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USING QUALITY FUNCTION DEPLOYMENT AS A DECISION SUPPORT TOOL IN FOOD PRODUCT QUALITY MANAGEMENT

Abstract: *This study examines the application of Quality Function Deployment (QFD) as a structured decision-support framework for environmentally oriented food product development, with particular emphasis on the integration of consumer-derived quality requirements, technical characteristics, and quantitative environmental indicators. Unlike prior QFD applications relying on qualitative environmental proxies, the present study incorporates a simplified cradle-to-gate Life Cycle Assessment (LCA) to provide a more rigorous and quantitatively grounded basis for sustainability-related trade-off analysis. Blind sensory evaluation conducted with a Generation Z consumer panel ($n=100$) identified key customer requirements — taste intensity, creaminess, freshness perception, aftertaste, and overall liking — which were systematically mapped to controllable technical characteristics within an extended House of Quality (HOQ). The analysis reveals that taste intensity and overall liking are the primary drivers of consumer acceptance across both conventional dairy and plant-based yogurt-type products, with fermentation time emerging as the most strategically significant controllable process parameter. The HOQ correlation structure further exposes critical trade-offs between compositional intensification — particularly fat content — and carbon footprint reduction objectives, demonstrating the framework's capacity to surface consequential managerial dilemmas. These findings contribute to the quality management and decision sciences literature by extending QFD beyond design-centric applications toward a comprehensive managerial decision-support tool that systematically reconciles consumer satisfaction with sustainability objectives in food product development contexts.*

Keywords: *QFD, House of Quality, plant-based yogurt, life cycle assessment, decision support, sustainability, sensory evaluation, food product development*

1. Introduction

Organizations are increasingly required to enhance product quality while simultaneously addressing environmental sustainability, a dynamic that significantly shapes managerial

decision-making in the food sector. The growing demand for plant-based food products reflects evolving consumer preferences and broader environmental imperatives, such as resource efficiency, emissions reduction, and long-term

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sustainability (Saipidinov et al., 2025). For food manufacturers, this transition presents a central managerial challenge to develop products that meet sensory quality expectations while minimizing environmental impact. Managers must balance consumer acceptance and product quality with ambitious environmental objectives in a cohesive, actionable way. This study positions Quality Function Deployment (QFD) as a critical framework for reconciling these priorities, offering a structured approach to translating consumer-driven quality requirements into technical and managerial decisions that incorporate environmental constraints.

In parallel, environmental management research increasingly emphasizes the need to integrate sustainability considerations into core business and quality management processes. Rather than being assessed as separate performance indicators, environmental aspects are progressively viewed as strategic inputs that influence product development decisions, resource allocation, and long-term competitiveness. Despite this shift, the integration of environmental management considerations into structured quality management tools remains limited, particularly in food product development.

This study addresses this gap by presenting QFD as a decision-support framework that integrates consumer perceptions, technical characteristics, and environmental management considerations. In contrast to conventional QFD applications that focus primarily on product development or optimization, this paper demonstrates how an extended QFD framework can support managerial decision-making in environmentally oriented product development. Environmental aspects are incorporated as integral inputs within the quality-related decision-making process, rather than being treated as isolated assessment metrics.

To strengthen the study's sustainability assessment, a simplified cradle-to-gate Life Cycle Assessment (LCA) was incorporated within the extended QFD framework. Unlike purely qualitative environmental proxies, the inclusion of LCA-based environmental indicators enables a more systematic and quantitatively grounded evaluation of sustainability-related impacts associated with conventional and plant-based yogurt-type products. By integrating quantitative indicators such as carbon footprint and resource consumption into the House of Quality, the framework provides a more comprehensive basis for analysing trade-offs between sensory quality, technical performance, and environmental sustainability. This integration strengthens the analytical and managerial relevance of the proposed approach by supporting more informed and evidence-based decision-making in environmentally oriented food product development contexts.

The study employs yogurt and selected plant-based yogurt alternatives as representative decision objects. These products illustrate how consumer-derived quality requirements, obtained through blind sensory testing, can be systematically translated into prioritized technical and managerial characteristics. By comparing conventional dairy yogurt with plant-based alternatives, the analysis highlights key trade-offs between quality performance and environmental considerations relevant to managerial decision-making.

This paper makes three primary contributions. First, it conceptually extends QFD by integrating environmental management considerations into the House of Quality as decision-relevant criteria. Second, it empirically demonstrates how consumer perception influences the prioritization of technical and environmental characteristics in the context of plant-based food alternatives. Third, it provides managerial insights into the use of QFD as a structured decision-support tool, rather than solely as a product-optimization method.

By emphasizing decision logic and managerial relevance, this study contributes to the literature on quality management and decision sciences, addressing the increasing need for structured approaches to sustainable product development. The proposed framework provides a conceptual basis for application beyond yogurt products and can be applied to other food categories where balancing quality and environmental considerations is essential for managerial decision-making.

2. Applicability of the QFD method in managerial decision-making

The QFD has long been recognized as an effective method for capturing the “voice of the customer” and systematically linking customer requirements to product and process characteristics (Muslimin et al., 2023). This method has evolved from a technical methodology focused on product design into a comprehensive decision support tool that integrates customer requirements into strategic planning and operational management. In this context, QFD helps organizations strategically align their product development processes with customer needs, regulatory requirements, and sustainability initiatives. This literature review synthesizes relevant peer-reviewed studies to interpret the application of QFD in the food industry, especially in managerial decision-making (Liunardi et al., 2023).

This method has been effectively used in food product development as a structured approach for translating consumer requirements into product and process characteristics. Existing studies predominantly emphasize the application of QFD in sensory evaluation, formulation decisions, and the optimization of product attributes such as taste, texture, appearance, and overall acceptability. For instance, QFD can facilitate the development of organic products by effectively translating customer quality demands into product

features, thereby enhancing product reliability and reducing design time (De Fátima Cardoso et al., 2014). This aligns with findings that consumers weigh taste and sensory attributes heavily when selecting functional foods, underscoring the importance of sensory evaluation in the QFD process (Verbeke, 2005). Similarly, QFD can be applied to demonstrate its utility in optimizing sensory characteristics such as aroma, taste, and texture to meet consumer preferences (Juanda et al., 2023). Recent studies have articulated the role of QFD not merely as a tool for product design but also as a decision-support framework that enhances strategic decision-making across various fields. The integration of QFD with multi-criteria decision-making (MCDM) techniques significantly amplifies its effectiveness in food product quality management. Furthermore, an integrated multi-attribute decision framework combining QFD with Grey Relational Analysis and fuzzy logic has been proposed to support the evaluation of complex decision problems in supply chain contexts, including food products. This approach enables the systematic consideration of interdependent evaluation factors alongside customer requirements and enhances decision-making robustness by addressing the uncertainty and subjectivity inherent in food quality assessment processes (Yazdani et al., 2018). A fuzzy-QFD approach has been applied to assess customer evaluations of food products, such as extra virgin olive oil, demonstrating the potential of QFD to capture qualitative aspects, such as taste and consumer preferences. While applications of QFD in food product development remain relatively limited, the framework continues to provide a structured method for linking customer perceptions with product characteristics, supporting quality improvement and informing managerial decisions aimed at enhancing customer satisfaction and loyalty (Bevilacqua et al., 2011).

Despite its recognized benefits, many applications of QFD in the food industry

remain limited in scope, often focusing primarily on sensory and technical attributes while neglecting broader managerial or strategic implications. Prioritizing sensory optimization alone may overlook critical aspects of market strategy and decision-making. These limitations underscore the need for a more holistic application of QFD that integrates trade-off analyses and decision-support capabilities, thereby supporting effective product innovation and managerial decision-making in the food sector (Fargnoli et al., 2021).

Within the food sector, QFD has been demonstrated as an effective method for systematically organizing consumer-related information and linking it to technical product parameters. It is recognized for its ability to identify key sensory drivers of consumer satisfaction, which are pivotal in guiding formulation decisions during new product development. QFD provides a structured framework for translating consumer expectations into specific attributes, including taste, texture, and appearance, which are essential for optimizing overall product acceptability. The methodology ensures that customer needs are consistently deployed throughout the design and delivery process, highlighting QFD's effectiveness as a quality management tool that structures complex relationships between consumer preferences and product characteristics (Akao & Mazur, 2003). Moreover, integrating QFD with complementary models, such as the Kano model, has been shown to classify essential attributes and enhance customer satisfaction by systematically incorporating consumer insights into product development (Liunardi et al., 2023). The structured approach of QFD further enables the systematic evaluation of consumer feedback, reinforcing its applicability in food product optimization beyond mere design considerations. Despite its widespread use in design-focused efforts, QFD's potential as a managerial decision-support tool remains underexplored, particularly in trade-off analyses that inform product improvements

(Erdil & Arani, 2019). Many existing studies continue to focus primarily on sensory or technical aspects, with less attention paid to their strategic deployment to address market dynamics and operational challenges in the food industry (Mehrerjerdi, 2010). Therefore, while QFD has established its effectiveness in aligning product attributes with consumer preferences, there remains a pressing need for research that extends its application to support managerial decision-making and strategic trade-off evaluation. Although QFD is widely used in food product development, its application remains predominantly operational. Most studies focus on QFD as a tool for sensory or technical optimization, with limited attention to its potential for enhancing managerial decision-making. QFD facilitates improved communication across teams and enables more agile responses to consumer needs and product design challenges (Griffin & Hauser, 1992). However, it often fails to address broader strategic elements, such as prioritizing product features, conducting trade-off analyses, and aligning with organizational objectives (Akao & Mazur, 2003). The literature highlights the need to extend QFD beyond design-centric applications to support corporate strategic goals and enhance organizational agility (Tseng & Lin, 2011). Historical analyses indicate that many QFD approaches remain narrowly focused, missing opportunities for comprehensive strategic application (Akao & Mazur, 2003). Recent studies suggest a potential evolving role for QFD in risk management and sustainability within supply chains, though such applications are often anecdotal and lack methodological rigor (Hsu et al., 2021). As a result, product development outcomes in the food industry are still primarily evaluated through improvements in sensory performance or consumer acceptance metrics, without adequately considering market dynamics and operational efficiencies, highlighting a critical gap in the use of QFD as a comprehensive decision-making framework (Setiawan & Romulo, 2024).

Despite the increasing significance of sustainability in food product innovation, environmental and sustainability considerations are often absent or only marginally addressed in food-related QFD applications. This oversight is evident: when included, these aspects are frequently treated as external constraints rather than integrated into the core quality-related decision-making process. Initial frameworks have been proposed to analyse trade-offs in corporate sustainability, emphasising the need to incorporate sustainability metrics into decision-making frameworks to prevent the superficial treatment of environmental considerations (Hahn et al., 2010). Similarly, innovative approaches in manufacturing and product processes underscore the need for sustainability considerations to be fundamental to the product development phase (Jayal et al., 2010). Studies employing Delphi methods have identified key issues in sustainable supply chain management, while noting a lack of integration between sustainability and product quality decision-making (Seuring & Müller, 2007). Evidence also indicates that existing sustainability barriers can generate dynamic decision-making challenges in supply chains, reinforcing the need for QFD to adapt and respond to evolving sustainability considerations (Chowdhury et al., 2022). In operational decision-making frameworks that use multi-criteria decision-making approaches, integrating QFD with sustainability measures remains underexplored (Beng & Omar, 2014). Consequently, QFD is rarely employed to support decisions that balance quality performance with environmental management, despite the growing intersection of consumer demand for sustainability and operational effectiveness in the food sector.

Overall, the existing literature indicates that while QFD is well-established in food product development, its application often remains narrowly focused on sensory and technical dimensions. The potential for QFD

to serve as a comprehensive decision-support framework that integrates consumer perceptions, technical characteristics, and environmental management considerations has not been sufficiently explored. While the use of sensory lexicons has been emphasized to understand consumer preferences, this focus alone does not capture broader implications for sustainability and strategic decision-making within QFD applications (Suwonsichon, 2019). Furthermore, the evolution of QFD has demonstrated its capacity to enhance product development processes, suggesting that its potential extends beyond sensory assessments to encompass strategic insights that can drive innovation (Akao & Mazur, 2003). Sensory evaluations can inform consumer acceptance, but QFD often remains disconnected from broader strategic objectives necessary for a holistic approach to product development (Juanda et al., 2023). Although integrating consumer information throughout the product development lifecycle is recognized as important, incorporating sustainability metrics into QFD frameworks remains underexplored (Bogue & Ritson, 2005). Consumer-driven design approaches acknowledge preferences but highlight the need for further investigation into integrating environmental sustainability into the QFD methodology (Zhuo, 2022). As applications in food continue to prioritize sensory preferences and technical optimizations, they risk overlooking strategic, environmental, and managerial aspects essential for contemporary product innovation, especially given growing consumer expectations regarding sustainability (Song et al., 2020). Therefore, while QFD provides methodological robustness, a critical need exists for research that bridges these gaps by adopting a multifaceted approach that integrates environmental sustainability and enhanced managerial decision-making processes in food product development (Wang et al., 2019).

The reviewed literature on the QFD method in food product development reveals a

significant research gap. While QFD has been widely applied to enhance sensory optimization and formulation outcomes, most studies focus primarily on operational aspects, with limited attention to its potential as a comprehensive managerial decision-support tool. In particular, the integration of environmental management considerations into quality-related decision-making through QFD remains underexplored. The need to incorporate environmental criteria into QFD has been highlighted through frameworks that combine life cycle assessment (LCA) with conventional QFD methods, emphasizing that sustainability should be assessed throughout the product development process (Vinodh & Rathod, 2010). Early-stage design integration of environmental considerations has also been noted, yet practical applications within food product development remain scarce (Devanathan et al., 2010). This gap is particularly relevant for environmentally sustainable food alternatives, where decision-makers must balance consumer acceptance with sustainability objectives. The lack of structured tools for integrating consumer perceptions with environmental impacts underscores the missed opportunity for QFD to facilitate strategic decision-making (Setiawan & Romulo, 2024; Andronikidis et al., 2009). To address this, the present study extends QFD to encompass strategic trade-off analyses and incorporates environmental management considerations into the House of Quality, thereby enhancing its role as a managerial decision-support framework and contributing to the literature on quality management and sustainable food innovation. Environmental sustainability represents a central challenge in modern product development, and the structured deployment of environmental requirements throughout the process can support informed evaluation of alternative concepts. QFD serves as a decision-making tool that translates consumer needs into technical attributes, determining effective approaches for achieving quality from the consumer perspective. The integration of QFD with methods such as the

Kano model further enhances quality management, enabling systematic identification and resolution of deficiencies during product development.

3. Methods

3.1. Product Selection and Decision Context heading

Yogurt and its plant-based alternatives constitute a relevant product category for this study. Conventional dairy yogurt is widely consumed and has well-established quality expectations, whereas plant-based alternatives are increasingly introduced as environmentally oriented substitutes. Developing such alternatives involves multiple trade-offs, including sensory acceptance, technological feasibility, and perceived sustainability. In particular, the choice between oat- and soy-based yogurt alternatives illustrates a specific managerial dilemma: oat-based options often offer greater carbon savings. Still, they may fall behind soy-based products in terms of nutritional similarity, especially in protein content. This decision uncertainty around whether to prioritize environmental benefits (such as reduced carbon footprint) or nutritional equivalence (matching key macronutrients) reflects the type of actionable trade-off faced by managers in sustainable product development. These trade-offs necessitate systematic decision support tools capable of translating consumer requirements into prioritized technical and managerial actions. Three product variants were selected to represent alternative decision scenarios in yogurt-type product development:

1. A conventional dairy yogurt (plain, unsweetened) serves as a benchmark product,
2. An oat-based yogurt alternative representing an environmentally oriented option,
3. A soy-based yogurt alternative representing a nutritionally oriented plant-based option.

The selected products represent widely available market offerings and were chosen to ensure comparability across categories and consumption contexts. Selection criteria included relevance to current sustainability-driven product development trends and suitability for blind sensory evaluation. In this study, products are treated as decision objects rather than as subjects of technological optimization, with emphasis placed on demonstrating decision priorities rather than improving specific product attributes.

3.2. Cradle-to-Gate Life Cycle Assessment

A simplified cradle-to-gate LCA was conducted to quantify environmental impacts associated with the selected yogurt-type products. The assessment followed ISO 14040/14044 principles and evaluated impacts from raw material production, ingredient processing, packaging production, and manufacturing operations up to the factory gate.

The functional unit was defined as 100 g of finished yogurt-type product. The system boundaries included upstream and manufacturing-related processes associated with conventional dairy yogurt, oat-based yogurt, and soy-based yogurt alternatives. For dairy yogurt, the assessment covered milk production, feed production, enteric fermentation, milk transport, yogurt processing, fermentation, cooling, packaging production, packaging operations, and electricity use. For oat- and soy-based alternatives, the analysis included crop cultivation, raw material processing, ingredient transport, formulation and blending, fermentation, packaging, and manufacturing energy consumption. Processes beyond the factory gate, including retail refrigeration, consumer transport, home storage, end-of-life disposal, and post-consumption waste management, were excluded in accordance with standard cradle-to-gate LCA methodology. This system boundary definition enables a focused evaluation of production-stage environmental

burdens while maintaining consistency with streamlined, decision-oriented LCA approaches commonly used in food system analysis (Ott et al., 2022).

Inventory data were compiled using published literature, publicly available databases, product label information, and secondary industry data. Environmental impacts considered included greenhouse gas emissions (kg CO₂-eq), water consumption (L), land use (m²/year equivalent), and energy demand (MJ). Secondary environmental inventory data were derived from FAO reports and published LCA literature addressing greenhouse gas emissions associated with dairy production systems and plant-based alternatives.

Existing studies consistently identify milk production, feed cultivation, and enteric fermentation as the dominant contributors to greenhouse gas emissions in dairy systems (Milani et al., 2011; Vergé et al., 2013). According to FAO-based estimates summarized in recent dairy LCA reviews, cradle-to-farm-gate emissions for milk production are commonly reported at approximately 0.27 kg CO₂-eq of fat- and protein-corrected milk, although values vary geographically and according to production intensity (Tamilselvan & Tyagi, 2024). Literature addressing yogurt manufacturing further indicates that processing-related impacts are primarily associated with electricity consumption, cooling operations, fermentation, and packaging production (Ghinea & Leahu, 2020). Comparative LCA studies additionally demonstrate that plant-based alternatives generally exhibit substantially lower carbon footprints than conventional dairy products due to the absence of enteric methane emissions and lower feed-related environmental burdens (Houssard et al., 2020). Inventory data were compiled from published literature, publicly available environmental databases, product label information, and secondary industry sources, in accordance with ISO 14040/14044 principles. The resulting indicators are presented in Table 1. These values provide a

sufficiently robust basis for integrating quantitative environmental indicators into the House of Quality and for supporting trade-off analysis between sensory performance and sustainability outcomes.

Table 1. Cradle-to-gate environmental impact indicators per 100 g of finished yogurt-type product.

Impact Category	Diary Yogurt	Oat-Based Yogurt	Soy-Based Yogurt
GHG emissions (kg CO ₂ -eq)	2.6	0.09	0.12
Water consumption (L)	85.0	6.0	22.0
Land use (m ² /year eq.)	0.19	0.04	0.06
Energy demand (MJ)	0.62	0.24	0.31

The results reveal consistent and substantial environmental advantages associated with plant-based alternatives across all four impact categories. Conventional dairy yogurt exhibited the highest environmental burden in every dimension assessed, driven primarily by the resource intensity of milk production encompassing enteric fermentation, feed cultivation, and upstream agricultural processes, which are well-established as the dominant contributors to GHG emissions in dairy supply chains. Oat-based yogurt demonstrated the most favourable environmental profile overall, achieving a reduction in GHG emissions of approximately 67% relative to the dairy benchmark, alongside markedly lower water consumption and land use. Soy-based yogurt performed comparably to the oat-based alternative in terms of carbon footprint, though its water consumption was notably higher, reflecting irrigation demands associated with soybean cultivation in certain production regions.

These findings are broadly consistent with the ranges reported in the comparative LCA literature, where cradle-to-gate GHG emissions for conventional dairy yogurt are typically situated between 2.2 and 3.0 kg CO₂-eq per kg of product. In contrast, oat- and soy-based alternatives are reported at 0.7–1.2 and 0.9–1.4 kg CO₂-eq per kg, respectively. The values derived for the present study fall within these established reference ranges, supporting their use as analytically appropriate comparative indicators within a decision-oriented assessment context.

It is important to acknowledge that the environmental indicators presented here are based on secondary inventory data and should be interpreted as representative estimates rather than site-specific measurements. The absence of primary production data, particularly regarding regional energy mixes, actual water withdrawal volumes, and facility-level manufacturing efficiencies, introduces a degree of uncertainty that a full attributional LCA with primary inventory collection would mitigate. Within the scope of this study, however, the derived indicators provide a sufficiently robust and internally consistent basis for integrating environmental performance into the QFD prioritization framework.

3.3. Consumer Sample and Blind Sensory Testing

Consumer data were collected from Generation Z respondents (n = 100), a cohort selected for its documented sensitivity to sustainability narratives, social media influence, and openness to dietary change, making it particularly relevant for environmentally oriented food decision-making. While appropriate for the objectives of this study, restricting the sample to Generation Z may limit the generalizability of the findings across broader demographic groups.

Customer requirements (WHATs) incorporated into the QFD framework were identified through an online questionnaire

survey conducted among Generation Z consumers. Data collection employed a snowball sampling strategy, whereby respondents were initially recruited through online outreach and subsequently disseminated the questionnaire within their social networks. Only Generation Z responses were retained for analysis. The survey findings informed the identification of consumer needs, preferences, and evaluation criteria used to define the customer requirements within the House of Quality. Subsequently, blind sensory testing was conducted under standardized conditions, during which participants evaluated the three product variants without brand identification. Using a Likert-type scale, respondents assessed key customer requirements, including taste intensity, creaminess, freshness perception, aftertaste, and overall liking. The blind testing design minimized expectation and branding effects, supporting evaluations based primarily on intrinsic product characteristics. The survey and sensory testing phases involved independent Generation Z participant groups.

3.4. Identification of Technical Characteristics and Construction of the House of Quality

Technical characteristics (HOWs) were identified based on a literature review and managerial relevance, focusing on parameters that can be controlled at the process or formulation level. The selected variables included fat content, protein content, fermentation time, culture type, viscosity, and pH. These attributes were chosen for their documented influence on sensory perception and their applicability to both conventional and plant-based yogurt-type products, forming the foundation for linking consumer requirements to actionable technical priorities within the QFD framework.

The HOQ was constructed according to standard QFD procedures, with customer requirements (WHATs) listed on the left and technical and environmental characteristics

(HOWs) along the top. Relationships between WHATs and HOWs were evaluated using a predefined scale (strong, medium, weak, none) and converted into numerical values for analytical purposes. Relationship strengths were assessed based on expert judgment informed by product information and literature. A correlation matrix (the roof of the HOQ) was included to identify positive and negative interactions among technical and environmental characteristics, thereby enabling the identification of potential trade-offs, particularly between quality performance and environmental considerations.

3.5. Prioritization and Decision Interpretation

Priority weights for technical characteristics were calculated by combining the importance weights of customer requirements with relationship scores in the HOQ matrix. These values indicate the relative importance of technical characteristics in supporting consumer satisfaction while accounting for environmental considerations. The analysis focused on identifying key quality drivers, critical technical priorities, and potential trade-offs between sensory and environmental objectives. Results were interpreted as decision priorities rather than direct product rankings.

To enhance methodological consistency, standardized conditions were applied during blind sensory evaluation and QFD construction followed established methodological procedures. The simplified cradle-to-gate LCA integrated into the framework relies on secondary inventory data obtained from published literature and publicly available environmental databases. Consequently, environmental indicators should be interpreted as comparative estimates rather than precise site-specific measurements, as environmental performance may vary across production systems and geographic contexts. Nevertheless, integrating quantitative LCA-

based indicators strengthens the evaluation of sustainability trade-offs compared with qualitative proxy approaches frequently used in comparable QFD applications.

4. Results

4.1. Identification of Customer Requirements (WHATs)

Based on the questionnaire survey, a set of key customer requirements (WHATs) was defined to capture consumer perceptions of yogurt-type products across conventional and plant-based variants. The selected attributes: taste intensity, creaminess, freshness perception, aftertaste, and overall liking represent core intrinsic quality dimensions that directly drive consumer acceptance.

Taste intensity and aftertaste reflect flavour-related expectations, while creaminess represents a critical textural attribute, particularly relevant for yogurt and yogurt alternatives. Freshness perception functions as an indicator of perceived product quality, whereas overall liking provides an integrated measure of consumer acceptance.

Although operationalized through sensory testing, the relevance of these WHATs extends beyond purely hedonic evaluation. Previous research indicates that acceptance of plant-based dairy alternatives is increasingly influenced by broader consumer attitudes toward environmental sustainability, resource efficiency, and perceived environmental impact. As a result, sensory quality remains a necessary but not sufficient condition for acceptance, reinforcing the need to align intrinsic product attributes with sustainability-oriented consumer expectations (Sabaté & Soret, 2014; Ares & Varela, 2017; Clay et al., 2020; Kumar et al., 2018).

Importance weights derived from sensory testing indicate that overall liking and taste intensity were the most influential customer requirements, followed by creaminess, while freshness perception and aftertaste showed moderate but meaningful relevance (Table 2).

Table 2. Blind sensory evaluation (n = 100, Generation Z) across conventional and plant-based yogurt variants revealed the following mean $\pm$ SD.

Attribute	Conventional Dairy	Oat-Based	Soy-Based
Taste intensity	4.5 $\pm$ 0.5	3.8 $\pm$ 0.6	4.0 $\pm$ 0.7
Creaminess	4.3 $\pm$ 0.6	3.7 $\pm$ 0.7	3.9 $\pm$ 0.6
Freshness	4.2 $\pm$ 0.5	4.0 $\pm$ 0.5	4.1 $\pm$ 0.5
Aftertaste	4.1 $\pm$ 0.6	3.6 $\pm$ 0.7	3.5 $\pm$ 0.8
Overall liking	4.6 $\pm$ 0.5	3.9 $\pm$ 0.6	4.0 $\pm$ 0.7

Collectively, these WHATs provide a structured and analytically robust representation of consumer expectations that can be systematically translated into technical priorities within the QFD framework.

Normalized importance weights derived from the sensory evaluation indicated that taste intensity and overall liking together accounted for over 50% of total importance, highlighting their dominant influence on consumer perception and their critical role in guiding managerial decision-making. These findings reinforce the prioritization of key sensory attributes within the QFD framework, ensuring that decisions on technical and environmental characteristics align with the product quality attributes most valued by consumers.

4.2. Identification of Technical Characteristics (HOWs)

Technical characteristics (HOWs) were defined as controllable compositional and process-related parameters influencing consumer-perceived quality in yogurt-type products across conventional and plant-based variants. The selected HOWs reflect intrinsic product properties relevant to sensory performance, formulation outcomes, and process control, while remaining suitable for managerial decision support.

The identified technical characteristics include fat content, protein content, fermentation time, culture type, viscosity, and

pH. These parameters represent key drivers of flavour development, texture formation, and overall sensory performance. Fat and protein content are central to mouthfeel, creaminess, and flavour intensity, while fermentation time and culture type shape acidification dynamics, aroma development, and textural consistency. pH serves as an indicator of fermentation progress and perceived freshness, and viscosity captures physical structure and creaminess perception.

Although defined as technical variables, these HOWs are directly linked to consumer acceptance. Previous research demonstrates that composition, texture, and acidity strongly mediate sensory perception and overall liking in both dairy and plant-based yogurt alternatives. Maintaining sensory quality through appropriate control of these parameters is particularly critical in plant-based formulations, where achieving parity with conventional dairy products remains a persistent challenge under evolving sustainability-oriented market conditions (Fiorentini et al., 2020; Chen & Antonelli, 2020; Gómez-Luciano et al., 2019; Schiano et al., 2020; Cardello et al., 2022; Oltman et al., 2014).

4.3. The relationship analysis within the House of Quality

The relationship analysis within the House of Quality reveals that fermentation-related parameters and product composition primarily drive overall liking and taste intensity. Fermentation time and culture type show strong relationships with multiple

customer requirements, indicating their central role in flavour development, aftertaste formation, and overall sensory acceptance across both dairy and plant-based yogurt-type products.

Fat and protein content emerge as critical drivers of creaminess and overall liking, confirming their importance in shaping mouthfeel and perceived product quality. This relationship is particularly relevant for plant-based alternatives, where structural differences from conventional dairy products necessitate careful formulation to achieve comparable sensory performance.

Freshness perception is most strongly associated with pH, highlighting the importance of acidification control and fermentation outcomes in consumer quality evaluation. In contrast, viscosity shows a strong relationship primarily with creaminess, while its influence on other sensory attributes remains limited, suggesting that texture alone is insufficient to drive overall acceptance without complementary flavour development (Table 3).

Overall, the results indicate that fermentation-related parameters and macronutrient composition represent the most influential technical characteristics in supporting consumer requirements. Of particular significance is the high-stakes trade-off between fat content, which strongly enhances taste intensity and creaminess, and carbon footprint, where increasing fat content—especially through dairy ingredients—directly elevates the product's environmental impact.

Table 3. Relationship Matrix between WHATs and HOWs

Customer Requirements (WHATs)	Fat content	Protein content	Fermentation time	Culture type	Viscosity	pH
Taste intensity	Strong	Medium	Strong	Strong	Weak	Medium
Creaminess	Strong	Strong	Medium	Medium	Strong	Weak
Freshness perception	Weak	Weak	Medium	Medium	Weak	Strong
Aftertaste	Medium	Medium	Strong	Strong	Weak	Medium
Overall liking	Strong	Strong	Strong	Strong	Medium	Medium

* Strong = 9, Medium = 3, Weak = 1

By explicitly highlighting this make-or-break tension between maximizing sensory appeal and minimizing carbon footprint, the analysis provides a concrete example of how QFD can surface the most consequential dilemmas for product development teams. The identified relationship patterns also reveal potential trade-offs between sensory optimization and process control, particularly in environmentally oriented product development, where formulation flexibility may be constrained. These findings demonstrate how QFD facilitates the prioritization of technical decision variables based on consumer-driven quality requirements rather than isolated sensory optimization.

These relationship patterns provide a basis for prioritizing technical and managerial decisions in the development of environmentally oriented yogurt-type products, as further discussed in the following section.

4.4. Interpretation of QFD Results from a Decision Support Perspective

The results of the blind sensory evaluation clearly indicate that taste intensity represents the most influential customer requirement in the assessment of yogurt-type products, followed by overall liking and creaminess. This finding is consistent across conventional and plant-based variants and confirms that flavour-related perceptions remain the primary driver of consumer acceptance, even within sustainability-oriented product categories.

When translated into the House of Quality, taste intensity exhibits the strongest relationships with fermentation time and culture type, positioning these process-related parameters as the most critical technical characteristics within the decision matrix. Unlike compositional attributes such as fat or protein content, fermentation-related variables offer a high degree of managerial controllability without necessarily increasing material inputs or compromising

environmental objectives. From a decision support standpoint, this highlights fermentation as a strategic lever rather than a purely technological parameter.

The correlation analysis in the roof of the HOQ provides a nuanced view of how technical and environmental characteristics interact within the decision framework. Positive correlations among fermentation time, culture type, and flavour development highlight synergistic opportunities, demonstrating that process parameters can be strategically managed to efficiently enhance sensory quality. In contrast, negative correlations between fat content and certain environmental considerations reveal trade-offs, indicating that compositional intensification to improve sensory attributes may compromise sustainability objectives (Table 4).

Table 4. Correlation analysis - relationships between HOWs and WHATs

WHAT	Strongest HOW Links
Taste intensity	Fermentation time, Culture type
Creaminess	Fat content, Viscosity
Freshness	pH, Fermentation control
Aftertaste	Culture type, Fermentation time
Overall liking	Combined effects of all HOWs

The grayscale HOQ matrix clearly visualizes the relationships between customer requirements (WHATs) and technical characteristics (HOWs) for both conventional and plant-based yogurt products. Darker cells denote stronger associations, lighter cells eaker connections, and white cells minimal or no impact. Fermentation time, fat content, and viscosity emerge as the most influential technical attributes in meeting key sensory expectations—taste intensity, creaminess, freshness perception, aftertaste, and overall liking—while reflecting environmental priorities. The correlation roof further supports identification of trade-offs, providing actionable insights for managerial decision-making.

Notably, the QFD results do not prescribe specific formulation adjustments. Rather, they establish a structured prioritization framework that guides managers to focus on technical and process parameters, balancing consumer satisfaction with environmental considerations. For example, if QFD prioritization indicates that viscosity strongly influences overall liking and creaminess, a manager could initiate a pilot run, adjusting the stabilizer amount in a plant-based yogurt to achieve the target viscosity while reviewing the environmental impact of each formulation option. By observing changes in consumer acceptance and environmental proxies before scaling up, the manager can make informed product development decisions that tangibly reflect QFD findings. Plant-based yogurt alternatives serve as an illustrative decision context, demonstrating how sustainability can be integrated into quality management without compromising consumer-perceived quality. By translating consumer requirements into actionable priorities and highlighting trade-offs, the HOQ demonstrates how QFD functions as a strategic decision-support tool, enabling informed managerial choices that align product development with both quality and sustainability objectives (Figure 1).

4.5. Prioritization Results and Managerial Interpretation

The prioritization of technical characteristics was derived by integrating normalized customer requirement weights with relationship intensities in the House of Quality. This approach enables the identification of technical parameters that exert the greatest influence on consumer-perceived quality and provides a structured basis for decision-making in environmentally oriented food product contexts.

The results indicate that viscosity, fat content, and fermentation time represent the most influential technical characteristics. Viscosity achieved the highest priority due to its strong relationships with creaminess and overall

liking, confirming its central role in shaping perceived quality across both conventional and plant-based yogurt-type products. Fat content was identified as a key determinant of taste intensity and mouthfeel; however, its prioritization also highlights a potential trade-off, as adjustments to fat content may entail environmental and formulation constraints in plant-based alternatives. Fermentation time emerged as a critical process-related parameter, influencing taste intensity, freshness perception, and aftertaste, thereby emphasizing the importance of process control as a quality management lever.

To operationalize these priorities, managers may conduct targeted pilot experiments focused on viscosity adjustment. For instance, varying the proportion of stabilizers, such as pectin or guar gum, in small batches of plant-based yogurt can help assess their impact on creaminess and overall liking among a sample group. Additional adjustments may involve modifying homogenization conditions or blending times to observe changes in texture. Rapid sensory evaluation of these pilot batches enables data-driven decision-making and helps managers identify optimal viscosity targets before scaling up product development. This approach establishes a practical link between QFD-derived priorities and actionable improvements in product formulation.

Protein content and culture type exhibited moderate priority, reflecting their targeted influence on specific sensory attributes rather than a broad impact on overall acceptance. In contrast, pH had a lower priority, suggesting it serves as an operational control indicator rather than a strategic decision variable within the QFD framework.

Overall, the findings indicate that consumer acceptance is driven by the interaction of multiple compositional and process-related characteristics rather than by isolated technical parameters. The QFD-based prioritization thus supports its application as a decision-support framework, enabling the systematic identification of critical quality drivers and trade-offs and providing

managers with actionable insights for aligning product development with both sensory expectations and sustainability objectives.

			⊕			⊕⊕	⊖		
				⊕	⊕	⊕			
					⊕⊕	⊕	⊖⊖		
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Customer requirements	Wt. (%)	Fat content	Protein content	Fermentation time	Culture type	Viscosity	pH	Abs. score	Rank
Optimization direction		▲	▲	●	●	▲	●		
Taste intensity	26	●	○	●	●	△	○		
Creaminess	20	●	●	○	○	●	△		
Freshness perception	14	△	△	○	○	△	●		
Aftertaste	12	○	○	●	●	△	○		
Overall liking	28	●	●	●	●	○	○		
Absolute importance		7.16	5.60	6.96	6.96	3.16	3.44		
Relative importance (%)		21.5	16.8	20.9	20.9	9.5	10.3		
Priority rank		1	4	2	2	6	5		

Environmental Performance Benchmarking — Cradle-to-gate LCA (functional unit: 100 g finished product)

Environmental indicator	Conventional dairy yogurt	Oat-based yogurt	Soy-based yogurt
GHG emissions (kg CO ₂ -eq)	0.27	0.09	0.11
Water consumption (L)	85.0	6.0	22.0
Land use (m ² /year eq.)	0.19	0.04	0.06
Energy demand (MJ)	0.62	0.24	0.31

Key trade-off identified: Fat content exhibits strong positive relationships with taste intensity, creaminess, and overall liking (HOQ), yet corresponds directly to the highest environmental burden across all LCA indicators — representing the central managerial dilemma in plant-based product reformulation.

Relationship symbols: ● Strong (9) ○ Medium (3) △ Weak (1) | Correlations: ⊕⊕ Strong positive ⊕ Positive ⊖ Negative
⊖⊖ Strong negative | Directions: ▲ Maximize · ● Target value

Figure 1. House of Quality (HOQ) Matrix for Yogurt-Type Products

5. Discussion

An analysis of recent trends in European milk production and dairy product output shows a generally stable upward movement in raw milk volumes delivered to dairies over the past decade. Total milk production in the European Union reached an estimated 160.8 million tonnes in 2023, increasing to approximately 161.8 million tonnes in 2024, reflecting continued growth in the dairy supply chain (Eurostat, 2025). Most of this production is processed into a range of dairy products, including drinking milk, acidified products such as yoghurt, cheese, and butter, illustrating both the scale and diversity of consumption patterns within the EU market (Clegg et al., 2021). These consumption patterns are further influenced by nutritional considerations, with comparative assessments highlighting differences between conventional dairy and plant-based alternatives (Clegg et al., 2021; Sethi et al., 2016). The emergence of plant-based dairy alternatives has been shaped by health, sustainability, and sociopolitical factors, creating new market opportunities (Sethi et al., 2016; Clay et al., 2020). Consumer perceptions of sustainability also play a key role in shaping preferences, with many opting for plant-based substitutes as environmental awareness increases (Schiano et al., 2020; Haas et al., 2019). These dynamics underscore not only the sustained importance of conventional milk and dairy products in European diets but also the growing relevance of plant-based alternatives in response to evolving consumer demand and sustainability considerations (McCarthy et al., 2017).

Consumption trends indicate increasing demand for plant-based alternatives, motivating the need for structured, quality-oriented product development. Dietary shifts toward plant-based foods are increasingly recognized as critical for achieving environmental sustainability and meeting evolving consumer preferences, as such changes can minimize environmental impacts while supporting health and ethical objectives

(Springmann et al., 2018). Similarly, dietary transitions toward plant-based foods can substantially reduce greenhouse gas emissions, land use, and water consumption, reflecting the growing market demand for plant-based alternatives driven by health and environmental concerns (Aleksandrowicz et al., 2016). Innovations in this sector are essential to address the challenges posed by plant-based diets and meet the needs of health-conscious consumers (Alcorta et al., 2021). Global shifts toward plant-based consumption are increasingly recognized as necessary to combat malnutrition and enhance sustainability within future agri-food systems (Ferreira et al., 2021). Emerging themes in alternative proteins indicate that sustainable meat and milk alternatives are becoming more aligned with ethical and health-driven consumer preferences (Lonkila & Kaljonen, 2021). Moreover, modelling studies suggest that transitioning to plant-based diets can significantly lower carbon footprints compared to traditional meat-heavy diets, highlighting both the feasibility and necessity of these changes (Aidoo et al., 2023). Collectively, these findings substantiate that the rising consumer interest in plant-based alternatives necessitates structured product development approaches that integrate quality and sustainability considerations across food systems.

Market dynamics in the dairy sector are increasingly influenced by structural changes in production, trade, and consumption patterns, shaping the strategic context for food product development. International trade dynamics and competitive pressures, such as dairy imports, can affect raw milk production and market stability; however, these factors alone provide limited insight into the growing consumer interest in alternative products (Bai et al., 2022). Recent research suggests that shifts in consumer demand are driven primarily by changing expectations related to health, sustainability, and product attributes rather than by supply-side or trade-related mechanisms alone (Setiawan & Romulo, 2024). As a result,

conventional market analyses often fail to support product-level decision-making when environmentally oriented food alternatives are considered. This highlights the need for structured decision-support approaches that systematically integrate consumer requirements with technical and managerial considerations. In this context, QFD can be used as a structured decision support tool to guide the development of environmentally oriented food products while maintaining quality performance.

The results of this study demonstrate that taste intensity and overall liking are the most critical drivers of consumer acceptance for both conventional and plant-based yogurt-type products, consistent with prior research highlighting the importance of flavour and mouthfeel in shaping consumer preferences (Fiorentini et al., 2020; Gómez-Luciano et al., 2019). Fermentation time emerged as the key controllable technical factor, strongly influencing taste, creaminess, and aftertaste, while other attributes, such as fat and protein content and viscosity, exerted moderate effects. The correlations identified within the House of Quality, including minor trade-offs between fermentation and viscosity, underscore the need for managers to balance sensory quality with process and environmental considerations in product development.

The study underscores the broader applicability of QFD as a structured decision support tool beyond traditional product optimization. By integrating customer requirements, technical characteristics, and environmental proxies, the extended House of Quality enables managers to prioritize attributes that simultaneously enhance consumer satisfaction and address sustainability objectives. This approach aligns with prior literature advocating for the strategic deployment of QFD in managerial decision-making and sustainable product innovation (Akao & Mazur, 2003; Setiawan & Romulo, 2024).

In the context of plant-based product development, the findings suggest that QFD can effectively guide managerial choices without compromising sensory quality, which is particularly important given the growing consumer demand for environmentally sustainable alternatives (Springmann et al., 2018; Aleksandrowicz et al., 2016; Aidoo et al., 2023). By providing a structured framework for evaluating trade-offs among technical parameters, sensory attributes, and sustainability considerations, QFD facilitates informed decision-making in the development of plant-based and other environmentally conscious food products.

The study also highlights opportunities to broaden the application of QFD in product development across food categories, particularly where environmental objectives intersect with consumer preferences. From a managerial perspective, a critical unanswered question remains: How can decision-makers accurately assess and mitigate the risk of misalignment between quality improvement efforts and environmental objectives in real time? Future research should prioritize addressing this decision risk, since its resolution could fundamentally alter managerial choices regarding investments in sustainable product development. Specifically, identifying which quality or environmental factors introduce the greatest uncertainty or trade-off potential into decision-making processes would provide more targeted and actionable guidance. In addition to this central gap, future studies could extend the framework by incorporating quantitative environmental impact metrics, larger and more diverse consumer samples, and additional product types, thereby enhancing the robustness and generalizability of the approach.

Several limitations of the present study warrant explicit acknowledgement. First, although a simplified cradle-to-gate LCA was incorporated to move beyond purely qualitative environmental proxies, the assessment relied on secondary inventory data derived from published literature and

publicly available databases rather than primary production-specific data. Consequently, the environmental indicators integrated into the House of Quality should be interpreted as comparative reference values rather than precise site-specific impact measurements. A full attributional LCA employing primary inventory data would provide greater accuracy and would further strengthen the robustness of sustainability-related conclusions.

Second, the consumer sample was deliberately restricted to Generation Z, a cohort selected for its documented sensitivity to sustainability narratives and openness to plant-based dietary alternatives. While this focus is methodologically justified within the study's scope, it limits the generalizability of the importance weights assigned to customer requirements. Consumers from older cohorts may prioritize different sensory attributes — such as protein content, price-quality ratio, or familiarity — potentially yielding divergent HOQ prioritization outcomes. Future research employing stratified multi-generational samples would allow testing of whether QFD-derived prioritization structures remain stable across demographic segments or whether cohort-specific House of Quality matrices are warranted.

The external validity of the present framework extends beyond yogurt-type products, as the underlying QFD logic is structurally generalizable to any food development context in which consumer-derived sensory requirements must be systematically reconciled with quantifiable environmental constraints. Three product categories represent particularly promising candidates for subsequent validation. First, plant-based beverages — including oat milk, soy milk, and almond-based alternatives share an analogous decision structure, wherein compositional parameters such as fat emulsification, protein stabilization, and flavour masking interact directly with supply-chain environmental footprints that differ substantially across raw material origins. Second, fermented vegetable products such

as plant-based kefir, kombucha variants, and lacto-fermented functional foods exhibit the same fermentation-driven process parameters (fermentation time, culture composition, and pH dynamics) that emerged as strategically critical in the present HOQ, suggesting that the framework's prioritization logic would transfer with minimal structural modification. Third, functional dairy alternatives — including probiotic drinking yogurts and high-protein fortified products — introduce additional trade-offs between bioactive ingredient integrity and processing intensity that the extended HOQ, augmented with LCA-based environmental indicators, is well-positioned to surface and systematically evaluate. Testing the framework across these categories would not only confirm its scalability but would also allow cross-category comparison of HOW prioritization patterns, contributing to a more generalizable evidence base for sustainability-oriented food product development.

Third, the empirical focus on yogurt-type products, while analytically appropriate for demonstrating trade-offs between sensory quality and environmental performance, constrains direct extrapolation to other food categories. The framework's transferability is, however, supported by the structural generality of the QFD methodology itself. Product categories sharing analogous decision contexts — such as plant-based beverages, fermented vegetable products, or functional dairy alternatives — represent natural candidates for subsequent validation studies.

The integration of quantitative environmental indicators revealed potential tensions between sensory optimization and sustainability objectives. While dairy formulations achieved stronger performance in selected sensory attributes, plant-based alternatives demonstrated lower estimated environmental burdens, highlighting the importance of balancing consumer expectations with sustainability-oriented product development priorities.

Finally, this study is positioned as a proof-of-concept demonstration of the extended QFD framework. In accordance with established norms for framework development research, empirical validation in real industrial decision-making contexts constitutes a distinct subsequent phase rather than a prerequisite for framework contribution. Future research should therefore prioritize industrial validation studies to confirm the practical effectiveness and managerial value of the proposed approach. Integration with advanced analytical methods — including fuzzy MCDM, multi-expert Delphi procedures for HOQ relationship scoring, and optimization or machine learning techniques — represents a further avenue for enhancing the analytical power and methodological robustness of QFD-based decision support in sustainable food product development.

6. Conclusion

This study demonstrates that QFD is an effective decision-support tool for environmentally oriented food product development. Results from blind sensory testing of conventional and plant-based yogurt variants identified taste intensity and overall liking as the primary drivers of consumer acceptance, with fermentation time emerging as a critical controllable factor. The extended House of Quality framework highlights the interplay among technical

parameters, sensory quality, and environmental considerations, providing managers with structured guidance for prioritizing attributes that align with consumer satisfaction and sustainability objectives. These findings underscore QFD's broader applicability beyond product optimization, offering a systematic approach for informed decision-making in the development of plant-based and other environmentally conscious food products.

Based on these findings, managers are advised to: (1) prioritize the adjustment of fermentation processes to enhance key sensory attributes without significantly increasing environmental impacts; (2) routinely integrate consumer sensory data with environmental proxy measures when constructing the House of Quality for new products; and (3) initiate small-scale pilot projects that apply QFD-based prioritization to develop or refine product lines, enabling rapid feedback on the impact of technical and environmental trade-offs. Implementing these actions can ensure that product development strategies are not only consumer-driven but also aligned with broader sustainability goals. The integration of quantitative environmental indicators within the House of Quality further supports the identification of trade-offs between sensory quality, technical performance, and environmental impacts in sustainable food product development contexts.

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