzy logic to handle uncertainties in expert opinions. It is widely used for achieving consensus on complex issues by analyzing linguistic variables through triangular fuzzy numbers.

Triangular Fuzzy Numbers
A mathematical representation of uncertainty in the Fuzzy Delphi method, defined by three points: lower limit, most probable value, and upper limit.

Random Forest Importance (RFI)
A machine learning technique that uses multiple decision trees to rank features (dimensions or indicators) based on their importance in predicting outcomes, calculated through measures such as impurity reduction.

Bootstrapping
A statistical technique used in the Random Forest method, involving repeated sampling with replacement to train multiple decision trees, enhancing robustness and accuracy.

Gini Impurity
A metric used in decision trees to measure the impurity or diversity of a node, indicating how well the node splits the data into distinct classes.

Defuzzification
The process of converting fuzzy numbers into crisp values to make them interpretable for decision-making or ranking purposes.

Importance Weights
Quantitative measures assigned to dimensions or indicators based on their relative significance in explaining or predicting outcomes, derived from the Random Forest model.

Cross-Validation
A statistical method for evaluating a model’s performance by partitioning the data into multiple subsets (folds). The model is trained on k-1 subsets and tested on the remaining subset, rotating this process through all folds. The results are averaged to estimate the model's generalizability and stability.

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