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Metodología integrada para el diseño de productos incluyendo criterios de sostenibilidad y los requerimientos de la cadena de valor del aceite de palma

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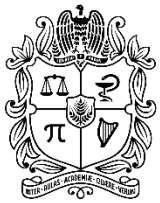
Facultad de Ingeniería, Departamento de Ingeniería Química y Ambiental

Bogotá, Colombia

2023



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Master dissertation presented as a partial requirement for the degree of:

Master of Engineering – Chemical Engineering

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Research groups:

Grupo de Investigación en Procesos Químicos y Bioquímicos

Équipe de Recherche sur les Processus Innovatifs - ERPI

Universidad Nacional de Colombia

Facultad de Ingeniería, Departamento de Ingeniería Química y Ambiental

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2023

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Fecha: 01/08/2023

Abstract

The decision-making process for the design of chemical products is a key activity to increase its acceptance in the market and to enhance its sustainability performance. For this, it is important to consider not only the preferences of the consumers but also the requirements of the supply chain, which are not taken into account in existing design methodologies. Therefore, this study presents a methodology to support the product design process considering the requirements of the supply chain. The methodology is implemented in 2 phases: a diagnostic phase of the supply chain where different stakeholders are interviewed to know their limitations; and a product design phase, where a workshop is developed including the identified limitations in the design problem. The methodology was tested in a case study: the design of chemical products from the palm oil supply chain. Palm oil is the highest vegetable oil productivity but it is in the spotlight because of its implications for environmental and social issues. The diagnostic phase involved the participation of 8 different stakeholders of the palm oil supply chain who were interviewed individually through semi-structured interviews of one hour. The information was systematically analyzed using qualitative methods. The second phase design workshop was conducted with three focus groups, two with chemical engineering students and one with expert product designers from a Latin American food company. The groups were asked to select between different surfactants (some of them based on palm oil) to create a vegetable milk drink; at first, without considering the limitations of the supply chain, and at a second time, considering them. The results of the first phase showed that the main requirements of the supply chain according to the interviewed stakeholders are the last of integration between the actors of the supply chain (overall in relation to the last stages when final products are developed), the dependency to the oil suppliers and the possible biodiesel/food competition, and the supply chain's lack of capacity to adapt to changes. When this information was used for the product design workshop, the two groups of students modified their design decision when they considered the supply chain limitations.

By their part, experienced designers did not modify their design, but they found that this type of analysis could be relevant for other products, for example those as the margarines with have a high oil content.

Keywords: Design methodology, Supply Chain, Value Chain, Sustainability, Chemical product design, Palm oil.

Resumen

El proceso de toma de decisiones para el diseño de productos químicos es una actividad clave para aumentar su aceptación en el mercado y mejorar su rendimiento en materia de sostenibilidad. Para ello, es importante tener en cuenta no sólo las preferencias de los consumidores, sino también los requisitos de la cadena de suministro, que no se tienen en cuenta en las metodologías de diseño existentes. Por lo tanto, este estudio presenta una metodología para apoyar el proceso de diseño de productos teniendo en cuenta los requisitos de la cadena de suministro. La metodología se implementa en 2 fases: una fase de diagnóstico de la cadena de suministro, en la que se entrevista a las diferentes partes interesadas para conocer sus limitaciones; y una fase de diseño del producto, en la que se desarrolla un taller que incluye las limitaciones identificadas en el problema de diseño. La metodología se puso a prueba en un estudio de caso: el diseño de productos químicos a partir de la cadena de suministro del aceite de palma. El aceite de palma es el aceite vegetal de mayor productividad, pero está en el punto de mira por sus implicaciones en cuestiones medioambientales y sociales. La fase de diagnóstico contó con la participación de 8 partes interesadas diferentes de la cadena de suministro del aceite de palma. Fueron entrevistadas individualmente mediante entrevistas semiestructuradas de una hora de duración. La información se analizó sistemáticamente utilizando métodos cualitativos. La segunda fase del taller de diseño se llevó a cabo con tres grupos focales, dos con estudiantes de ingeniería química y uno con diseñadores de productos expertos de una empresa latinoamericana de productos alimenticios. Se pidió a los grupos que seleccionaran entre distintos tensioactivos (algunos de ellos a base de aceite de palma) para crear una bebida no láctea de origen vegetal; en un primer momento, sin tener en cuenta las limitaciones de la cadena de suministro, y en un segundo, teniéndolas en cuenta. Los resultados de la primera fase mostraron que los principales requisitos de la

cadena de suministro según las partes interesadas entrevistadas son la falta de integración entre los actores de la cadena de suministro (sobre todo en relación con las últimas fases en las que se desarrollan los productos finales), la dependencia de los proveedores de aceite y la posible competencia entre biodiésel y alimentos, y la falta de capacidad de la cadena de suministro para adaptarse a los cambios. Cuando se utilizó esta información para el taller de diseño del producto, los dos grupos de estudiantes modificaron su decisión de diseño al considerar las limitaciones de la cadena de suministro. Por su parte, los diseñadores experimentados no modificaron su diseño, pero descubrieron que este tipo de análisis podría ser relevante para otros productos, por ejemplo, aquellos como las margarinas con alto contenido en aceite.

Palabras claves: Metodología de diseño, Cadena de suministros, Cadena de valor, Sostenibilidad, Diseño de productos químicos, Aceite de palma.

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Introduction

1.1 General Context

Product design and development is the basis of our technological society. It drives growth, innovation, and prosperity. Nevertheless, within the field of chemical engineering, product design presents its own set of opportunities and challenges. On one hand, chemical products have the potential of creating value for the customer, the companies that developed it and also for all the stakeholders that participate directly or indirectly in their creation. On the other hand, the design of chemical products requires the comprehension of the complexities of chemical interactions to adhering to stringent safety and environmental standards. Moreover, products design as any other human activity should be oriented towards sustainability, creating social, environmental and economic value (Argoti et al., 2019).

Several authors have proposed different methodologies for chemical product design (Bernardo & Saraiva, 2005)(Gani & Ng, 2015)(Kontogeorgis et al., 2022). For example, Cussler and Muggeridge proposed a product design methodology comprising four design stage: needs identification, product ideas generation, best idea selection and process design (E. L. Cussler & Moggridge, 2011). Some authors have complemented that methodology by implementing sustainability assessment. For example, Heintz proposed a framework for molecular design considering sustainability indicators (Heintz, 2012); Narvaez-Rincon et al. proposed sustainability indicators for the design of formulated products at early design stages based on the Globally Harmonized System of Classification and Labelling of Chemicals (Narváez Rincón et al., 2020). Previous systems only considered chemical nature of products and their virtual environmental effects but do not take into account the real context of the products.

The implementation of sustainability requires evaluating a product's environmental and social effects within its full real context. This context includes the geographical environment

and the interconnected network of actors that enables production (Voinov & Bousquet, 2010)(Fritz et al., 2018). Actors are economically, socially, and geographically organized in supply chains (Roth et al., 2021). The 'supply chain' concept defines the intricate network comprising organizations, individuals, and stakeholders that collaboratively contribute to the production and delivery of a product (Marche et al., 2017). All the activities developed by the actors of the supply chain constitute the value chain. This includes all product life cycle activities from the collection of raw materials to their initial transformation, distribution, and finally, the delivery of the finished product to consumers (Marche et al., 2017).

Therefore, the transition towards sustainability-centric design is not an isolated process only related to the final transformation (Eddy et al., 2013). It is deeply intertwined with the broader value chain that encompasses not just the design, but also the extraction of raw materials, production, distribution, consumer usage, and disposal (Hellin & Meijer, 2006). This integration adds a layer of complexity to the design process. The challenge lies in aligning supply chain requirements with product design fulfilling the requirements of all stakeholders involved. This is why we need a design methodology capable of listening to the voice of customers but also to the voice of stakeholders and other actors in the supply chain, in order to create a product with a high social value and therefore more sustainable.

For the active inclusion of stakeholders, Roth et al. (2021) proposed the implementation of participatory workshops. The inclusion of the point of view of different stakeholders enables designers to incorporate the social dimension in the analysis of the problem. Moreover, the application of interactive workshops that focus on framing and co-modeling difficulties, as well as including stakeholder representation as active agents inside the model, serves to encompass a diverse range of objectives and perspectives. This study is inspired by the proposal of Roth et al. (2021) and Marche et al. (2019) and proposed a chemical product design methodology that explicitly integrates the voices of the stakeholders. The aim is to understand the explicit requirements and underlying intentions of stakeholders in entire the supply chain, reason why information will be collected from stakeholders in different parts of the supply chain and qualitative methods will be used to analyze the collected data.

Qualitative research is an effective analysis method, especially when investigating subjective and nonnumerical data. According to Mertler (2018), this approach provides profound insights across a variety of disciplines, such as market trends and product design. It performs well in the field of chemical product design, where it has the potential to reveal

hidden consumer preferences and unmet requirements that quantitative research might miss. Such insights can guide the creation of innovative products or the improvement of existing ones (Berger et al., 2023). The strength of qualitative research is its ability to provide an in-depth comprehension of stakeholders' perceptions. This enhanced comprehension may reveal areas suitable for advancement, thereby presenting new opportunities for the design of chemical products (Mertler, 2018).

The integration of supply chain requirements for the design of products may have important impacts in real-world scenarios such as the production of palm oil, a significant source of vegetable oils worldwide (FAO, 2021), the application of those methodologies may generate a more social inclusive and sustainable path within the chemical industry. Palm oil has prospered in countries like Colombia, where land and climate conditions are favorable for its cultivation. According to Mohd et al. (2005), Colombia produced 1.65 million tons of palm oil in 2020, making it the fastest growing crop in the country. Moreover, on a global scale, the country is the fourth-largest producer, accounting for 2.16 percent of the total global output (Minagricultura, 2020).

Thanks to its composition, palm oil has many and varied applications in different industries, including foods, feed, fuels, cosmetics, personal care, home care, paints, and coatings, etc. As a result, the demand for palm oil is rising quickly worldwide (Lipsa, 2018). Governments in palm oil producing countries have encouraged its growth because they recognize its potential for promoting rural development and employment. However, consumer markets in industrialized countries, are becoming more concerned about the social and environmental issues connected with the production of palm oil (Ávila & Albuquerque, 2018).

As a result, there have been significant discussions over the advantages and disadvantages of oil palm farming among producing countries. Various voluntary and market-based sustainability standards have also been developed as a means of reducing some of the adverse effects (Cárdenas González, 2016). As example, the Roundtable on Sustainable Palm Oil (RSPO), which was founded by the major world's palm oil producers (who are also important consumers of palm oil), responsible for the Certified Sustainable Palm Oil (CSPO) (WWF, 2012). However, the discussion to achieve a sustainable production of palm oil and its derivatives is still open and requires actions from all actors in

the supply chain, including the producers of final chemical products, who are specifically targeted by the application of the methodology proposed in this document.

1.2 Research scope and associated problems

The scope of this study focuses on the integration of the actors of the supply chain in the product design process to improve their sustainability performance, especially in the social dimension. The palm oil supply chain in Colombia was selected as a case study, because of its inherent complexity and significant implications for environmental and social sustainability (Ávila & Albuquerque, 2018). The consideration of the requirements of the supply chain has the potential of minimizing the environmental and social impacts of its products, as well as promoting ethical and fair labor practices (Boons & Mendoza, 2010). Current palm oil supply chain has limitations as, for example, the frequently poor communication among its actors regarding a particular product or group of products (Mosquera & Lopez, 2017). In response to this, the incorporation of the requirements of stakeholders has the potential of creating more comprehensive and sustainable products and transforming the supply chain so it benefits all the involved actors (Burgess & Sunmola, 2021).This approach may be interesting not only for the supply chains, but also for the companies that compose them, whose environmental and social responsibility is increasingly analyzed. Thus, implementing supply chain requirements into the design process could allow companies to demonstrate their commitment to sustainability and social responsibility in a practical way. Moreover, this strategic approach may help companies to meet market demands and customer expectations in a sustainable manner, enhancing its reputation and providing a potential competitive advantage (Chiriacò et al., 2022).

Considering the above, this work addresses the following research question:

How to design palm oil derived products considering sustainability criteria and value chain requirements?

The hypothesis statement responding this question is the following:

Product design implies changes in its supply chain and vice versa. Product design from a systemic point of view must be done considering the possible effects on its supply chain. Within this framework, product designers will be able to have a complete understanding of the entire palm oil process and the criteria they should consider for designing sustainable products if they use a design methodology based on the analysis of the supply chain requirements. As a result, product designers will have global information on the product/supply chain system to support decision-making during the design phase.

1.3 Research Objectives

The methodology should contain methods to understand the current context of the supply chain and integrate this context into the decision-making process of product designers. The methodology should in a first step analyze the sustainability performance of the supply chain; and it should in a second step indicate how designers can apply the information from the supply chain in order to improve their decision-making process.

Considering the above, this research proposes the following general objective:

To propose a methodology applicable to the design of palm oil products that includes the principles of sustainability and the requirements of its value chain.

The specific objectives of the research are:

Objective 1: To develop a conceptual framework for sustainability concepts, criteria, and indicators that can be applied to product design while taking the palm oil value chain into consideration.

Objective 2: To complete the product design methodology proposed by the Chemical and Biochemical Process Design Group and the ERPI laboratory for considering the requirements of the value chain into account.

Objective 3: To apply the conceptual framework and design process to a case study that corresponds to the creation of a product made from palm oil.

Through the examination of key concepts and criteria in sustainability, as well as the incorporation of supply chain considerations, our research endeavors to offer a systematic and informed approach to designing in palm oil as study case. Furthermore, this work strives to complement existing product design methodologies proposed by the Chemical and Biochemical Process Design Group and the ERPI laboratory by aligning them with the specific requirements of the supply chain. By applying this methodology to a practical case study, we seek to demonstrate its effectiveness and relevance in guiding sustainable product design decisions. **Figure 2-1** shows the general research methodology implemented in this work. The development of this study considers four main steps: 1) Literature research, 2) Development of the methodology 3) Testing of the methodology and 4) application.

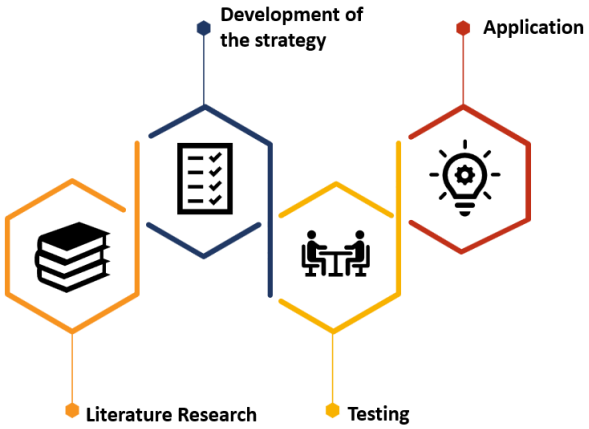


Figure 2-1. Outline of the research methodology

The purpose of the literature research is to review the state of the art of supply chain and chemical product design methodologies. Additionally, qualitative analysis methods will be reviewed to understand and include the voice of stakeholders in the product design process.

Once the conceptual framework is defined, a methodology for product design including the requirements of the supply chain will be proposed. For this, methods for information collection and analysis are proposed and tested in a case study. To obtain information from stakeholders, and because it is difficult to coordinate a meeting with all of them, individual

information gathering methods such as interviews are preferred. To implement stakeholder information in a product design exercise, design workshops are preferred to achieve a dynamic activity and enhance the exchange of opinion among designers.

The proposed methodology is initially tested with a reference group of students and then with real members of the palm oil supply chain. This enables a first evaluation of the methodology to identify unclear aspects of the participant. In a second time, the methodology is tested with the actual stakeholders of the palm oil value chain.

The general structure of the document is presented in the **Figure 2-2**.

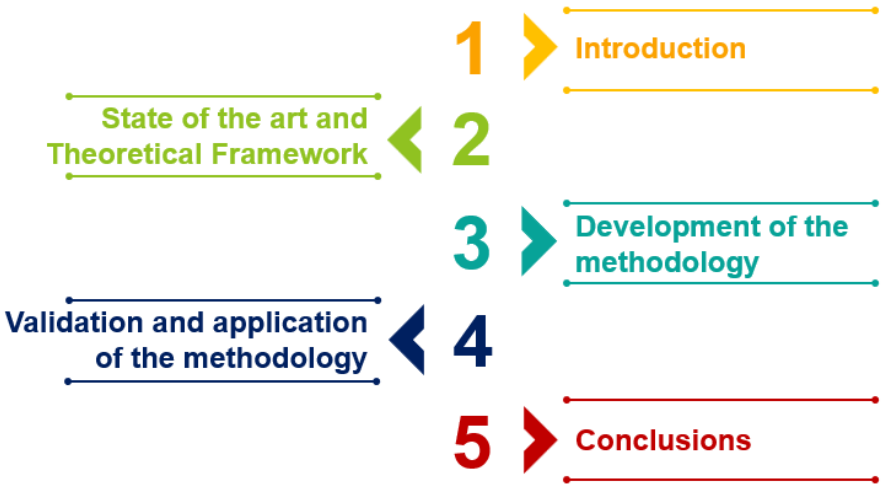


Figure 2-2. Structure of the document

The document is divided in five chapters. Chapter 1 introduces and presents the general context of the research, the scope, and the contribution. Chapter 2 presents the analysis of the state of art considering two aspects: the literature that relates to the topics: product design, sustainability criteria and supply chain requirements, and the specific theoretical framework of the qualitative analysis. Chapter 3 explains the design methodology which has two parts: 1) the diagnosis based on a literature review and a qualitative analysis of interviews with key supply chain stakeholders, and 2) the design workshop where designers integrate the results of the diagnosis during the design process. Chapter 4 shows the results of the application of the design methodology to the case study. This was done in two steps:

First it was applied with the help of students and then with the real stakeholders. Finally, chapter 5, presents the general conclusions of this work, as well as the perspectives.

2. State of art and Theoretical Framework

This chapter explores the state of the art for proposing the intended design methodology of this study. The chapter begins with a background of chemical product design followed by the research group's previous work on chemical product design and supply chain design. On that basis, a literature review is carried out to learn about the advances made in the field of chemical product design in the integration of the supply chain in the decision-making process. After examining the current state of the art, a theoretical framework on methods of information acquisition and qualitative analysis to be applied for the study of the supply chain is examined.

2.1 Chemical product design

Chemical product design stands at the forefront of modern industrial innovation, playing a vital role in shaping and revolutionizing various sectors (Zuin, 2016). From the pharmaceutical industry's life-saving medications to the personal care products that enrich our daily lives, and from the agrochemicals that bolster agricultural productivity to the consumer goods that fill our homes, chemical products permeate countless aspects of our daily existence (Lu & Xu, 2013)(Matos & Hall, 2007). With ever-increasing consumer demands, stringent regulatory requirements, and a growing emphasis on environmental sustainability, the field of chemical product design has evolved to meet the challenges of a rapidly changing world (Gani, 2004a)(B. V. Smith & Ierapepritou, 2010)(Rivera Gil et al., 2022a). With an emphasis on sustainability and environmental responsibility, chemical product design has evolved to prioritize resource efficiency, waste reduction, and the use of eco-friendly materials (Heintz et al., 2014). Innovations in green chemistry, biodegradable materials, and renewable resources have become integral to the design process (Zuin, 2016). Additionally, the growing influence of digital technologies, such as artificial intelligence and computational modeling, has opened new avenues for product optimization and rapid prototyping (Gani, 2004b)(Kalakul et al., 2016)(Frutiger et al., 2017).

Traditional chemical product design principles have long served as the cornerstone of product development in the chemical industry (B. V. Smith & Ierapepritou, 2010). These principles, rooted in fundamental chemical engineering concepts, aim to create products that meet specific performance criteria, while considering factors such as safety, cost-effectiveness, and environmental impact (Cisternas & Gálvez, 2006)(Kavanagh & Lant, 2006). Historically, chemical product design relied on empirical methods and trial-and-error approaches, driven by the knowledge and experience of chemists and engineers (Seider et al., 2009). However, with advancements in technology and the growing demand for sustainable and environmentally friendly solutions, traditional design principles have evolved to encompass a more systematic and interdisciplinary approach (Lai et al., 2017; Mattei et al., 2012). This evolution has led to the integration of principles from fields such as green chemistry, process engineering, materials science, and life cycle analysis (Allen & Shonnard, 2001; Zuin, 2016). In this context, understanding the foundations of traditional chemical product design principles is crucial as it lays the groundwork for embracing modern methodologies and enabling the development of innovative and eco-conscious products for a rapidly changing world (Charpentier, 2010).

As mentioned in the introduction over the last few years, different methodologies and tools have been proposed to guide the chemical product design process. In that respect, (B. V. Smith & Ierapepritou, 2010) discusses the changing landscape of the chemical industry, which is transitioning from producing bulk chemicals to more complex specialty chemicals and consumer products. This shift necessitates new approaches to product design, as the traditional focus on molecular structure-property relationships for basic chemicals is no longer adequate for handling the complexities of structured and configured products. Current industry practices show limited integration, necessitating the establishment of standards and frameworks to facilitate cross-functional collaboration. Embracing integrated methodologies offers numerous benefits: streamlined design activities, efficient use of expertise across disciplines, avoidance of rework, and faster time-to-market. To address these challenges the author proposes that integrated design strategies are necessary. Incorporating consumer preferences systematically through techniques like quality function deployment is crucial to meet diverse and rapidly changing consumer needs. Integrating product and process design is vital as the manufacturing process significantly influences

the final product's properties. Moreover, linking product design decisions to business decisions ensures alignment with resource allocation and portfolio optimization.

One issue to consider in integration is multi-scale processes. Martinez-Hernandez (2017) discussed the impact of sustainability on the conceptualization of new processes in chemical engineering. It points out that the pursuit of sustainability is introducing complexities due to economic and social uncertainties, the diversity of renewable resources, and globalization. As a result, process design problems have evolved, prompting the development of new methods that incorporate multidimensionality and multiscale boundaries. Two main trends have emerged in methods development: one that considers expanded boundaries from the molecular level to the process level and another that spans from the process level to higher levels, including value chains, ecosystems, and the planet.

Khan et al., (2016) emphasized the importance of integrating product design into supply chain management, showing how it can impact costs, agility, and risks. However, product design is often neglected in supply chain strategy due to functional silos. To address this, the authors conducted a multiple case study to identify opportunities and challenges. Key opportunities include cost reduction, faster time-to-market, improved customer service, and reduced supply chain risks. Challenges involve internal issues like misaligned goals and external factors such as supplier/customer integration and geographic distance (Uhlemann et al., 2020). The article suggests a balanced approach based on a company's existing resources and capabilities, emphasizing that there's no one-size-fits-all solution. The provided examples support the arguments made, showing how cross-functional coordination and collaboration lead to benefits. Overall, the article makes a convincing case for integrating product design into supply chain management strategically, based on internal resources and the external environment, offering practical guidance to achieve competitive advantages.

2.2 Background of the research group

L'Équipe de Recherche sur les Processus Innovatifs (ERPI) from Université de Lorraine has long been researching innovative approaches for product design and supply chain design and management considering sustainability criteria. Its research focuses on creating design strategies that reduce negative social and environmental impacts while preserving economic viability. For this, they incorporate sustainability assessment methodologies

based on criteria and indicators created from standards and available measurements. The main works on this domain are presented in **Table 2-1**.

Table 2-1. ERPI background in supply chain design and management

Topic	Reference
Supply chain analytic approach	(Hamdani et al., 2022)
Supply chain optimization	(Santander et al., 2020)
Optimization of supply chain	(Espinoza Pérez et al., 2019)
Methodology for supplier selection	(Garzon et al., 2019)
Product and supply chain design	(Marche et al., 2019)
Innovation in supply chain	(Marche et al., 2017)
Supply chain design and management	(Espinoza Pérez et al., 2017)

The most recent paper published by ERPI brings attention to the implementation of Big Data Analytics (BDA) within the supply chain management, which could be useful for processing large amounts of data related to the value chain and sustainability criteria (Hamdani et al., 2022). Though the paper "Multiobjective optimization for the design of phase III biorefinery sustainable supply chain" focuses on designing sustainable supply chains using multi-objective optimization (Garzon et al., 2019). By their part, Marche et al (2019) offered a perspective on supply chain agility during the product design phase, which could be beneficial for ensuring flexibility the product design process. Additionally, Marche et al (2017) investigated the impact of innovation on a company's supply chain, which could provide essential insights, given the focus on the development of a new methodology but in a different scale. Lastly, Espinoza Perez et al. emphasizes the need for a comprehensive approach to sustainability in supply chain design (2017).

The ERPI has a tight partnership at the forefront of research in these fields with the Research Group of Chemical and Biochemical Processes from the Universidad Nacional de Colombia, with the purpose of addressing interdisciplinary problems in the fields of innovation in product and process related to industrial and chemical engineering issues. More specifically, the research teams have focused on developing integrated approaches for chemical product design considering multiple scales, involving the development of

multiple approaches and methodologies for the chemical product design as shown in the **Figure 2-1**.

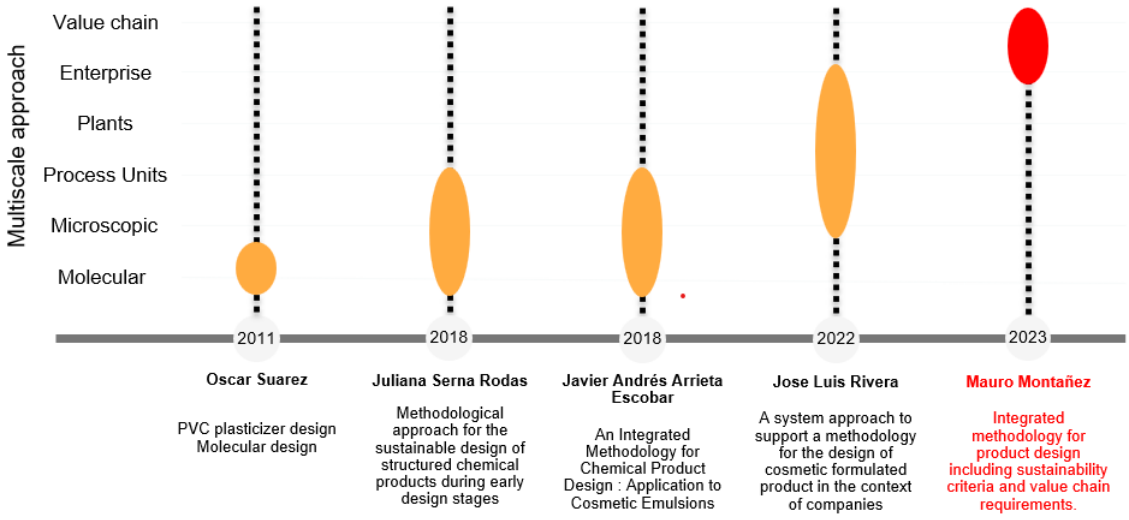


Figure 2-1. ERPI-UNAL background in chemical product methodologies

Research on the design of chemical products has been previously examined at different scales. At the molecular scale, studies have focused on designing chemical structures that yield desired properties and functionalities (Suárez Palacios, 2011).

Moving to the microscopic scale, the works highlight the growing importance of chemical product formulation in the chemical process industry. With the consumer market becoming more demanding, designing and formulating chemical products that align with consumer needs and market trends is crucial for sustained success. The focus on creating high value-added chemicals necessitates constant innovation and the integration of cutting-edge technologies and the product formulation. By adopting methodological approaches and leveraging chemical engineering principles, industries can develop efficient, effective, and diverse consumer products that cater to modern market demands and ensure long-term competitiveness. (Arrieta Escobar, 2018; Serna Rodas, 2018).

On the process scale, the research discusses the competitive nature of the chemical products market and the increasing demand for high-quality products. To address these challenges, industry and academia are seeking new methods for chemical product design. The proposed methodological approach aims to facilitate decision-making in the design of emulsion-type products. It includes three key steps: analyzing consumer needs, generating

ideas for product design, and selecting the best product. The methodology focuses on creating innovative and customer-centric products that meet market demands. The impact of this approach could lead to more efficient and effective product design processes, benefiting various industries beyond the chemical products market (Serna Rodas, 2018).

The scale of companies brings into focus the strategies for managing multiple plants or businesses, the work also addresses the complexities involved in managing a new chemical product design and development project. It emphasizes that beyond technical challenges, design teams must also consider the organizational requirements of the company conducting the product design. The research demonstrated its effectiveness in evaluating and improving the actual design process. The tool provided tailored improvement solutions aligned with the company's core values. Moreover, the study highlighted the role of the design team as both evaluators and builders of their own design methodology, reinforcing the importance of involving employees in the improvement process(Rivera Gil, 2022).

This study involved conducting an examination of the references found in the investigations described before. The decision was made to prioritize the primary sources to guarantee the inclusiveness and reliability of the gathered material. This approach facilitated the efficient identification and integration of the most significant advancements and existing information. The utilization of well acknowledged sources enhanced the validity of the conducted analysis. Furthermore, this strategic approach resulted in time and resource savings in comparison to doing a comprehensive study of all accessible references. Through a deliberate emphasis on primary sources, the current study was able to provide a rationale and framework for understanding its own contributions, therefore establishing their connection to prior advancements in the respective sector. The correlation established between the present study and prior research underscores the significance and novelty of the current investigation. By examining the title, abstract and keywords content of these references, 54 articles were chosen as relevant in the context of keywords like: product design, methodologies, supply chain requirements, sustainability and stakeholder participation. The **Figure 2-2** presents a comprehensive view of the distribution of publications that center around these five keywords, individually as well as in their various combinations.

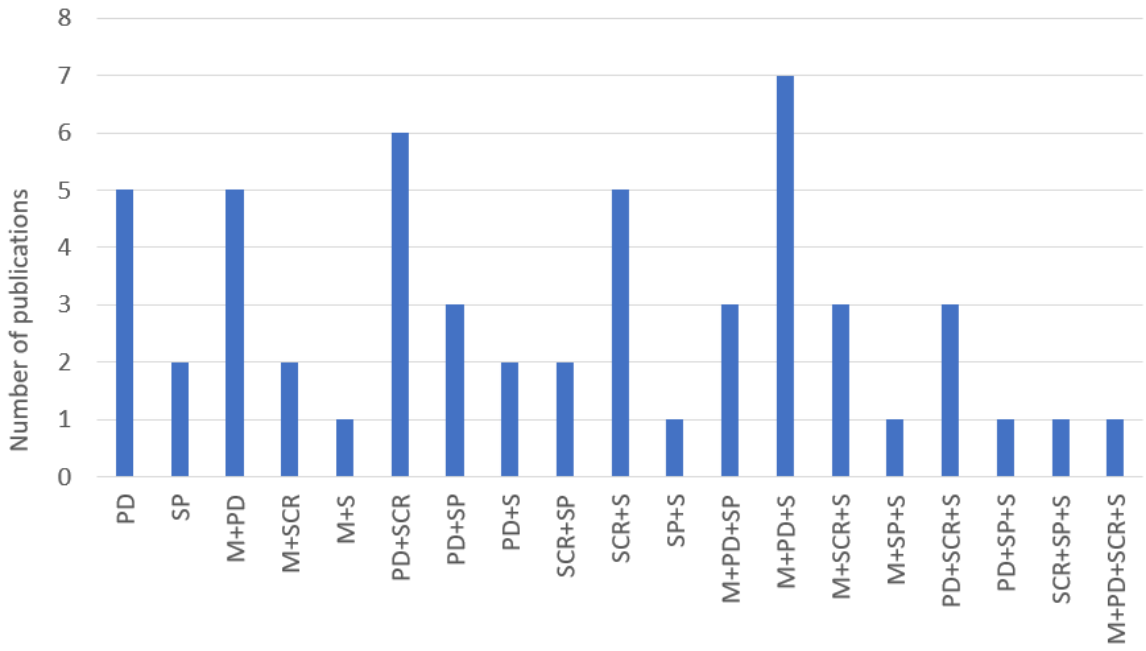


Figure 2-2. Distribution of publications based on the five keywords of scope classification (M=Methodology, PD=Product/Process Design, SCR=Supply Chain Requirements, SP=Stakeholder Participation, S=Sustainability)

Within this, it is worth mentioning that in the only reference that involves four of the key words Fung et al. (2016) introduces the "Grand Product Design Model" (GPD-Model) as a framework for enhancing the design of chemical products. It combines various elements, such as process design, property prediction, quality requirements, costs, pricing, and economic factors. The GPD-Model consists of six sub-models, each focusing on a specific aspect and utilizing methods, tools, databases, and experiments. The article presents two case studies illustrating the application of the GPD-Model. The first case involves designing a die attach adhesive to meet thermal conductivity requirements while maximizing profitability, showcasing the influence of pricing and market factors on the optimal formulation. The second case deals with designing a hand lotion to meet viscosity and texture requirements, demonstrating how product quality affects profitability.

To augment the findings from the keyword analysis and ensure an understanding of the articles' contents, a content analysis was performed. Each article was read and analyzed to discern the intricate details of the research context and to identify any supplementary themes or subtopics discussed within. This qualitative assessment allowed us to delve into

the nuanced complexities of the publications and ascertain the presence of the latent themes. Remarkably, the category that intertwines Methodology, Product Design, and Sustainability stands out as a prominent theme due to its potential to address environmental and social issues, align with consumer values, meet regulatory standards, and foster long-term business success. However, it is crucial to acknowledge that the category encompassing Methodology, Product/Process Design, Supply Chain Requirements, and Sustainability remains an underexplored research space. Despite its promising prospects, we only identified one publication, and surprisingly, none were found to cover all five components together.

The **Table 2-2** presents the detailed review of selected articles from the examination of the references. The articles were analyzed to determine their relevance to the chosen keywords, and each checkbox indicates whether the article addresses the corresponding theme.

Table 2-2. Review of the selected articles and their relevance to the key words

Reference	Keywords				
	Methodology	Product/ Process Design	Supply chain requirements	Stakeholders Participation	Sustainability
(Rajeev et al., 2019)		X	X		X
(Shohan et al., 2019)			X		X
(Fung et al., 2016b)	X	X	X		X
(Martín & Martínez, 2013)	X	X			
(Nishanth G. & Ng, 2013)	X	X			X
(Conte et al., 2011)	X	X			
(Ng et al., 2014a)	X	X			
(Uhlemann et al., 2020)		X			

(Rajeev et al., 2019)			X		X
(Chowdhury et al., 2019)			X	X	X
(Burgess & Sunmola, 2021)	X		X		
(Vogt et al., 2005)		X	X		
(Zhang et al., 2020)		X			
(Grote et al., 2007)	X	X			X
(Yan et al., 2009)	X	X			X
(Matos & Hall, 2007)			X		X
(Azapagic et al., 2006)	X	X			X
(E. Cussler, 2011)		X			
(Escribano et al., 2018)	X				X
(Ramírez et al., 2015)	X			X	X
(Auch & Pretzsch, 2020)		X	X		
(van den Berg et al., 2014)	X		X		X
(Tapia & Samsatli, 2020)	X		X		X
(Pacheco et al., 2020)			X		X
(Contreras-Zarazúa et al., 2021)		X	X		X
(Bairamzadeh et al., 2016)	X		X		X
(Serna et al., 2021)	X	X			
(Zarei et al., 2021)		X	X		

(Choi et al., 2020)		X		X		
(Santibañez-Aguilar et al., 2019)				X		
(Diaz-Barriga-Fernandez et al., 2017)				X		
(Garriga, 2014)			X	X		
(Yue et al., 2013)		X	X		X	
(Haussmann & Wuttke, 2020)	X	X		X		
(Reitsma et al., 2023)		X	X			
(Raj & Lakshminarayanan, 2008)	X		X			
(Hapuwatte & Jawahir, 2021)	X	X			X	
(Ng et al., 2015)		X			X	
(le Van et al., 2019)		X		X	X	
(Earl & Clift, 1999)			X	X		
(B. V. Smith & Ierapepritou, 2009)	X	X		X		
(Ng et al., 2014b)	X	X				
(Cignitti et al., 2018)		X				
(Sahebi et al., 2014)			X		X	
(Rivera Gil et al., 2022b)		X				
(Herremans et al., 2016)				X	X	
(Weiss, 2004)		X		X		

(Agouridas et al., 2006)		X			X	
(Tseng & Abdalla, 2006)	X	X				X
(Gan & Grunow, 2016)		X	X			
(Sun et al., 2019)	X	X			X	
(Sakao, 2007)		X				X
(Eddy et al., 2013)	X	X				X
(Özkir & Başligil, 2012)		X	X			

*C*hemical product design methodologies are increasingly integrating more and more considerations in their study (B. V. Smith & Ierapepritou, 2010). An example of this is the methodology proposed by Smith & Ierapepritou (2009) for consumer-integrated optimal design of chemical-based consumer products, aiming to incorporate consumer preferences, technical considerations, and economic factors. The methodology involves steps like consumer preference identification through evaluations and validation. Consumer preferences are quantified using regression analysis to determine attribute importance weights, integrated into the utility function for systematic optimization of consumer satisfaction within cost constraints. Haussmann & Wuttke (2020), on the other hand, focused on designing and integrating Industrial Product-Service Systems offered by manufacturing companies. The primary goal is to ensure market success by effectively involving customers and stakeholders throughout the design process. The methodology involves a workshop-based analysis to identify goals, risks, and stakeholder integration conditions. The methodology is supported by literature research and three case studies, emphasizing the significance of customized design and stakeholder integration to enhance market success. And additionally, Nishanth G. & Ng (2013) integrated sustainability through a methodology to design an integrated biorefinery producing sustainable biochemicals that meet customer requirements. The overall integration of sustainability is achieved by starting with customer needs, employing efficient computational models, optimizing reaction routes for maximum yield and productivity, and utilizing renewable biomass feedstocks. This results in targeted, viable products manufactured efficiently from renewable sources,

making the biorefinery economically and environmentally sustainable. This indicates a significant interest and research effort in product and process development and refinement. Participation of stakeholders has received less attention, indicating that this subject may be understudied.

This review of the state of the art reveals significant research interest and progress in chemical product design methodologies, but also highlights some gaps that present opportunities for further study. The examination of recent literature shows a predominant focus on incorporating sustainability principles into product design methodologies. However, there remains room for advancement, particularly in systematically integrating supply chain requirements into the design process. While research has explored supply chain considerations in relation to sustainability or product design individually, publications simultaneously addressing product design, supply chains, and sustainability are limited. This suggests an under-exploration of the interlinkages between product design, supply chains, and sustainability factors. Additionally, a few studies were identified that addressed the participation of diverse stakeholders in chemical product design. This reveals an area requiring more research to enhance engagement with stakeholders throughout the design process.

In summary, this review has identified promising directions for enhancing chemical product design through holistic integration of sustainability, supply chains, and stakeholder involvement. An opportunity exists to develop a comprehensive methodology bridging these domains to enable the creation of innovative chemical products that balance economic, environmental, and social objectives. The proposed research aims to address this gap through an integrated methodology that incorporates supply chain requirements and sustainability criteria during product conceptualization, while soliciting meaningful input from stakeholders. The outcomes can provide both theoretical and practical contributions to the field of sustainable chemical product design.

After having discussed the state of the art and the background, now explore the fundamental principles and essential terminology that constitute the foundational framework of our study's technique. The identification and comprehension of these fundamental concepts and keywords are crucial elements in the research, as they provide the foundation upon which our inquiry is built.

2.3 Qualitative Methodology

Including an exploration of qualitative research methodology in this document is required to comprehensively address the research problem at hand. While quantitative data analysis offers valuable insights into numerical trends and patterns, qualitative research offers a deeper understanding of the perspectives, experiences, and social context of the community under study (Aspers & Corte, 2019). By systematically seeking answers to specific research questions and delving into stakeholders' viewpoints, qualitative research enriches our investigation of the topic, particularly when exploring complex and intangible aspects like sustainability (Mack et al., 2011). This section delves into the advantages of qualitative research, highlighting its ability to produce detailed textual descriptions and uncover valuable insights about behaviors, attitudes, and relationships.

The advantage of this kind of research is that it may produce detailed textual descriptions of how people perceive and comprehend a particular research issue. The behaviors, experiences, attitudes, and relationships of the stakeholders involved are all revealed by this research methodology, which also offers information about people's perspectives and solutions to a situation (Babu et al., 2013). Intangible elements that are hard to quantify, such as social norms, socioeconomic position, and in this case some factors like sustainability, can also be identified using qualitative methods. Qualitative research can assist researchers in a better interpreting and comprehending the complicated realities of a given scenario and the implications of quantitative data when utilized in conjunction with quantitative methodologies (Mack et al., 2011).

An example of the application of a methodology in a case of decision making such as product design is the research done by Ramírez et al. (2015) who proposed a methodology to support participatory decision-making with vulnerable communities for engineering projects. The goal is to select the best solution to a social problem that involves and impacts a vulnerable community. The methodology integrates conventional decision-making techniques like the Analytic Hierarchy Process (AHP) with more systemic and participatory methodologies. The case study is a project by Engineers Without Borders Colombia to improve water quality for a rural community in Colombia. The community-driven problem-solving process involves several key steps. First, alternative solutions are defined collaboratively with the community following a comprehensive diagnosis of the problem and understanding the community's needs. Next, information gathering workshops are

designed, applying syntegration principles, to gather insights from all beneficiaries and stakeholders. These workshops foster open communication and participation. Subsequently, the information gathered in the workshops is scrutinized and analyzed, carefully examining various messages and perceptions shared by the participants. This approach ensures a thorough and inclusive decision-making process, promoting effective and sustainable solutions. The analogous case has demonstrated considerable success in achieving sustainability objectives within its context. By actively involving stakeholders in the decision-making process, they were able to identify synergies, navigate trade-offs, and co-create solutions that enhanced ecological integrity, social equity, and economic viability. This success validates the importance of stakeholder integration and the potential positive outcomes that can be achieved through an integrated approach.

The shared principles between the analogous case and our integrated methodology underscore the suitability of focus groups as a qualitative data collection method. By leveraging the advantages of focus groups, we can engage stakeholders, explore diverse perspectives, and uncover critical insights necessary for designing sustainable chemical products within the palm oil value chain. The participatory and interactive nature of focus groups aligns seamlessly with our objectives of stakeholder integration and sustainability considerations, making it a valuable and complementary component of our research methodology. Therefore, the selection of suitable qualitative research methodologies is a topic you face to establish a comprehensive approach to have results with good quality. These strategies function as a mean to comprehend the complexities of stakeholder viewpoints, facilitating the development of inventive and socially conscious resolutions.

In addition, the scholarly publication offers a comprehensive examination of diverse tools and methodologies employed in the practice of participatory modeling (PM). PM involves the active involvement of stakeholders in the construction of models aimed at tackling intricate problems. In the publication Voinov & Bousquet (2018) present a typology of PM methods, accompanied by illustrative instances and an evaluation of their respective merits and limitations. This can facilitate the process of selecting appropriate methods. Based on the nature of the problem we are addressing, which involves complex social like integration of stakeholders and sustainability matters, and our desire to deeply understand diverse stakeholder perspectives as an initial step, we recommend using focus groups and semi-structured interviews as our key participatory modeling methods. Focus groups will allow

interactive discussions among stakeholders from different backgrounds, surfacing insights into areas and discussion of their points of view. Semi-structured interviews with key informants will let us delve more deeply into individual viewpoints about the supply chain and the perspectives of stakeholders from different stages of the value chain. The qualitative data gathered from these techniques will inform the development of conceptual models representing the stakeholders' mental models, beliefs, and subjective opinions related to the problem. This aligns well with our current phase of work focused on problem formulation and fact-finding and for now these qualitative methods suit the scope of the work.

Process observation, in-depth interviews, and focus groups are the three most common qualitative research approaches. However, with the recent interest in this subject, more techniques have evolved, as illustrated in **Figure 2-3**.

Figure 2-3. Types of qualitative research methods (Mack et al., 2011)

Process Observation is a technique where information is gathered by seeing actions, occurrences, or physical traits in their natural habitat. The benefit of observation is that it allows for a greater grasp of the context being researched because people are more inclined to act normally when being observed (Morgan-Trimmer & Wood, 2016).

An **in-depth interview** is the approach used to get the participant's viewpoint on the research issue. The format of interview questions is designed to allow the researcher to glean as much information about the subject as possible. Researchers engage with participants by neutrally posing questions, paying close attention to their answers, and then probing in response to their answers (Jamshed, 2014). The objective is to question the

interviewee's knowledge rather than leading them along by any preconceived notions (Mack et al., 2011).

Interviews can be utilized as the main method of data collection to learn more about people's habits, beliefs, or attitudes. They can be used to gather data about actions or experiences from the past or the present. Interviews can also be used to learn more about a subject or draw on a person's knowledge (Harrell & Bradley, 2009). Depending on the needs being met and the available information, interviews can be designed in many ways.

A **focus group** is a qualitative data gathering technique in which one or more researchers meet with a group of participants to discuss a certain research topic (Gundumogula, 2020). Participants react to open-ended questions, or questions that demand more than a single sentence or a simple "yes" or "no" response, as one researcher (the moderator) guides the debate. The note-taker, a second researcher, carefully records the conversation. Focus groups offer a lot of information in a short amount of time, which is one of its key advantages. Instead of establishing group unanimity, they are also good at evoking a wide range of viewpoints on a particular subject (Gundumogula, 2020; Mack et al., 2011).

Ethnographic research is qualitative data collection technique known for being used in social and behavioral sciences (Reeves et al., 2013). To make inferences about how societies and individuals operate, data are gathered through observations and interviews. Instead of trying to influence the situation, ethnographers study it as it develops (Spradley, 2016). Given the unpredictable nature of most topics studied using this method, ethnographers frequently struggle to document their work in a way that can be reproduced in other cases (Reeves et al., 2013).

Record keeping entails gathering secondary or existing data to use it in a new research project (Mack et al., 2011). In this kind of research there are two different types of data: constructed that refers to items created by study participants, which covers all kinds of recently created documents and secondary which is existent data that have already been compiled, typically by a different party and frequently for a completely unrelated reason to the current investigation (Mertler, 2018).

Case study is a type of research methodology that produces a thorough understanding of a case from many different viewpoints and in its actual context. It is a research method that

is widely used across many academic fields and results from the necessity to thoroughly examine an event or phenomena in its natural context (Crowe et al., 2011). There are two different kinds of case study research: instrumental case studies, which use a specific scenario to develop a more thorough understanding of a problem or phenomenon, and collective case studies, which involve studying several cases concurrently or sequentially in an effort to develop an even more thorough understanding of a specific problem (Crowe et al., 2011; Hyett et al., 2014).

In the forthcoming sections, we will delve into the detailed exploration of the selected qualitative research methods employed in this study. These methods encompass semi-structured interviews and focus groups, meticulously chosen to align with our research objectives of stakeholder integration, understanding supply chain requirements, and incorporating sustainability criteria. Through the following sections, we will elucidate the characteristics and advantages of each method, offering step-by-step guides followed to effectively design and implement them.

2.3.1 Interview

The interview is a technique for collecting information that has value in and of itself, in addition to its use in research processes. It has the same characteristics and follows the same stages, regardless of whether it is developed as part of a research endeavor or outside of a systematic study. Everything that follows will therefore serve both to refine the technique within an investigation and to use it in an isolated fashion (Harrell & Bradley, 2009). The primary purpose of an interview is to obtain verbal and customized information about events, experiences, and people's opinions. Always at least two individuals participate. One of them assumes the role of interviewer, while the other assumes the role of respondent, creating an interaction between them regarding a topic of study. When more than one individual is being interrogated, a group interview is taking place. Consequently, as described below, the interview is also characterized by the number of individuals interviewed. In accordance with this criterion, we will discuss individual and group interviews (Kallio et al., 2016).

Just as the quantity of interviewees determines the interview type, so does the level of interview structure. They fall into one of three categories (Easwaramoorthy & Zarinpoush, 2006):

- Structured interview: the interviewer asks a prepared list of questions in a precise sequence about predetermined subjects. The questions can be open or closed so the respondents can choose their responses from a list of available possibilities.

- Unstructured Interview: The interviewer does not have any detailed guidelines, constraints, prewritten questions, or a list of alternatives. To encourage an open, casual, and spontaneous conversation with the interviewee, the interviewer starts by asking some generic questions. To learn more about the subject in-depth, the interviewer probes with further questions and/or investigates discrepancies. Unstructured interviews are particularly helpful when there is little information available on a topic or when it is important to hear the stories behind interviewees' experiences.

- Semi-structured interviews: the respondents answer in their own words after the interviewer asks a series of reference questions. Some interviewers use a topic guide as a checklist to make sure all respondents provide information in line with the interview's goals. Based on the respondent's responses, the interviewer can focus on particular topics or ask follow-up questions to get more information. Semi-structured interviews can be helpful when to obtain in-depth information systematically from many respondents or interviewees is required (Harrell & Bradley, 2009).

Kallio et al. (2016) proposed the following guide to develop a semi-structured interview, by utilizing a set of predetermined questions while allowing room for exploration, these interviews offer rich and nuanced insights into participants' experiences and perspectives. This comprehensive guide aims to provide researchers with a step-by-step process for conducting effective semi-structured interviews.

Step 1: Define the Research Objectives

Before embarking on your interviews, it is crucial to have a clear understanding of your research objectives. Articulate the specific information or insights you seek to gather

through the interviews. These objectives will guide the formulation of your questions and ensure your research remains focused and purposeful.

Step 2: Select Your Participants

Identify the target population that aligns with your research objectives. Determine the number of participants needed and establish specific criteria for their selection, such as age, gender, occupation, or other relevant characteristics.

Step 3: Develop the Interview Guide

Create an interview guide comprising open-ended questions that are pertinent to your research objectives. Start with general introductory questions to ease participants into the interview and build rapport. As you progress, transition to more specific inquiries, avoiding leading or biased questions that may influence responses.

Step 4: Pilot Test the Interview Guide

Prior to the actual interviews, conduct a pilot test with a small group of individuals resembling your target population. This pilot phase will help identify any ambiguous or problematic questions, allowing you to refine the interview guide for maximum effectiveness.

Step 5: Choose the Interview Format

Determine the most appropriate format for your interviews, whether they will be conducted in-person, over the phone, via video conference, or through written communication like email or chat. Consider logistical factors and the comfort level of your participants.

Step 6: Consider Ethical Considerations

Adhere to ethical guidelines throughout your research. Obtain informed consent from all participants, ensuring they understand the purpose and implications of the study. Assure confidentiality and respect participants' rights to withdraw from the study at any time.

Step 7: Conduct the Semi-Structured Interviews

Schedule interview sessions with your chosen participants. Begin each interview by introducing yourself, explaining the study's purpose, and obtaining consent. Start with broad, open-ended questions and let the conversation flow naturally. Utilize follow-up probes to explore interesting responses and seek clarification when needed. Be an active listener and adapt your follow-up questions based on participants' responses to gain deeper insights.

Step 8: Transcribe and Analyze the Data

Transcribe interview recordings or convert your notes into a readable format suitable for analysis. Utilize qualitative analysis techniques, such as thematic analysis or content analysis, to identify common themes and patterns in the data collected.

Qualitative data analysis by coding is a systematic process of organizing and making sense of textual, visual, or audio data collected during qualitative research. Coding involves identifying, categorizing, and labeling meaningful themes or patterns within the data, allowing researchers to draw meaningful conclusions and generate insights from the information gathered.

Step 9: Draw Conclusions

Analyze the data to draw meaningful conclusions that address your research objectives. Look for overarching themes and unique perspectives shared by participants. Use direct quotes from interviews to support your conclusions and add credibility to your findings.

Step 10: Report Your Findings

Compile your research findings into a comprehensive report. Describe your research methodology, provide a detailed analysis of the data, and present your conclusions with clarity and organization. Use visual aids, such as charts or graphs, to enhance the presentation of your data.

2.3.2 Focus group

A focus group is a qualitative data collection method that involves a small group discussion, guided by a moderator, to explore a specific topic. This approach is characterized by its

focused and informal nature, aiming to gain valuable insights and perspectives from participants. Various definitions from different authors align in recognizing focus groups as an effective means of gathering qualitative data (Harrell & Bradley, 2009).

When organizing focus group sessions, several logistical considerations are essential. The venue should be convenient, quiet, and spacious, promoting a conducive environment for interaction among participants. Group size can vary, but it is generally recommended to have 6-12 participants, with at least 3 groups conducted for comparability. Each session typically lasts 1-2 hours, allowing sufficient time for meaningful discussions. Ensuring consistency across groups is crucial to facilitate meaningful comparisons during analysis (Mertler, 2018).

A person has the role of moderator guiding the focus group discussion. They use prepared open-ended questions to facilitate the conversation and keep the discussion focused on the chosen topic. For inexperienced moderators, observing experienced facilitators can be beneficial to learn effective moderation techniques and group dynamics. Selecting appropriate participants is essential for the success of a focus group (Mack et al., 2011). Participants should possess knowledge of and interest in the topic under discussion. Additionally, demographic factors should be considered when forming groups to ensure diverse perspectives are represented. Each participant should be able to actively contribute to the discussion, encouraging a dynamic exchange of ideas (Mertler, 2018).

Focus group sessions generally last 1-2 hours and begin with the moderator introducing the topic and setting expectations. To ensure consistency and comparability, all groups should follow the same format during their discussions. Data collection in focus groups can be achieved through audio or video recording, although notetaking is also a viable option. Qualitative analysis methods, such as thematic analysis, are commonly employed to interpret and make sense of the data gathered (Mack et al., 2011). The quality of the data obtained depends on various factors, including the formulation of questions, the proficiency of the moderators, and the rigor of the analysis. Focus groups hold significant importance in research for several reasons. They promote interaction among participants, leading to deeper insights compared to individual interviews. The flexibility in implementation and relatively low cost makes focus groups an attractive option for exploring a wide range of topics and uncovering new information (Gundumogula, 2020; Mack et al., 2011).

While focus groups offer numerous benefits, they also have limitations that researchers must consider. Dominant participants can introduce bias, influencing the direction of discussions. Distinguishing individual perspectives from the collective group view can also pose challenges. Furthermore, the small and non-representative sample sizes in focus groups limit the generalizability of findings. Lastly, data analysis and interpretation may be complex due to the diverse perspectives shared within the group. Focus groups are a valuable qualitative research tool that provides unique insights from a group perspective. When carefully planned and conducted, they offer rich and meaningful data to explore topics in-depth. By acknowledging their strengths and limitations, researchers can effectively utilize focus groups to gain valuable insights into various subjects. (Gundumogula, 2020).

In conclusion, this overview demonstrates the value of qualitative research methodologies, specifically semi-structured interviews, and focus groups, for comprehensively exploring our research topic. The qualitative data gathered through these techniques will allow us to gain a nuanced understanding of diverse stakeholder perspectives within the supply chain. By actively engaging stakeholders through interviews and focus group discussions, we can uncover critical insights into their experiences, attitudes, relationships, and sustainability needs. The participatory nature of these methods aligns with our objectives of stakeholder integration. Furthermore, the textual data collected will facilitate identification of key themes related to supply chain requirements and sustainability considerations. While qualitative research has limitations in terms of subjectivity and generalizability, it serves as an indispensable component of our mixed methods approach, complementing and enriching the quantitative data analysis.

3. Development of the methodology

Considering the main objective of this work, this chapter presents a generic methodology that aims to integrate supply chain requirements into the chemical product design process. The methodology has four phases as depicted in **Figure 3-1**: the first three phases help to diagnose the supply chain and identify its limitations or requirements: in the first phase, a theoretical background of the value chain is reviewed to have a global overview of the context; in a second phase, stakeholders from different activities of the supply chain are interviewed to have their vision of the supply chain; in the third phase, the information is analyzed through qualitative techniques to identify the supply chain limitations that hinder its development and sustainability. The last phase of the methodology consists of a product design workshop, where the results of the supply chain diagnosis are applied to solve a design problem. The design workshop was initially tested with bachelor chemical engineering students of last year and then with experienced stakeholders.

Figure 3-1. Proposed methodology for incorporating supply chain requirements and sustainability criteria into product design.

This chapter gives a clear description of the methodology, so the following sections detail each of the phases and explain the reason for each of the activities proposed. Chapter 4 shows its application in the case study of the palm oil supply chain.

3.1 Supply chain´s theoretical framework

The objective of the first phase, the theoretical framework of the supply chain is to achieve a global comprehension of the supply chain, including its general context, current state, and key stakeholders involved. This phase involves exploring various publications and academic sources related to the raw material concerned, sustainability, and the specific case of the country's industry providing a solid theoretical foundation for the research.

In order to accomplish this goal, a comprehensive literature search is conducted in scholarly articles, research papers, reports, and other published works that provide insights into the supply chain and its associated sustainability dimensions. The analysis of this information can be facilitated with collaborations with experts in the value chain to get an understanding of the most recent trends, advancements, and areas of knowledge that have yet to be explored within the sector.

By synthesizing and analyzing the information gathered during the literature review, the researcher can form a comprehensive understanding of the palm oil supply chain's intricacies, strengths, and weaknesses. This information functions as a fundamental basis for later stages of the study, such as the planning of the interviews and design focus groups, so facilitating a more knowledgeable and focused approach to the collecting of data.

3.2 Supply chain identification by stakeholders

The primary aim is to get insights and viewpoints from stakeholders, as well as to establish a diagnostic of the value and supply chain. For this, semi-structured interviews are applied to allow stakeholders to freely describe the supply chain, the value chain, their role in the supply chain, its main characteristics, and problematics. For this, a semi-structured interview is proposed based on the framework of Hanna Kallio (2016) (**Figure 3-2**).

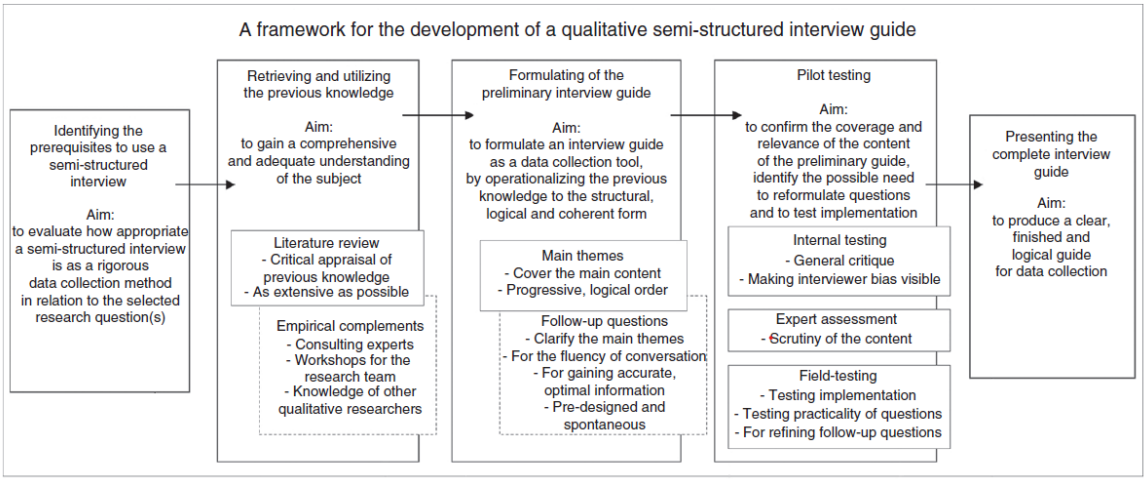


Figure 3-2. A framework for the development of a semi-structured interview guide. Adapted from: (Kallio et al., 2016)

The interview guide is divided in four stages: 1) the interview presentation where the purpose of the interview is explained to participants; 2) the interviewee information, where information for the participants and from their organization is collected; 3) the supply chain diagnosis workshop, were participants are asked to explain graphically the supply and value chain; 4) the closing, where participants are thanked and the activity is closed. The structure of the interview is shown in detail in the **Table 3-1**.

Table 3-1. Proposed guide for interviews.

Stage	Duration (min)	Description	Required material
1. Interview presentation			
1.1. Interviewer presentation	3	Give information from the interviewer: name, profession, role in the project.	Short Presentation in power point (Annex A.1)
1.2. Introduction	5	Explain to the interviewee a brief context of the project, emphasizing why his/her contribution is important.	
1.3. Activity description	5	Describe the procedure of the workshop, explaining its structure, objectives, activities to develop, and duration.	
2. Interviewee information			

2.1. Interviewee data	5	Questions are asked to find out details of the interviewee's profile, such as his/her area of work, position, profession, experience. This is done to have a background about his/her knowledge and his/her role in his/her organization and in the supply chain. Questions: • What is your profession? • What is your length of experience working in this value chain?	Complete questions guide for the interviewer (Annex A.2)
2.2. Description of the interviewee's company	5	The interviewee is asked about his/her organization to obtain information about the role of the organization in the supply chain. Information is sought such as: size of the organization, where it is present, what it produces. Questions: • In which company do you work? • What is the size of the company you work for? • Where does the company have a presence? • What type of products does the company produce?	
3. Supply chain diagnosis workshop			
3.1. Value Chain	20	**Objective** To obtain the palm oil value chain according to the perspective of each of the interviewee. **Activity** A series of ordered drawings are shown to participants representing the chain obtained from the literature. Based on their experience	Value chain Board (Annex A.3) Questions guide for the

		in the palm oil sector, participants are invited to determine the order and relationships among value chain activities. They also identify the most critical and important activities. Questions: • What activities do you consider provide value in the palm oil value chain? • Which activity do you consider to be the most valuable and why? • What is the sequence of these value-generating activities?	interviewer (Annex A.2)
3.2. Supply Chain	20	**Objective** To obtain the supply chain according to the perspective of each of the interviewee. **Activity** Participants are invited to react and discuss the dynamics of the stakeholders of the palm oil value chain. This is done through an activity where the participants are asked to organize the actors of the supply chain according to their knowledge. Actors are proposed based on the literature review. Participants can add/delete according to their experience. Questions: • What activities do you consider provide value in the palm oil value chain? • Which activity do you consider to be the most valuable and why? • What is the sequence of these value-generating activities?	Supply chain Board (Annex A.4) Questions guide for the interviewer (Annex A.2)

		• According to the activities described in the previous exercise, what would be the chain of actors involved in the process of this product? • Which actor do you consider to be the most important in this chain and why? • Which actor plays a critical role in the sustainability of the chain and why? • What is the role of the organizations considered in the chain of actors? • Are there actors that coordinate activities in the value chain as a whole? How do actors exchange information and learn about solutions to improve products and chain performance?	
4. Closing the interview			
4.1. Conclusion	5	The interviewee is asked for additional comments on the topic or about the interview and its development in order to find out details of his/her feelings about the activity and to make improvements and reinforce the parts of the interview that stand out.	-
4.2. Acknowledgement	2	The interviewee is thanked for the time he/she dedicated to the activity and for the information he/she provided about his/her company and about the palm oil process. Within this section you can ask about their participation in a future workshop.	-
Total Duration	70		

During the semi-structured interviews two specific activities are implemented to diagnose the value and supply chain (Stage 3 from **Table 3-1**). These activities involve requesting

the interviewee to draw the value chain and supply chain based on their experience. An interactive board is given to them as a support (Annex A.1 and A.2) where they can add any activity or actor according to their integral perception of the supply chain. This activity is preferred instead of an exchange of questions and answers because it can notably enhance the participatory aspect and make the session more engaging: They not only captivate the attention of the participants throughout the interview, but they're also highly beneficial when discussing complex or sensitive topics(Harrell & Bradley, 2009).

For the case study, interviews were done at distance through Microsoft teams and were transcribed for a further analysis. The platform mural was chosen to develop the drawing activities of stage 3.

3.3 Supply chain´s Limitations Identification

This stage aims to systematically analyze the responses given by stakeholders and identify which are the limitations of the supply chain that it would face in achieving stable and sustainable development. To achieve this, a qualitative analysis of the interview transcripts by codification is used. This involves reviewing and coding the data collected from the interviews. Through this process, specific topics, issues, and limitations mentioned by the stakeholders are identified and organized systematically (Gundumogula, 2020).

The qualitative analysis by codification enables to categorize and interpret the data, allowing an exploration of the underlying patterns and trends within data from the interviews. It helps in connecting different pieces of information and deriving meaningful insights about the challenges faced by various stakeholders. The analysis method is based on the work of (Miles et al., 2014) and it shortly described as follows:

1. Transcribe the audio or video recordings into text.

2. Read the transcripts several times to become familiar with the facts and have a first code of the key information. With these first readings, the limitations of the supply chain that the different stakeholders repeat in the interviews are identified by the researchers.

3. Similar limitations are grouped into the same category until a set of distinct limitations are defined. For example, if stakeholders mention “water problems”,

“high water consumption”, “deforestation”,” environmental problems”, the researcher, according to the degree of generalization that he establishes in the analysis, may group these categories under the name of "environmental effects".

4. Code the transcription by giving labels or codes to text passages that illustrate a specific limitation of the supply chain. Following the example of the previous number, the researcher will search for all the text fragments in the scripts that correspond to the problem "environmental effects" and its related sub-problems and synonyms (water consumption, deforestation, etc.), and will put the label “environmental effects” to each segment of the script where he/she finds them.

5. Once the data has been categorized, interpret the findings by looking for patterns and repetitions among the interviews. This involves examining the data in-depth and identifying the underlying meaning of the words of the stakeholders and implications of the findings. The researcher can also look quantitatively at the number of times a problem is mentioned or stakeholders mention a given problem more or less often.

6. Analyze the findings qualitatively for the second phase of the methodology.

The analysis is done with NVivo software, a versatile tool designed for qualitative research. NVivo enables us to efficiently manage and analyze the vast amount of information gathered from the interviews. Through its intuitive interface, we organized the data, identified key topics, and detected patterns and relationships that may have been otherwise challenging to identify manually.

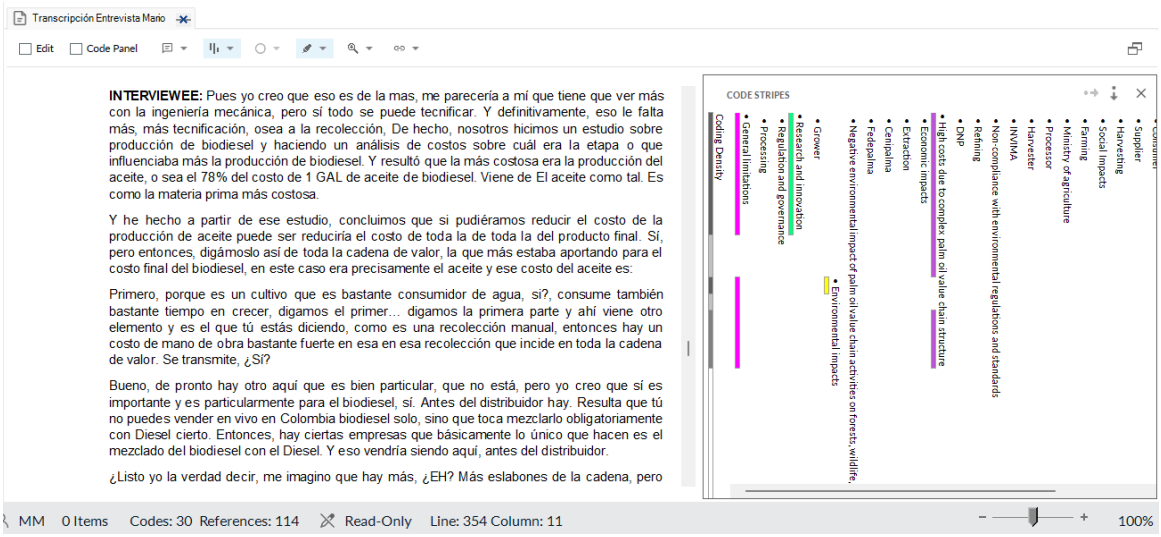


Figure 3-3. NVivo Interface: Coding Analysis of interviews

The **Figure 3-3** presented here showcases a segment of an interview transcript within the NVivo interface. The software allows us to organize the data by creating codes, each representing a specific topic. As seen in the image, different segments of the interview text have been associated with relevant codes that capture the essence of the topic discussed. NVivo can assess multiple codes to a single text segment and organize all of them to present it. This capability allows for nuanced and in-depth exploration of the data, as certain limitations may intersect with multiple aspects of different thematic.

Through the visual representation of code assignments and the ability to link various segments with corresponding codes, NVivo empowers us to discern patterns and connections in the data. This comprehensive approach enables us to gain deeper insights into the limitation's identification.

3.4 Inclusion of the supply chain's limitations in Product Design

The phase aims to analyze the potential effects that knowledge of the constraints the value chain may have on the design decisions of a downstream product. For this, a design workshop is proposed. The workshop has three parts. In the first part, the product scenario approach, a group of designers is invited to solve a product design product without any information about the supply chain. In the second part, evaluation of limitations by the participants, the information about the supply chain is given to the designers, making them

aware of the constraints of the value chain of which they are a part. In the third part, product definition, the designers are invited to rethink their design in the light of the information from the chain.

The structure of the workshop is presented in **Error! Reference source not found.** and is explained in detail in the following paragraphs.

Table 3-2. Outline of the product design workshop

Stage	Duration (min)	Description	Required Material
1. Workshop presentation			
1.1. Animator's presentation	1	Participants are given information about the facilitator and assistants who collaborate with them	Presentation (Annex B.1)
1.2. Introduction	5	**Objective:** Give an introduction of both the product design and the beverage to be worked on. It explains a brief context of product design formulated for the consumer and why it is important to make decisions there.	
1.3. Description of the activity	5	**Objective:** Explain how the design exercise will be done. The product is presented in such a way that the indications of the activity are given. Details such as duration, objective and explanation of the material are also given.	
2. Stage 1: Initial product design			

2.1. Ingredient selection	8	Participants are guided through the process of selecting the appropriate emulsifier. Attendees will work in groups and use a previously established format to evaluate different emulsifier options given along with information on each of the substances, based on specific selection criteria that they define and assign a level of importance to each criterion to justify the selection of the ingredient.	Criteria format (Annex B.3) Ingredient Cards (Annex B.2)
2.2. Discussion of options	10		
2.3. Identification of selection criteria	7		
3. Stage 2: Supply chain limitations			
3.1. Value Chain Presentation	8	**Objective:** To present the value chain along with the related limitations associated with the corresponding parties. The participants are shown a series of ordered activities that essentially represent the chain gathered from the interviews so that they can begin to determine the activities that add value to the basic materials based on initial visual information. In conjunction with these activities, the identified limitations are associated with the portion of the supply chain in which they occur, and a specific limitation is assigned to each group so that each group can	Presentation (Annex B.1)

		address a distinct topic before the results are shared.	
3.2. Activity about limitations	15	**Objective:** Obtain solutions to value chain limitations that will make the participants immerse themselves in the context of the value chain and make them think critically about the current state and propose solutions to certain sustainability problems. Participants are encouraged to react and discuss the chain's limitations. They are given the limitation card, which contains more specific information on the limitation, and they discuss their position in relation to the limitation, where they must propose solutions to make the chain more sustainable. These solutions are then ranked according to how easily they can be implemented and their impact on the value chain.	Cards of the limitations (Annex B.4) Brainstorm solution board. (Annex B.5)

3.3. Socialization of Solutions		**Objective:** Socialize the solutions given to the limitations addressed by the other groups and the most feasible solutions. A review is made of the easiest to apply solutions of each group and both the limitation and the solution are briefly presented.	-
4. Stage 3: Second product design			
4.1. Presentation Sustainability context		**Objective:** Question them if they would change his first design once they know the full context of the supply chain and its limitations. Participants are informed that they will now work with the information given about the supply chain and its limitations. So, the new design must consider this new context	Presentation (Annex B.1)
4.2. Ingredient selection and consideration of criteria		**Objective:** Obtain the selection criteria that each team considers when choosing an ingredient for this new scenario. Participants are invited to perform the same design exercise consisting of the selection of the emulsifier from step 1, but this time with this new scenario in mind, where they will redefine the selection criteria and assign a level of importance to each	Criteria format (Annex B.3) Ingredient Cards (Annex B.2)

		criterion to justify the selection of the ingredient.	
5. Step 3: Closing of the workshop			
5.1. Conclusion		Summary of the workshop's key findings.	-
5.2. Acknowledgment		The participants are acknowledged for the time they devoted to the activity, as well as for their enthusiasm and participation.	-

3.4.1 Product Scenario Approach

The initial part of the workshop is a scenario approach, and it focuses on product design, disregarding any limitations imposed by the supply chain. This is done to investigate the impact of unconstrained design processes on the creation of ideal solutions by providing participants with the freedom to explore design without the limitations of the real world. This practice enables participants to transcend conventional limitations and unleash their creativity.

The scenario approach phase of our methodology gives the participants a formulation design problem. They are asked to select one or various ingredients for a product. The participants receive information about the product to be designer, its requirements, functions, and suggestions of ingredients to be used. They also receive information about the possible ingredients to be used. Some of them come from the supply chain under study and some others have other origins, some of them are natural, some may be synthetic. The relation between the ingredients and the supply chain is not explicitly mentioned. For the

case study of the palm oil value chain, designers are asked to select an emulsifier for a vegetable milk beverage. They are introduced to the case through a presentation that describes the requirements of the product on which participants will focus their work. The presentation for the case study is available in Annex B.1.

Ingredients are provided to participants with a set of ingredient cards. Each card, as shown in the **Figure 3-4**, represents a different potential emulsifier for the product, with detailed information and properties of each ingredient. The cards (all of them are available in Annex B.2) provide insights into the origin, chemical properties, price, and other relevant characteristics of each emulsifier. This includes elements such as HLB values, molecular weight, melting point, lethal dose (LD50), and the national or imported nature of each ingredient.

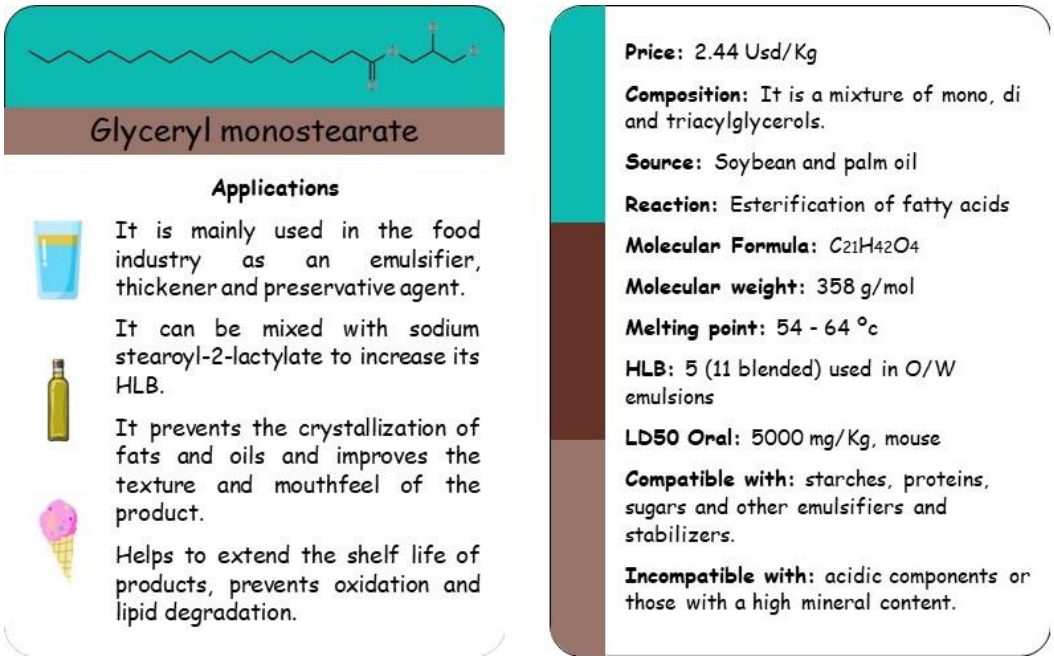


Figure 3-4. Example of ingredient card, front and back

These ingredient cards serve as essential tools for the participants, providing them with the necessary information to make informed decisions regarding ingredient selection. They enable participants to compare the different emulsifiers in a structured, systematic manner, thereby facilitating a more nuanced and informed decision-making process. Participants are invited to select from the cards the emulsifier that best meets the conditions of the problem and to give its selection criteria.

3.4.2 Evaluation of limitations by participants

This phase seeks to make the participants aware of the different problems of the supply chain of which the product is likely to be a part. The relationship between the problems of the chain and the design is not explicitly mentioned. This part provides an overview of the value chain, highlighting the interrelationships of the various stages involved.

Once the general concept of the value chain is well established, the limitations of the supply chain that were previously identified with the stakeholders are presented. These are inefficiencies, bottlenecks, lack of resources, or other limitations that hamper the overall productivity, profitability, or sustainability of the supply chain. The presentation of these limitations is enhanced with real-world examples (parts of the interviews where the stakeholders refer to the limitation studied) in presenting limitations enhances the participants' understanding and makes it more tangible and relatable.

The workshop shifts to an interactive format after the presentation. The objective of the task is to identify potential solutions to the presented limitations. The task at hand serves as a mean to apply acquired knowledge and stimulates creative thinking, collaboration, and active engagement with the subject. Solutions may be of any type and not necessarily related to the design of products. Through discussion, brainstorming, and formulation of innovative solutions, participants can overcome limitations and classify solutions based on the effort required for their implementation and their impact on the problem. Encouragement to think outside the box and propose radical or novel approaches is emphasized.

For the case study, limitations were presented in the form of information cards to make them accessible and easy to understand. Each card was dedicated to a specific limitation within the palm oil supply chain and provided a comprehensive overview of that issue.

The information presented on each card included:

1. **General limitation:** A concise statement identifying the primary issue or challenge.
2. **Description:** A brief yet detailed explanation of the limitation, providing more context and clarity.

3. **Related problems:** An outline of associated challenges or issues that stem from this primary limitation.

4. **Consequences:** An overview of the potential impacts or outcomes if the limitation remains unaddressed.

5. **Stakeholders involved:** A list of key actors within the supply chain who are directly or indirectly affected by or involved in this limitation.

6. **Supportive statements:** Authentic quotes from the stakeholder interviews that provide real-world perspectives and insights into the limitation.

As an example, the **Figure 3-5** shows a card that outline the limitation related to the inflexibility of the palm oil value chain.

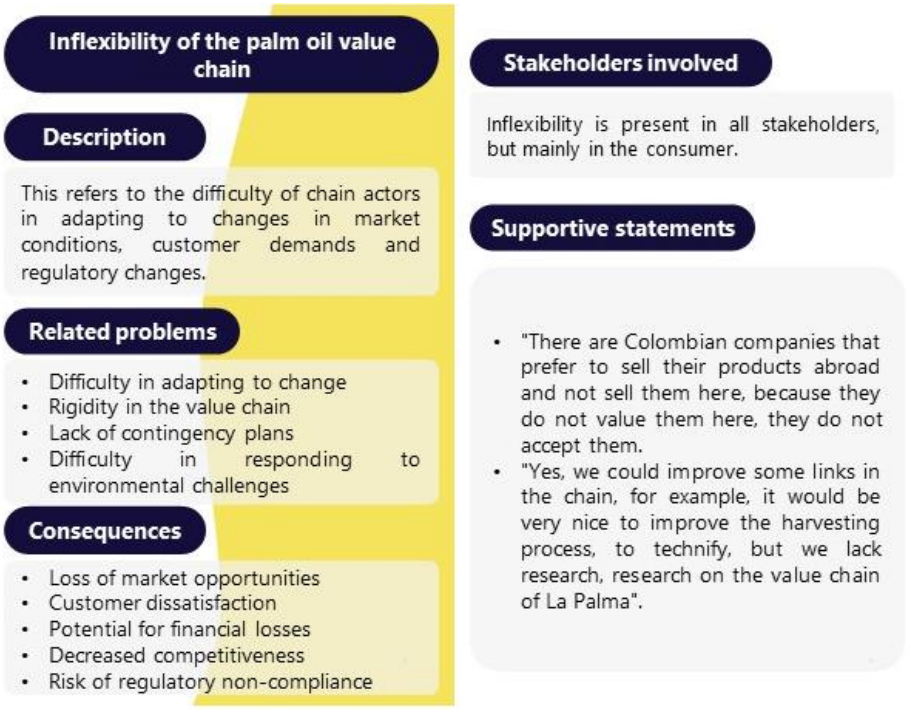


Figure 3-5. Example of card of limitation, front and back

This card-based approach was designed to provide a comprehensive yet digestible overview of each limitation. By segmenting the information in this manner, participants could gain a clear understanding of the complex challenges within the palm oil supply chain. It allowed them to comprehend the scope of the problem, the stakeholders involved, and

the potential impacts of each limitation. Participants were then asked to propose potential solutions for the identified limitations. This interactive problem-solving activity sought to foster an in-depth understanding of the challenges inherent in the palm oil supply chain and to inspire innovative approaches to the design of sustainable products within these limitations.

The categorization of proposed solutions based on their effort and impact was a determinant aspect of this assignment. For this, they were asked to write their solutions in post-it and to place them in the format of **Figure 3-6**.

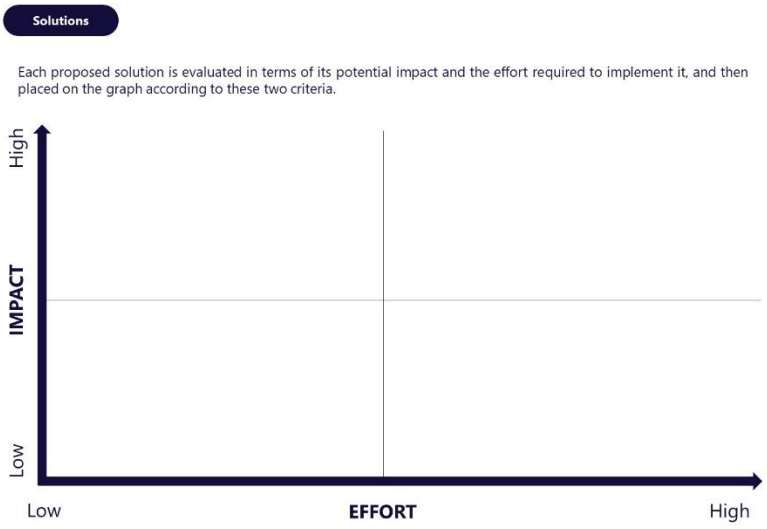


Figure 3-6. Format for solutions classification.

This exercise encouraged participants to consider the viability and efficacy of their proposed solutions, thereby incorporating practical considerations into their approach to problem-solving. By the end of this phase, participants are expected to have a comprehensive understanding of the supply chain and its limitations, as well as a range of possible solutions, fostering a mindset of continuous improvement and problem-solving that can be applied in their respective roles and industries.

3.4.3 Product definition

The subsequent part of the workshop is the final definition of the product, which is designed to encourage participants to rethink their previous product designs with their newly acquired understanding of the supply chain and its limitations. This phase aims to emphasize the influence of the supply chain on the decisions made in product design and highlight the need for a shift in perspective and decision-making approach.

After the activity with the limitations of the supply chain, the facilitator requests the participants to recall the product design they had previously studied in the first part of the workshop. The participants are then tasked with re-evaluating this initial design in the context of their newfound knowledge about the supply chain. They may affirm their decision, change their decision, and/or modify their decision criteria, if they deem it appropriate. Participants are invited to discuss. Participants are invited to ask themselves questions such as: How might the supply chain limitations affect the availability, cost, or quality of the ingredients they selected? How could they adapt their product design to overcome these limitations? Would they choose different ingredients knowing what they know now about the supply chain?

By comparing their original design decisions with their new insights, participants can clearly see how understanding the supply chain can influence product design. They may adjust their designs accordingly, or not.

By the end of this phase, researchers should have a deeper understanding of how knowledge of the supply chain and its limitations can directly impact product design decisions. They should be better equipped to enhance make more informed, practical, and sustainable choices in their future design work, leading to products that are not only innovative but also feasible and responsible in the context of the supply chain.

4. Testing and application of the methodology

This chapter introduces the application of the integrated product design methodology, which incorporates considerations specific to the palm oil supply chain. This methodology was explained in detail in Chapter 3. It stands out for its emphasis on both stakeholder perspectives and requirements, and it consists of six key steps: literature review, semi-structured interviews, identification of supply chain limitations via qualitative analysis and the product design workshop (**Figure 3-1**).

This chapter shows the application of the proposed methodology: a test with students and a test with stakeholders of the supply chain. The student test provides insight into how the methodology is applied by those who are new to product design, providing a fresh perspective on the methodology's phases. The stakeholder implementation, on the other hand, allows us to test the methodology in a more practical, real-world setting. Engagement with actual stakeholders guarantees that our approach can effectively address the complexities and nuances of real-world product design, sustainability concerns, and palm oil supply chain requirements.

4.1 Supply chain´s theoretical framework

Serving as the cornerstone of this chapter, the literature review establishes the theoretical scaffolding for the application of the methodology. This includes investigating the current state of knowledge concerning the palm oil supply chain focusing on the Colombian case, the related value and supply chain, and sustainability considerations.

4.1.1 Study Case: Palm Oil

Palm oil is now the most consumed vegetable oil in the world. Even more remarkable is the recent sharp increase in production in the last few years, up from around five million tons in the early 1980s to almost 80 million tons annually today as shown in the **Figure 4-1**

(FAO, 2021). The palm oil market was estimated to be worth $32.4 billion in 2020, with Indonesia accounting for 56.3% of this value, followed by Malaysia (30.3%), Guatemala (1.44%), and Colombia (1.25%) (FAO, 2021). The presence of these countries at the top is due to their climatic conditions as oil palm is a tropical plant species. It thrives in conditions of high rainfall, adequate sunlight, and humidity, which means that the best growing areas are in a narrow strip around the equator (Mohd et al., 2005).

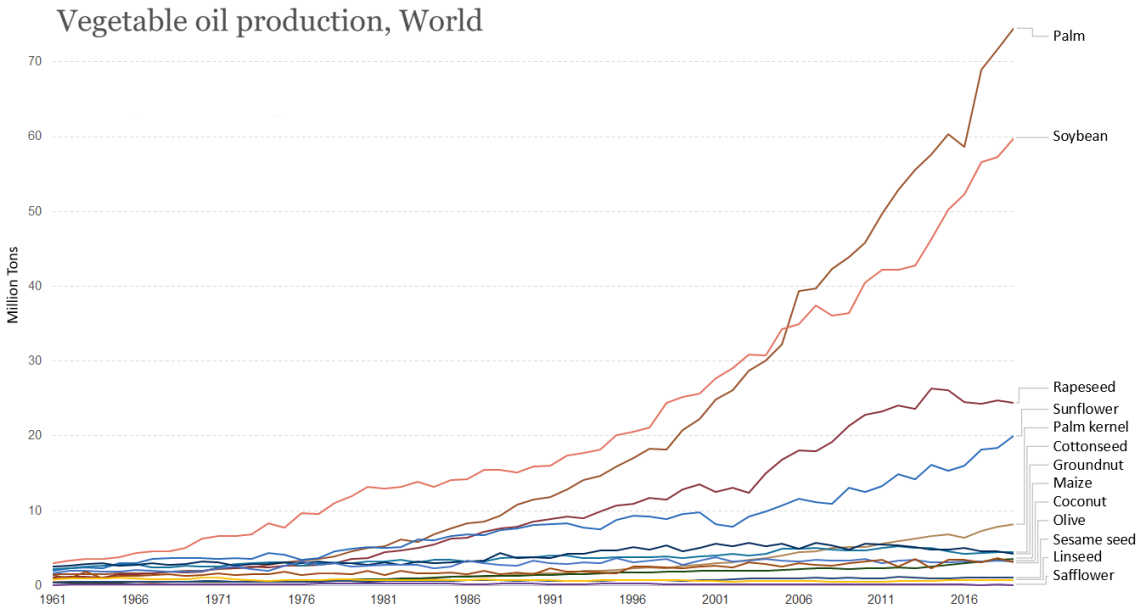


Figure 4-1. Vegetable oil production (FAO, 2021)

The question of which feedstocks are the most economically viable arises due to the growing global demand for vegetable oils for both food and biofuels (Muscat et al., 2020; Zahraee et al., 2022) . But the answer to this question depends on many variables, raising issues such as if there is a systematic difference between the various crops and production systems in economical terms, and which crop is best to meet this expanding demand. Because of this, the major oil crops, such as palm and soybean, have been competing for the past few years (Parkhomenko, 2004; Zimmer, 2010).

In terms of production, palm oil yield is between 4 and 10 times higher than that of other top vegetable oils as shown in **Figure 4-2**, making it the highest yield oil crop in the world (FAO, 2021). However, the high labor demand and intensity of crop labor could become a

strategic disadvantage compared to other crops, because social issues become more and more significant in the consideration of sustainability (Chiriacò et al., 2022).

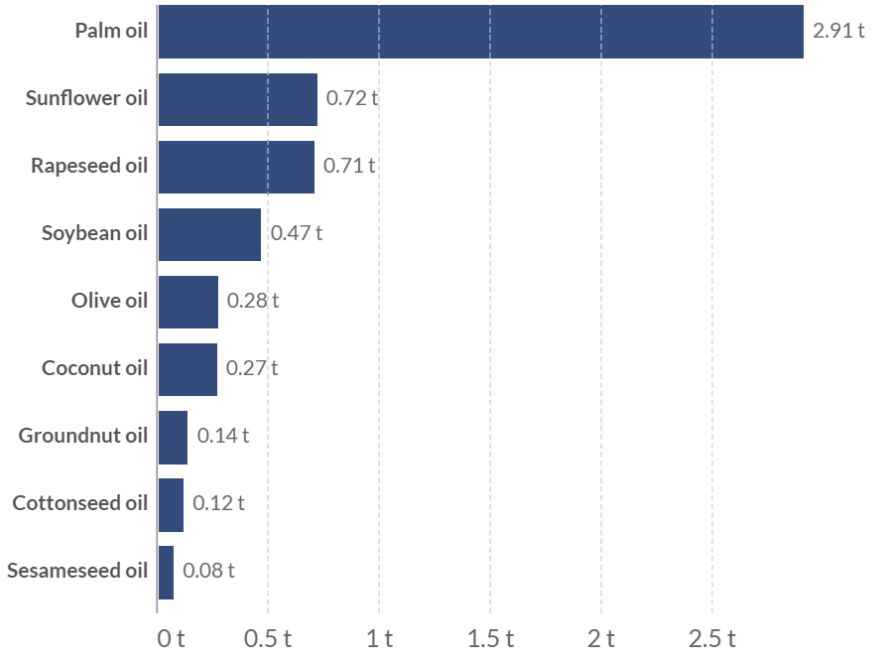


Figure 4-2. Oil yield by crop type (FAO, 2021)

In addition, palm oil is highly versatile; it can be used as a raw material for a wide range of products, such as foods, biofuels, surfactants, and cosmetics, among many others (Lipsa, 2018). This is due to its historically low costs, stable shelf life and nutritional advantages due to its high content of natural antioxidants such as vitamin A and E precursors (Sayago et al., 2007). **Figure 4-3** shows the market share of African oil palm goods in each product type category for the year 2021.

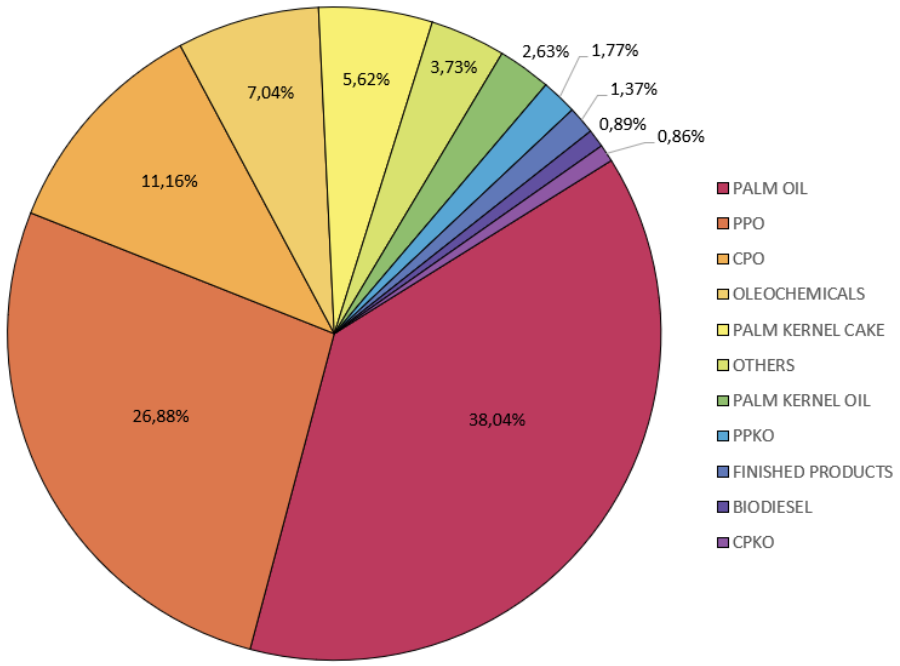


Figure 4-3. Participation of African oil palm goods by type of product in 2021 (PPO= Processed palm oil, CPO= Crude palm oil, PPKO= Processed Palm kernel oil, CPKO= Crude palm kernel oil) (Malaysian Palm Oil Board, 2021)

4.1.2 Palm oil sustainability

The concept of sustainable development is difficult to put into practice. It must strike a balance among economic, social, and environmental requirements. Moreover, that balance should also consider differences between developed and developing countries, as well as between the perspectives of producers and consumers (United Nations, 2020). The UN Environment has established general criteria, according to which sustainable palm oil is thought to reduce irresponsible production while directing the industry toward sustainable ways. Significant stakeholders in the palm oil sector, such as the RSPO or conglomerates like the POIG (Palm Oil Innovation Group) have been working to increase sustainability (ROBECO, 2022).

The circumstances behind the expansion of palm oil plantations as well as their social and environmental implications continue to raise concerns in the international market (Castellanos-Navarrete et al., 2021). On the one hand, the expansion of palm oil has significantly boosted the economies of the country where it is grown, improving the

infrastructure and lowering rural poverty (Ávila & Albuquerque, 2018). On the other hand, local community ecosystems have been highly affected; local communities have been displaced and natural ecosystem have been replaced by palm plantations (Sakai et al., 2022). Thus, palm oil industry development has frequently come at the expense of fundamental human rights and biodiversity (Rafflegeau S., 2013). Now, and due to the unfavorable public image and effects of its rapid expansion, the palm oil industry is looking towards sustainable production and consumption. Strong pressure from international organizations, and eventually the final consumer in developed economies is driving this change (Wang et al., 2022).

Different sustainability certifications and standards have been developed, covering a similar range of topics but with varying degrees of emphasis and detail. The absence of standardization and widespread adoption of norms or corporate requirements, however, limits their usefulness (Boons & Mendoza, 2010). Additionally, the idea of sustainable palm oil which evolves over time, serves as the foundation for the expectations of both consumers and companies (Brandi et al., 2015).

According to Schmidt & de Rosa (Schmidt & de Rosa, 2020), sustainable palm oil is linked to lower rates of deforestation and biodiversity loss, less soil erosion and water pollution, better productivity, and efficiency, resulting in higher yields with less use of fertilizers, water, and land.

Other challenges to achieve sustainable palm oil production are (United Nations, 2020):

- The lack of communication between actors from different points along the supply chain, which limits stakeholders' capacity to exert influence and pushes for the adoption of sustainability standards.

- The traceability challenges make it less appealing for companies to take ownership of their own operations and reduce the implementation of commitments.

- The perceived incompatibility of sustainability and economic development. Manufacturers and customers, for example, see "no deforestation" laws as achievable objectives, but upstream stakeholders worry that these commitments will impede growth, development, and business.

- Limited capacity in terms of human and financial resources of companies combined with a lack of training, knowledge, and awareness of the relevant concerns.

4.1.3 Colombian Case

Regarding the specific palm oil supply chain in Colombia, the smallholder farmer plays a significant role, there are close to 7,000 oil palm producers, 72% of which are smallholders, i.e., they cultivate less than 20 hectares. These smallholders account for 40% of national palm oil production (Fedepalma, 2019). Similar to the larger producers of palm oil, smallholder farmers in Colombia have made substantial contributions to the country's palm oil output, helping rural communities, increasing local government revenue, and improving community welfare (Castellanos-Navarrete et al., 2021).

To increase the productivity and competitiveness of the palm oil sector the Ministry of Agriculture and Fedepalma (National Federation of Palm Oil Growers) have generated initiatives including reduction of production costs, feasibility studies, promoting sustainability certification, implementing promotional campaigns, and facilitating credit approval through FINAGRO (organization promoting rural sector development by the Ministry of Agriculture)(Minagricultura, 2017) (DNP, 2007) By its part, the National Institute of Food and Drug Surveillance (Instituto Nacional de Vigilancia de Medicamentos y Alimentos, INVIMA), an organization affiliated with the Ministry of Health and Social Protection, regulates the quality of palm oil and its derivatives for local consumption or the requirements for trade with other countries.

The palm oil supply and value chain in Colombia involves various stakeholders from production to end use. **Figure 4-4** outlines the activities present in the value chain and the key actors of the supply chain including the specific governmental institutions and the national organizations mentioned before.

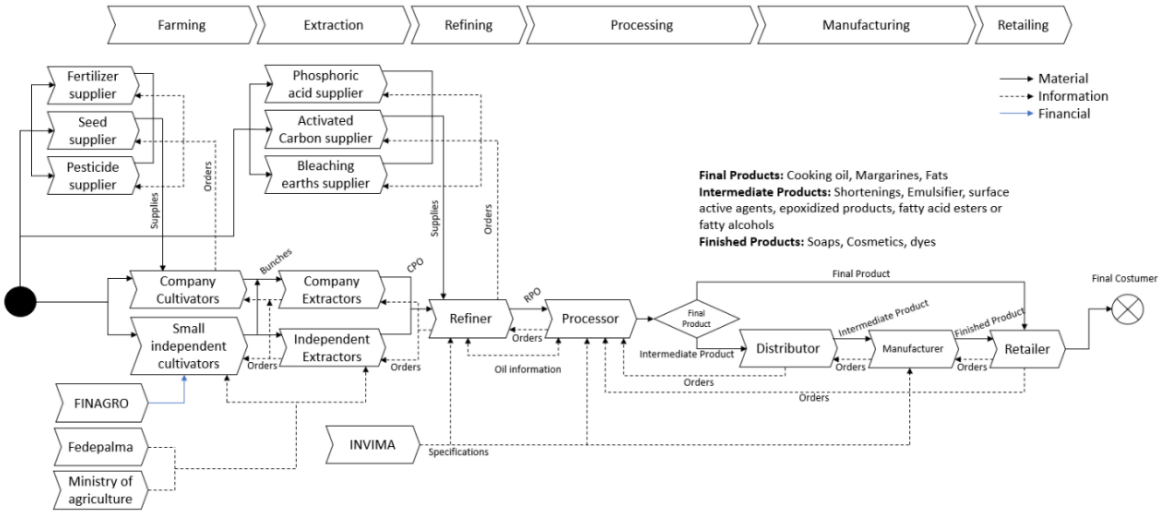


Figure 4-4. Theoretical Colombian Palm oil value and supply chain

The acreage set aside for palm in Colombia has increased fourfold since the 1990s, when palm oil production had its peak growth worldwide (FAO, 2021). Because of this, Fedepalma has overseen the National Sustainable Palm Oil Program (APSCO) since 2019, which aims to accelerate and scale up the efforts of its affiliates to adopt more socially and environmentally responsible practices across the supply chain (Solidaridad Network, 2020).

For instance, in order to encourage the expansion of palm oil production, the Colombian government has implemented a number of regulations, some of which forbid the clearance of primary forests (Barthel et al., 2018); However, implementation problems still exist, such as the ineffective application of the law, the competing interests of investors and municipal officials, among others (Millán-Quijano & Pulgarín, 2023).

4.2 Supply chain identification by stakeholders

The implementation of semi-structured interviews is the focus of the second phase of the methodology. In chapter 3, the design of the interviews was detailed and in this section the execution and analysis of these semi-structured interviews is explained.

Participants working within different areas of the Colombian supply chain were searched from a contact database of 21 names (provided by a Colombian expert in palm oil supply chain) and invited to participate in interview. Finally, ten participants agreed to take part in the interview.

The semi-structured interviews lasted between fifty and eighty minutes and took place over an online conference held on the platform Teams. The number of participants and their areas of expertise are outlined in **Table 4-1**.

Table 4-1. Description of the expert's areas of the participants in the supply chain identification process

Participant	Profession	Time of experience	Role	Stage of the value chain
Expert 1	Chemical engineer	20 years	General manager	Farming, Harvesting and Extraction
Expert 2	Chemical engineer	30 years	Director of quality management	Farming, Harvesting, Extraction and refining
Expert 3	Agro-industrial engineer	11 years	Formulator	Processing
Expert 4	Chemical engineer	14 years	Innovation and development manager	Processing
Expert 5	Business Administrator	16 years	Environmental sustainability Manager	Organization (Fedepalma)
Expert 6	Environmental engineer	7 years	Environmental specialist	Organization (Fedepalma)
Expert 7	Biologist	2 years	Environmental specialist	Organization (Fedepalma)
Expert 8	Chemical Engineer	20 years	Professor and Researcher	Institution of higher education
Expert 9	Chemical engineer	7 years	Professor and Researcher	Institution of higher education
Expert 10	Chemical engineer	13 years	Professor and Researcher	Institution of higher education

During the 'value chain mapping' exercise, it was observed that respondents had differing perspectives on the value chain. Based on the results of the interview, the **Figure 4-5** was created as a synthesis of the supply chain. While there was agreement in certain stages, individual interpretations revealed distinct perspectives on the procedure.

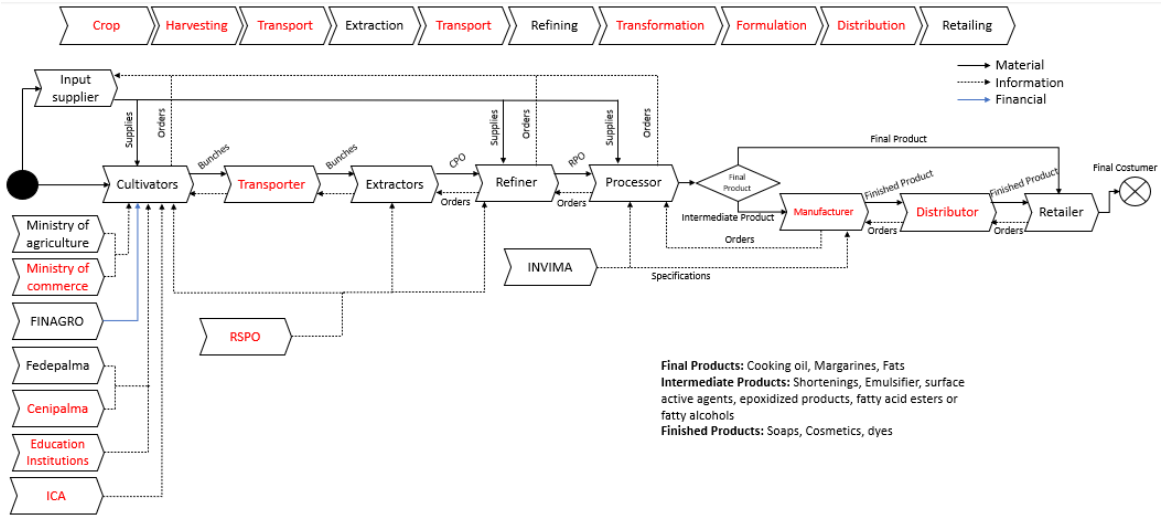


Figure 4-5. Value and supply chain resulting from the development of the interviews.

During the interviews experts 2, 3, 5, 8, 9 and 10 highlighted the impact of transportation on environmental sustainability. This more inclusive view of the palm oil value chain includes both production and logistical operations. Stakeholders demonstrated a deep understanding of sustainability by considering indirect effects of the supply chain, such as greenhouse gas emissions from transportation.

Experts 1, 2, 3, 8 and 9 also highlight the importance the product development in the supply chain. Product formulation is essential for transforming palm oil into numerous end products. It recognizes that the value chain includes stages that transform raw materials into finished products that satisfy consumer demands and preferences.

The activity of supply chain mapping with the stakeholders enables a new understanding of the supply chain. This network included both apparent and less obvious actors, including regulatory bodies, non-governmental organizations, researchers, and consumers. For

example, stakeholders included the Colombian Agricultural Institute (ICA), which plays an important role in the cultivation, and certification bodies such as the RSPO in the supply chain. Also, experts from the research sector explain in the interviews that higher education institutions are highly involved in researching productivity of both crops and refining and transformation. The variety of identified actors reflects the complex character of the palm oil industry and its impact on the product design process.

4.3 Supply chain´s Limitations Identification

This section examines the palm oil supply chain and its inherent limitations using coding to analyze the collected data which are the transcripts of the interview to the 10 stakeholders in a systematic manner. The objective is to identify possible limitations that are currently present in the supply chain of palm oil in relation to its productivity and sustainability.

In NVivo, the software selected for qualitative analysis, the transcripts of the interviews were uploaded to the software in Spanish. As shown in **Figure 4-6**, as documents are coded, the software keeps track of the frequency with which each code appears, the number of documents in which it appears. Then, to generate graphs or visualizations, the software can produce something like a graph showing the most frequently assigned codes in the entire data set. This allows you to quickly identify the key themes or concepts that emerged most frequently during the analysis.

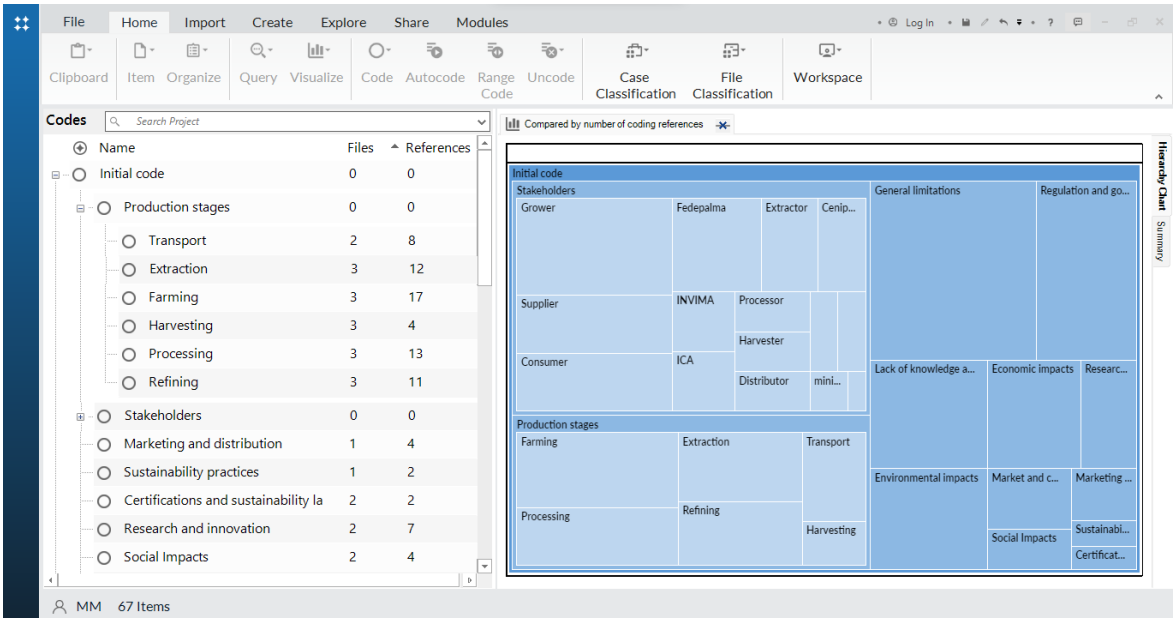


Figure 4-6. Visualization of the most used codes in the software NVivo.

As mentioned in section 3.3 above, the analysis was done in two stages. During the first stage, documents are read, and the main themes are identified by the reader. These included the most frequently mentioned stakeholders as well as the activities within the value chain. The **Figure 4-7** shows the results of this phase, generated using the software. Specifically, the figure presents a chart with the most frequently assigned key codes or themes during the initial coding of the documents read. This provides an overview of the predominant concepts and themes identified when reviewing the qualitative data sources.

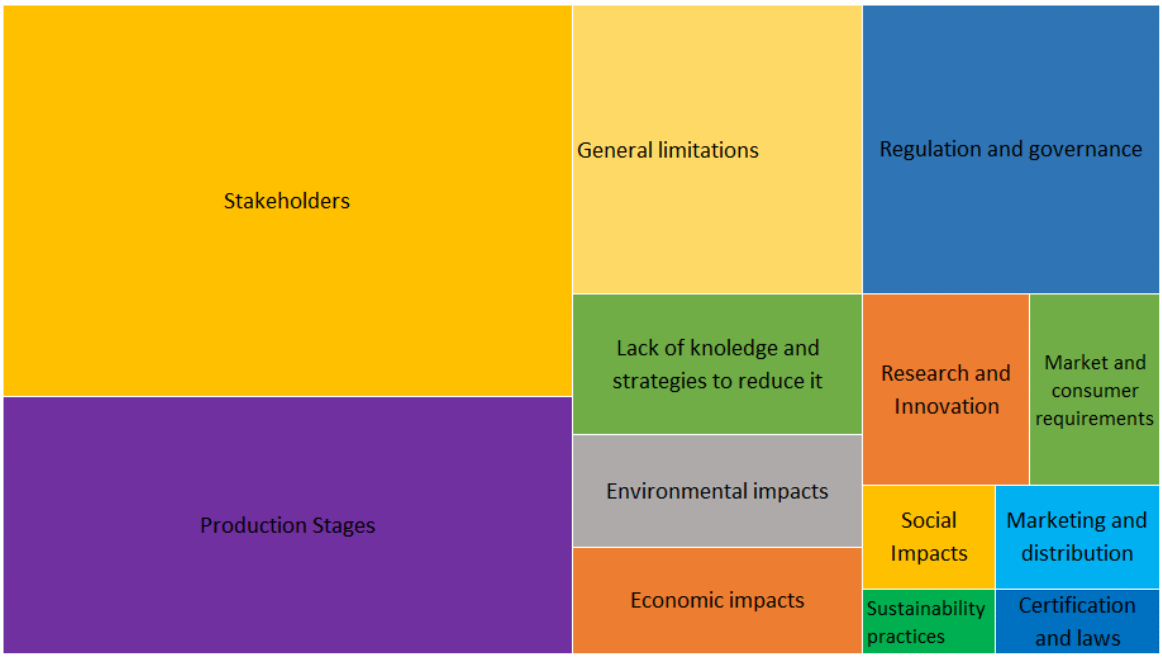


Figure 4-7. Most frequently mentioned topics

The interviews revealed that growers and suppliers were the most frequently mentioned stakeholders as shown in the **Figure 4-8**. The prominence of producers in the value chain highlights the importance that stakeholders give to agricultural activities in palm oil production in Colombia. According to them, the knowledge of agricultural practices and sustainable farming techniques is important for the successful cultivation of oil palm and the production of high-quality palm crops (Expert 1 said: “from the end of this cycle, they are very profitable because the soil conditions have improved a lot and it helps that you have to use less water because it is retaining more soil moisture and you are using less agrochemicals which favors the same biodiversity of both the soil and the crop.”). In

addition, stakeholders stated that growers' decisions regarding land use, crop management, and pest control have a significant impact on the overall productivity and sustainability of the palm oil supply chain supported by expert 5, who said: ”There are better agricultural practices that help overcome phytosanitary challenges and improve productivity for palm growers, but it is also focused on investigating the best agricultural practices: soil use, use of water resources, improvement of biodiversity both in the soil and with the crop itself, and the use of the soil itself.”.

Suppliers contribute to the supply chain by ensuring that growers have access to the resources essential for maintaining and optimizing their plantations. Collaboration between producers and suppliers is essential for the successful implementation of sustainable agricultural practices and the overall productivity and efficiency of the supply chain.

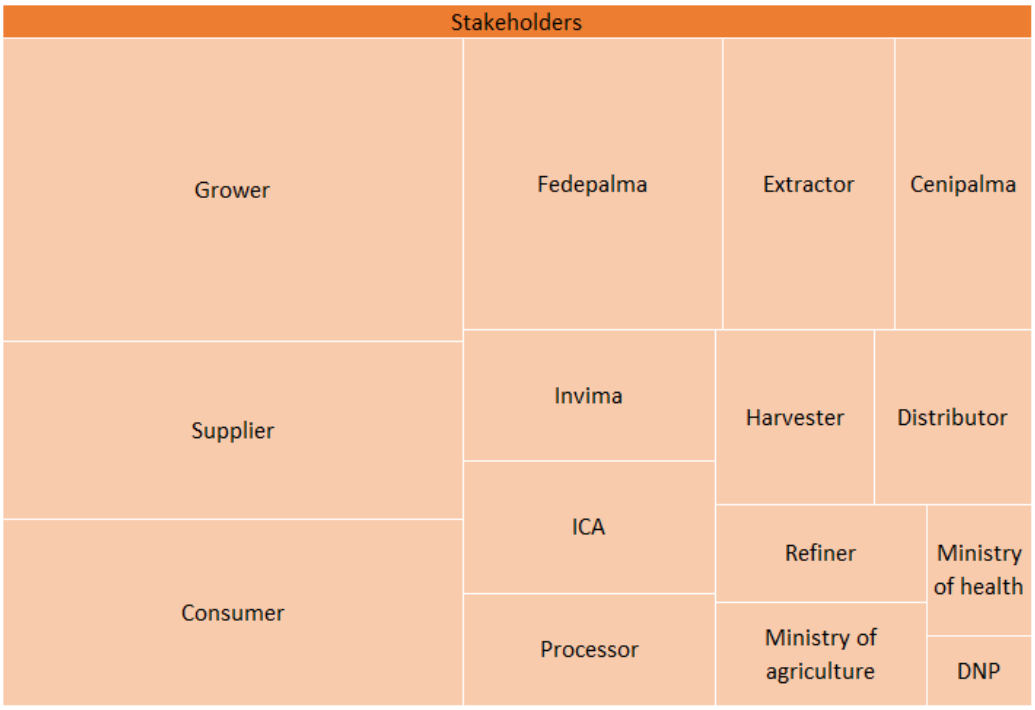


Figure 4-8. Results of the stakeholders most frequently mentioned in the interviews.

Additionally, **Figure 4-9** shows that activities most frequently mentioned by stakeholders during the interviews. The emphasis giving by stakeholders on farming and processing activities within the value chain reflects that they give importance mainly to the primary phases involved in transforming raw materials (palm fruits) into valuable products (palm oil and its derivatives). For instance, as indicated by the statement made by Expert 3

“Harvesting is the stage that requires the most hours and where we help the community the most to generate employment. It is key because the other stages, such as extracting, are done with machinery where there are few people, refining is done by engineers, there are few people, but in the cultivation and harvesting stage a lot of people are needed, so this has a great impact.”

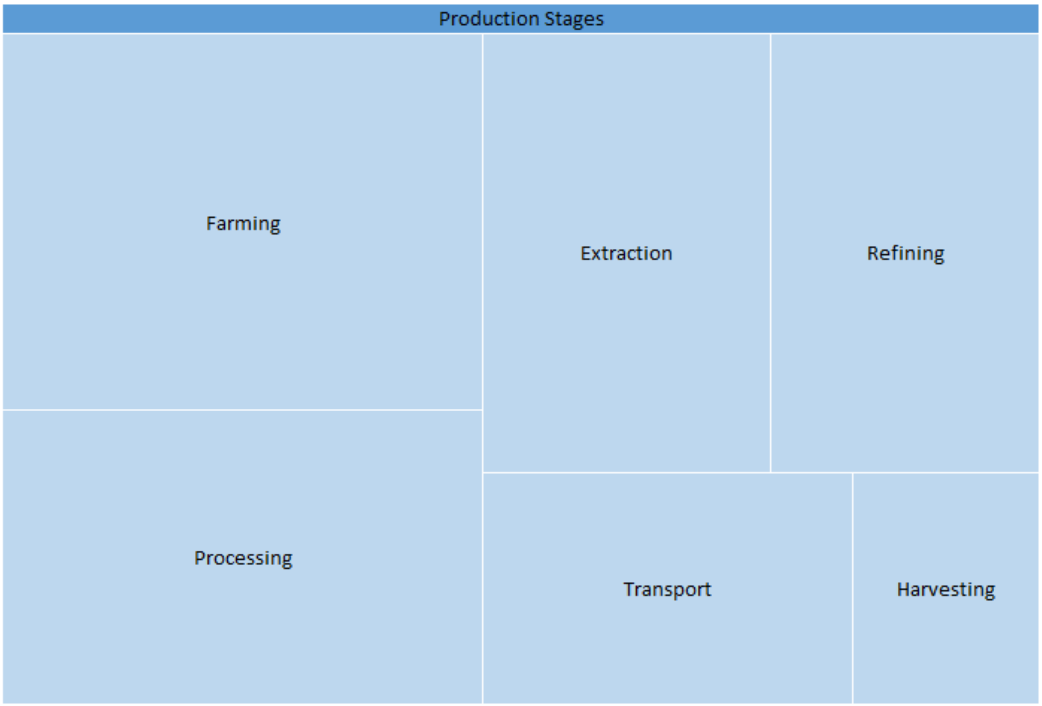


Figure 4-9. Results of the stages of the process most frequently mentioned in the interviews.

During the second phase of the coding procedure, the attention now shifts to a more in-depth investigation of the limitations and difficulties within the supply chain. the identification of specific obstacles to the supply chain's seamless operation that were commonly identified by stakeholders due to the procedure just completed.

In the first phase of coding, as shown in the **Figure 4-7**, there is a category called general limitations. It was feasible to ascertain a collection of general limitations that were widespread across the palm oil supply chain. The use of the NVivo software proved useful in easing the analytical process. Through the utilization of the software's functionalities for coding and arranging data as show in the **Figure 4-10**, it was possible to classify interview fragments that were linked to the general limitations. This facilitated the examination of the data and grouping them in the second code.

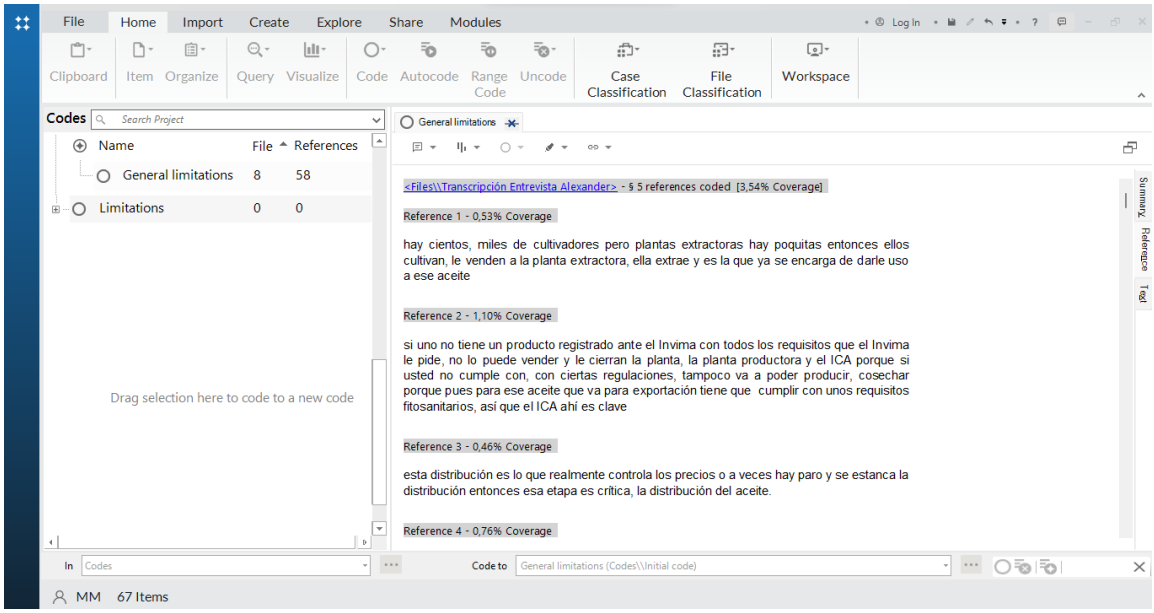


Figure 4-10. NVivo's functionality to arrange data related to a specific code.

The second code corresponds to highlighting the limitations that were recurrently mentioned by the different stakeholders. As shown in **Figure 4-11** the most frequently cited theme was "environmental impact," which emerged as a major concern for stakeholders.

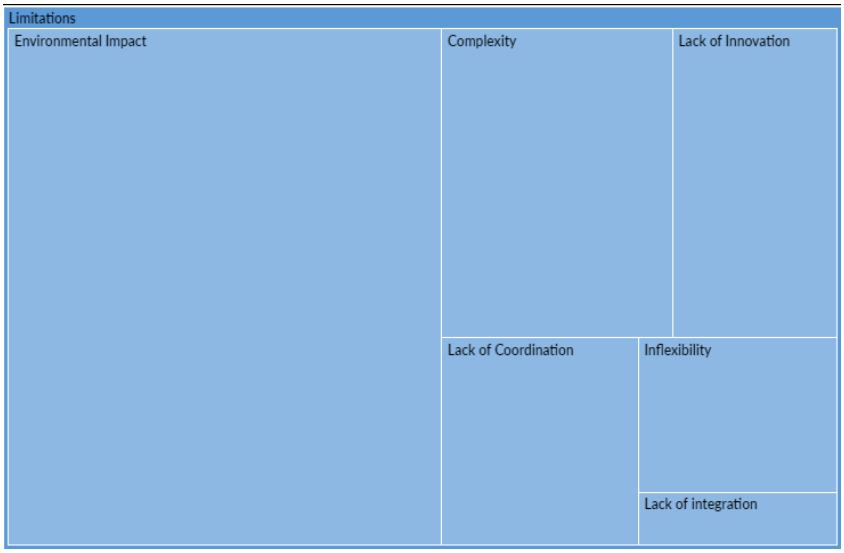


Figure 4-11. Chart illustrating the frequency of the supply's chain limitations mentioned by stakeholders

This finding indicates that environmental considerations are crucial in their perceptions of the supply chain. The second most mentioned theme was the "complexity of the supply

chain," suggesting that stakeholders perceive the supply chain as intricate. These results highlight the significance of addressing environmental concerns and streamlining the supply chain to meet stakeholders' expectations and improve overall sustainability.
The limitations identified are presented in the following list with the translation of fragments of the interviews that justify the corresponding limitation:

1. **Lack of Integration:** There is poor communication and alignment between different actors across the supply chain. Information sharing and collaboration is lacking.
    - Expert 2: “But there is a lack of communication from there and selling the idea to the people, but selling the idea with reality, with our Colombian reality, not with the reality of the gentlemen in Malaysia.”
    - Expert 4: "So, the role is to understand, that is, from the government, part of that lack of knowledge and that taboo that they are putting on oils, especially palm oil, which prevents you from using them."
2. **Dependence on Suppliers:** The supply chain relies heavily on a small number of major suppliers for key materials like palm oil. This dependence creates risks and vulnerabilities.
    - Expert 4: "In general, I think supply. Because price and supply also have their complexity, because of who we are competing for that. I mean, I hear a lot in my company, of the rise and fall of prices and availability."
    - Expert 9: "There is a strong dependency there. In fact, one of the great criticisms of biodiesel production is that it enters into direct competition with the generation of food."
3. **Inflexibility:** The supply chain has difficulty adapting to changes in market conditions, regulations, or consumer demands. Production processes are rigid and slow to evolve.
    - Expert 2: "There are Colombian companies that prefer to sell their products abroad and not sell them here, because they do not value them here, they do not accept them.
    - Expert 9: "Yes, we could improve some links in the chain, for example, it would be very nice to improve the harvesting process, technifying it, but we lack research, research on the palm value chain".
4. **Complexity:** The extensive network of actors and activities makes the supply chain overly complex. This leads to inefficiencies, delays, and increased costs.

- Expert 9: “In fact, we conducted a study on biodiesel production and made a cost analysis on which was the stage that most influenced biodiesel production. And it turned out that the most expensive was the production of the oil, that is, 78% of the cost of 1 GAL of biodiesel oil. It comes from the oil as such. It is like the most expensive raw material”, “As it is a manual harvest, there is a high labor cost in that harvest, which affects the entire value chain.”
- Expert 4: “Because price and supply also have its complexity, because of who we are competing for. I mean, I hear a lot in my company, in the company where I work about the rise and fall of prices and availability.”

6. **Lack of Innovation:** There is limited investment and incentives for research and development to improve practices and technologies across the supply chain.
    - Expert 10: “at this moment there is no political or economic context for investment because they are becoming ultra millionaires with the value of palm oil which is what they are trying to get more palm oil as much as possible.
7. **Environmental Impact:** Activities within the supply chain like farming, processing, and transportation have negative environmental effects like deforestation, pollution, and carbon emissions.
    - Expert 9: “I do believe that in Colombia there are problems of deforestation due to palm oil.”
    - Expert 4: “And it also has a lot to do with this because in the future you will not have so much supply of Palma or it will cease to be so attractive, it will enhance those negatives that La Palma has associated with the whole issue of environmental impact.”

In terms of the second coding, the mentioned limitations reflect the multifaceted challenges and complexities inherent in the Colombian palm oil supply chain according to the interviewed stakeholders. Growers, processors, distributors, and organizations, as well as those involved in other stages of the value chain, have undoubtedly encountered these limitations during their involvement in the industry. Contributing to the emergence of these

limitations is the interaction of factors such as the fragmented character of the supply chain, inadequate coordination, and communication gaps among stakeholders.

The highly decentralized structure of the palm oil industry in Colombia may be a contributing factor to the frequent mention of limitations associated with a lack of integration. It becomes difficult to establish seamless integration and effective collaboration when numerous actors operate in diverse geographical regions. Absence of standardized processes and protocols can lead to inefficiency, duplication of efforts, and stakeholder conflicts.

The industry's reliance on a handful of major palm oil suppliers can be attributed to market dynamics and historical relationships. Due to the potential risks associated with supply disruptions, variations in product quality, and limited availability of local palm oil, stakeholders may have expressed concerns about overreliance on specific suppliers. In addition, the absence of contingency plans may indicate a lack of readiness to mitigate the impact of a failed supplier, leaving the supply chain vulnerable to potential disruptions.

Inflexibility and complexity are typical obstacles for agricultural production and refining industries. Long production cycles, resource-intensive processes, and regulatory limitations may account for the rigidity and difficulty of change adaptation in the palm oil supply chain. These limitations can hinder the industry's ability to respond rapidly to evolving market conditions, shifting consumer demands, and emergent product specifications.

The diverse interests, goals, and objectives of stakeholders at various phases of the value chain may contribute to a lack of integration. Inefficiencies, delays, and misunderstandings can result from competing priorities, varying levels of understanding, and misaligned expectations, impeding effective collaboration and cooperation.

In the palm oil industry, the limitations associated with innovation and environmental impact are emphasized in certain improvement areas. Resistance to change and a lack of innovation incentives may result from risk aversion, limited resources for research and development, and an emphasis on short-term profitability. The environmental impact of palm oil production, which includes deforestation, the loss of wildlife habitat, and pollution, highlights the need for sustainable practices and compliance with environmental regulations.

4.4 Inclusion of the supply chain's limitations in Product Design

From the knowledge gained from our literature review, stakeholder interviews, and the identification of limitations within the palm oil supply chain, we move on to the product scenario approach, the next phase in the proposed methodology. This part explores the product design process where theoretical knowledge and practical insights converge to inform actionable steps.

4.4.1 Product Scenario Approach

In the product scenario approach, the scenario was presented to two groups of chemical engineering students for the test and the group of two designers of the food industry, without any context-specific information regarding the palm oil supply chain. The objective was to comprehend their decision-making process in an uninformed state, simulating a typical situation in product design where specific supply chain knowledge may not be readily available. The groups were asked to choose an ingredient for a commercial beverage containing natural cocoa and almonds, as explained in full detail in chapter 3 (section 3.4).

The beverage is a formulation of several ingredients. The participants were tasked to select one of the ingredients, the emulsifier, from a pre-done list of options. The emulsifier maintains the stability of numerous food and drink products. In our scenario, we evaluate three potential emulsifiers: soy lecithin, glyceryl monostearate, and polysorbate 80. Each emulsifier brings unique properties to the product. Soy lecithin is commonly used in food and beverage products and is not derived from palm oil, often perceived as a more natural alternative. On the other hand, glyceryl monostearate and polysorbate 80, both of the options were presented as derivatives from palm oil (although they may be produced from other sources), are also widely used in the industry and offer specific functional benefits. The full characteristics of the options were given to the participants and are available in annex B.2.

Based on this information, each design group selected independently the emulsifier of the product, giving the justification of their choice. **Table 4-2** illustrates the emulsifier choices made by the participants in the first round of selection.

Table 4-2. Results of the first selection of the participants.

Group	Selection Criteria	Justification
Students 1 Selection: Soy Lecithin	Price	The one with the lowest price is sought
	Health	The one with the lowest molecular weight (related to synthesis in the organism).
	Source	Products of local production and related to the generation of employment.
	Features	It is widely used so it is better known by the consumer.
	HLB	A value that is in the range of values of the products in which it is commonly used.
Students 2 Selection: Glyceryl Monostearate	Reduction of environmental impact	Choose a product that does not have a petrochemical origin.
	Usefulness in everyday applications	Choose the emulsifier that can withstand higher temperatures
	Health impact or risk	Choose the emulsifier with a medium-low lethal dose.
	High temperature compatibility	Choose the emulsifier that withstands high temperatures.
	HLB of emulsifier	Choose an emulsifier with a low HLB but with the possibility of being modified
Designers Selection: Soy Lecithin	Naturalness	Naturalness
	Functionality	Level of fat to be emulsified in the product
	Nutritional contribution	Less saturated fat content, the others have a higher index.
	Cost	Lower price

In the first portion of the product scenario approach, the group of students 1 initiated their process by creating a table to organize and evaluate the most critical criteria provided on the emulsifier information cards. These criteria included origin, HLB (Hydrophilic-Lipophilic

Balance), molecular weight, national or imported status, LD50 (Lethal Dose, 50%), emulsifier characteristics, and price.

Polysorbate 80, despite being an option, was initially the least favorable due to its petrochemical origin. When juxtaposed against lecithin and monostearate, both of which are wholly natural, it garnered less acceptance. However, LD50, indicative of a substance's toxicity and directly influencing consumer health, was a significant factor in their deliberations. The team reasoned that a higher LD50 value would suggest safer utilization.

Additionally, a high HLB value was regarded critical, given the nature of the product in question: an almond and cocoa-based beverage. A high HLB value assists the coexistence of the oil and water phases, steering the team towards emulsifiers with higher HLB values, provided they aligned with the team's other criteria. Molecular weight also factored into their ultimate decision. The team believed that an emulsifier with a larger and denser chain might be more slowly or complexly metabolized in the body. The melting point of the emulsifier was considered in relation to the processing conditions of the ultimate product, particularly the impact of high temperatures.

Ultimately, the team's decision inclined towards a naturally derived emulsifier that could contribute to consumer health, be profitable for the production process (with price being a key indicator) and possess properties conducive to the product's composition. Therefore, after a comprehensive examination of the options against these criteria, lecithin was the final selection made by students' group 1.

Group 2 systematically contrasted various criteria to identify an appropriate emulsifier for the proposed product. They considered various factors including origin, lethal dose (LD50), Hydrophilic-Lipophilic Balance (HLB), molecular weight, import status, and price. Polysorbate 80, due to its petrochemical origin, was the least favored option among the team members. Their shared concern for environmental impact drove them towards contemplating naturally derived emulsifiers, with lecithin and monostearate emerging as top contenders.

Apart from these factors, the team also considered the melting point and thermal tolerance of the emulsifiers. Initially, lecithin was a popular option, but upon discovering that its properties could be affected when heated beyond 80°C, it was discarded. The team

reasoned that consumers often favor hot beverages, and a reduced heat tolerance would limit their product's versatility. LD50, a measure of toxicity, was another critical factor in their decision-making process. In consideration of consumer health, the team intended to select an emulsifier with a high minimal lethal dosage.

The HLB value, a determinant of oil and water phase compatibility, was also a key consideration. The team was inclined towards emulsifiers with high HLB values, as this would facilitate greater integration of the oil phase with the aqueous phase. Despite contemplating factors like density and molecular weight, these properties were not the decisive factors in the team's selection process.

Ultimately, despite being the most expensive option, monostearate was chosen. It fulfilled the team's main criteria: it was naturally derived, had a high LD50, and while its HLB wasn't the highest, it could be improved with the incorporation of other substances. This decision represents the team's endeavor to balance various considerations including environmental impact, consumer health, and product functionality.

Group 3, comprised of designers with over a decade of industry experience, contributed an original perspective to the product scenario approach. They were able to conduct a thorough analysis of both the proposed product and the potential emulsifiers due to their extensive experience. As the scenario's product was a natural beverage, Team 3 carefully considered its potential consumer base. They concluded that the probable consumers would be health-conscious individuals who value the quality and naturalness of the products' constituents. This led the team to prioritize natural origin as their primary selection criterion for emulsifiers.

Moreover, functionality was identified as an important factor. Given that cocoa and almonds contribute lipids to the beverage, the chosen emulsifier had to effectively homogenize these fat-containing components to prevent separation. Consequently, the Hydrophilic-Lipophilic Balance (HLB) of the emulsifiers was an important factor for the team. The team also considered the nutritional qualities of the emulsifier. The interaction between the emulsifier's naturalness, functionality, and nutritional value determined their final choice.

The designers selected soy lecithin as their emulsifier of choice after considering these criteria, as it efficiently met all of their identified criteria. This decision highlights the team's

comprehensive comprehension of the product and its potential consumers, demonstrating their ability to make well-informed and comprehensive product design decisions.

4.4.2 Evaluation of the limitations by participants

The next stage of the methodology involves a comprehensive evaluation of the identified limitations within the palm oil supply chain. This step aims to enhance the understanding of the various challenges and limitations associated with the palm oil supply chain, as identified through our earlier interviews with key stakeholders. This phase of the workshop was fully explained in chapter 3 (subsection 4)

In this phase, each participant group was presented with a detailed overview of the palm oil supply chain (Annex B.1). This overview was a power point presentation with the results of the diagnosis phase (in section 4.3 included a breakdown of the various stages within the value chain, from the cultivation and extraction of palm oil to its processing, transportation, and final use in various products. Each stage was discussed in detail, providing the participants with a thorough understanding of the complex processes involved. Additionally, the presentation identified the key stakeholders involved at each stage of the value chain. This allowed the participants to gain a nuanced understanding of the value chain's broad range of actors, their roles, and their potential influence on the overall process.

This stage highlighted the limitations that were identified in the stakeholder interviews. These limitations were discussed, providing a practical context for the participants and enabling them to understand the real-world challenges faced within the palm oil supply chain.

As indicated in chapter 3, Participants were asked to propose solutions for palm oil supply chain limitations. Group 1 began developing potential solutions after obtaining a comprehensive comprehension of the identified limitations within the palm oil supply chain. These solutions shown in the **Figure 4-12**, reflected their collective analysis and ingenuity, aimed to address the obstacles and limitations at various phases of the value chain.

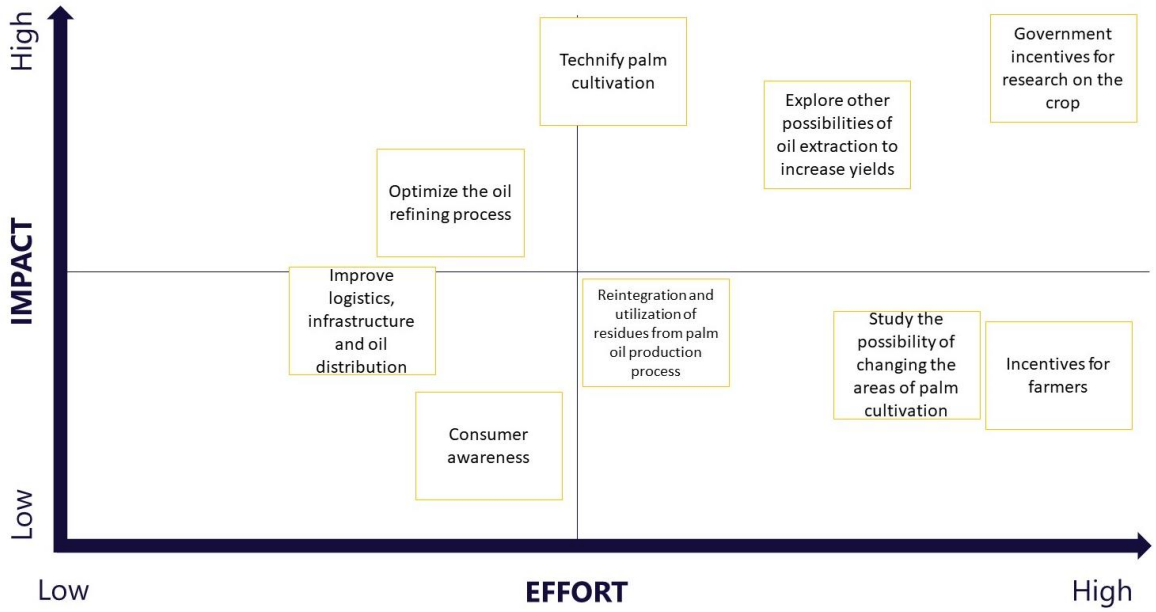


Figure 4-12. Results of the solutions proposed by student group number 1.

An important observation regarding Group 1's proposed solutions is that they seek a balance between impact and effort. For instance, their recommendations to 'improve logistics, infrastructure, and oil distribution' and 'optimize the palm oil refining process' imply moderate impacts and efforts, indicating that these could be 'low-hanging fruit' solutions that could be implemented with relatively less resource investment.

In the meantime, solutions such as "technify palm oil cultivation" and "government incentives for crop research" are viewed as high-impact but also high-effort solutions, indicating that their potential for significant positive change is acknowledged, as well as the considerable resources required to achieve them.

On the other hand, "raise consumer awareness" is viewed as a relatively low-impact, low-effort solution, suggesting that it may serve as a supplement to more effective strategies.

In conclusion, Group 1's proposed solutions demonstrate a nuanced understanding of the limitations within the palm oil supply chain and present a balanced combination of high effort and low effort strategies with varying levels of impact. These proposed solutions serve as a beneficial starting point for further investigation and validation in later phases of the methodology.

Group 2 engaged in a deliberative process to generate potential solutions after gaining a comprehension of the limitations of the palm oil supply chain. Recognizing the diversity of challenges within the supply chain, Group 2's solutions shown in **Figure 4-13** go with a range from grassroots interventions to structural adjustments at the highest levels.

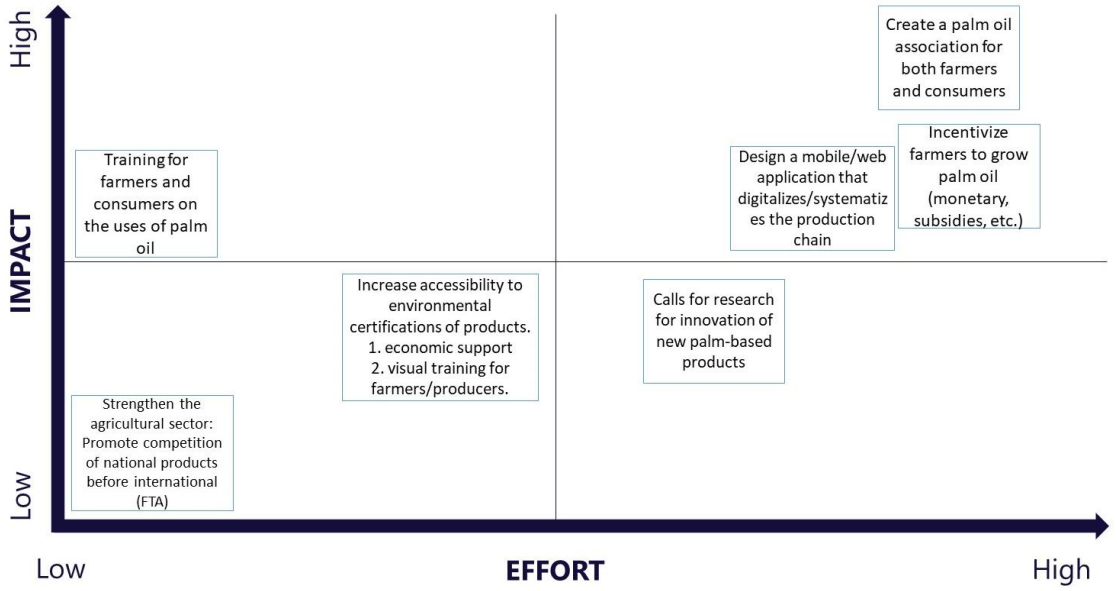


Figure 4-13. Results of the solutions proposed by student group number 2.

Group 2's solutions reveal thoughtful consideration for a variety of stakeholders, including producers, consumers, researchers, and the agricultural community at large. Their proposed solutions suggest an emphasis on education, with initiatives such as farmer and consumer training and demands for research, indicating a belief in the efficacy of knowledge dissemination as a change agent. In addition to a comprehension of the power of digital tools and organization, their solutions include the creation of a mobile application to systematize the production chain and the formation of a farmers' and consumers' association. Nonetheless, these solutions are acknowledged as requiring more effort.

Their suggestions regarding environmental certifications and incentives for producers demonstrate an awareness of the balance between economic viability and sustainability in the palm oil value chain. Group 2's proposed solutions demonstrate a balanced approach to resolving the limitations in the palm oil value chain, taking multiple stakeholders and strategic approaches into consideration.

As we advance through the evaluation phase of our methodology, we are now focusing on the distinct insights provided by our team of seasoned industry designers. With their vast experience and nuanced knowledge of the food industry, this group provides a unique lens through which to examine the limitations within the palm oil value chain. By combining their understanding of product design, consumer preferences, and industry dynamics, they proposed an array of innovative solutions as shown in the **Figure 4-14**.

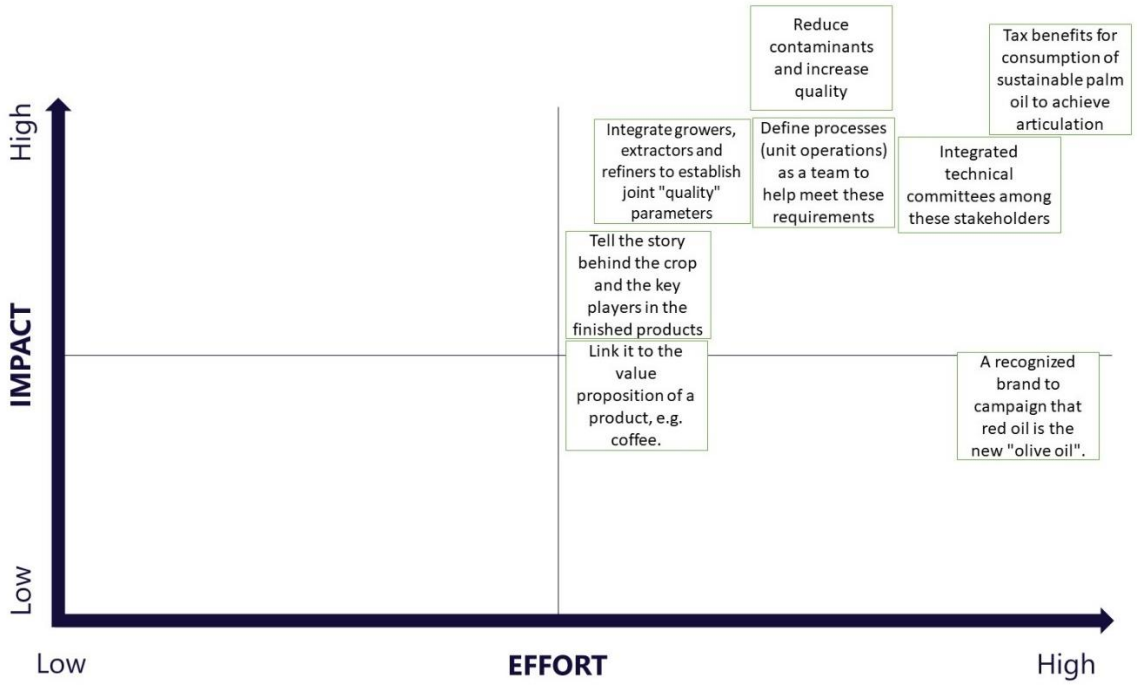


Figure 4-14. Results of the solutions proposed by the food product designers.

Analyzing these solutions reveals that the designers are highly aware of the influence of narrative and branding on consumer perception and behavior. They propose utilizing these tools to improve the perception of palm oil, drawing parallels to successful initiatives in other industries such as coffee. Their emphasis on collaboration and integration across the value chain, as reflected in their recommendations for establishing joint quality parameters, forming integrated committees, and aligning processes, demonstrates a systemic approach to overcoming limitations.

In addition, their proposals to advocate for tax incentives for sustainable palm oil consumption and to enhance product quality demonstrate an awareness of the need for both industry incentives and product-level improvements to support sustainable practices. Overall, the industry designer group's proposed solutions offer a unique perspective to the

table, reflecting their knowledge of the consumer end of the palm oil supply chain and their experience in the industry.

4.4.3 Ingredient definition

As we reach the final phase of our integrated methodology, we revisit the scenario-based approach that was previously implemented. The selection procedure is now informed by the context of the palm oil supply chain. This modification ensures that participants use the palm oil supply chain, its stakeholders, and its limitations to inform their decision-making.

In this phase, participants are tasked once more with selecting an emulsifier for the proposed natural cocoa and almond beverage. Nonetheless, their decisions are now influenced not only by the physical and chemical properties of the emulsifiers, but also by their comprehension of the complexities of the palm oil supply chain. This method demonstrates how an awareness of the larger context can influence the selection of ingredients by integrating sustainability criteria into product design.

Below, in **Table 4-3**, the results of this activity will be examined, analyzing how the context of the palm oil value chain influenced participants' ingredient selection and reflecting on the implications of these findings for sustainable product design.

Table 4-3. Results of the emulsifier selection after knowing the value chain context.

Group	Selection Criteria	Justification
Students 1 Selection: Polysorbate 80	Agronomic aspects	Agronomic practices used during palm cultivation, environmental impacts
	HLB	Highest value
	Source	Partly from a natural source and a national product that contributes to employment generation
	Price	Higher quality/price ratio
	Features	Comes with sorbate, which is an emulsifier that helps to add sweetness to the final product
Students 2	Source of origin	The emulsifier must come from renewable sources that contribute to the value chain.

Selection: Glyceryl Monostearate	Effectiveness in daily use	The emulsifier must provide the product with properties suitable for consumer use
	Added value	Quality-price ratio and contribution to the value chain.
	Emulsifier efficiency	The HLB is the indicator that allows to evaluate the quality of the emulsion
	Health risk	The emulsifier should not have high indications of health risk.
Designers Selection: Soy Lecithin	Naturalness	Lecithin is a known ingredient in beverages, the others have a less natural origin
	Functionality	Lecithin has a higher HLB and is more compatible with the current base.
	Nutritional contribution	The saturates/soy content issue

Group 1 began the final phase of the methodology with a fresh perspective after gaining new insights into the limitations of the palm oil value chain. In a previous endeavor to select an emulsifier, they had prioritized health considerations, which led to the selection of lecithin. With a greater comprehension of the limitations within the palm oil production chain, their decision-making process changed. The group acknowledged the complexity of the palm oil production procedure and the potential for development at multiple phases. They realized that their solutions primarily addressed environmental limitations and the rigidity of the supply chain, and they acknowledged the role that research plays in fostering necessary changes. In light of these new insights into the context of palm oil production, the group reconsidered their prior choice of lecithin as the emulsifier. Noting that polysorbate 80 could be derived from palm oil, which could be sourced domestically and grown in a more sustainable and soil-friendly manner, they decided to alter their choice.

This change reflects the incorporation of new selection criteria into their decision-making process, highlighting the significance of the origin of the emulsifier and its connection to the palm oil supply chain. Interestingly, a once-important criterion, health, was emphasized. Since all of the emulsifiers were FDA-approved and had safe LD50 values, this criterion

was deemed less important in the group's final decision. This modification to the selection criteria and ultimate selection of emulsifier demonstrates Group 1's ability to modify their decisions in response to new information and their enhanced understanding of the complexities within the palm oil supply chain.

In the concluding phase of our methodology, Group 2 reconsidered their initial emulsifier choice in light of their newfound understanding of the limitations within the palm oil supply chain. Initial considerations in selecting an emulsifier included its source, the Hydrophilic-Lipophilic Balance (HLB), and the price. Given these factors, polysorbate 80, which could be derived from both petrochemicals and palm oil, appeared to be the best option.

The group's proposed solutions to the limitations of the supply chain centered on strengthening connections among actors and increasing knowledge of palm oil's potential applications. These factors prompted a reevaluation of the selected emulsifier. The group discovered potential health risks associated with polysorbate 80 consumption, including colon irritation and an increased risk of cancer, after conducting additional research. This discovery caused them to promptly abandon polysorbate 80 as their emulsifier of choice, despite its previously favorable properties.

The group ultimately decided on monostearate as the emulsifier for the natural cocoa and almond beverage, considering the new information and their concentration on the palm oil value chain. They reasoned that since lecithin was derived from soybean oil, it was not as closely connected to the palm oil supply chain as monostearate was. This decision demonstrates Group 2's capacity to reevaluate their choices analyzing vital new information. It emphasizes the significance of considering both the broader context of ingredient procurement and the specific health implications of ingredient selection when designing a product.

In the concluding phase of the methodology, the team of food designers demonstrated a unique perspective. Despite acquiring a deeper comprehension of the palm oil supply chain and its associated limitations, they chose not to modify their initial emulsifier choice or the criteria they had considered. The designers continued to use soy lecithin as the emulsifier of choice for the natural cocoa and almond beverage. Their decision was based on the following factors:

1. Familiarity: Soy lecithin is a prevalent constituent in beverages, making it a trusted and familiar option.
2. Natural Origin: Soy lecithin has a more natural origin than the other emulsifiers, which correlates with the designer's understanding of consumer preferences.
3. Compatibility: With a higher Hydrophilic-Lipophilic Balance (HLB), soy lecithin is more compatible with the beverage's almond and cocoa base.
4. Saturates/Soy: The group was aware of the saturated fat content of palm oil and the consumer perceptions surrounding it. Therefore, they deemed the soy content to be the least controversial option.

In this instance, the designers prioritized product quality, consumer preferences, and market trends, based on their knowledge of the industry and consumer-centric perspective. This decision offers valuable insight into how a customer-centric strategy can interact with sustainability concerns and the complexities of ingredient procurement.
Despite expanding their knowledge of the complexities and limitations of the palm oil value chain, the group of industry designers reaffirmed soy lecithin as the preferred emulsifier. The relative impact of their choice on the palm oil supply chain was one of the primary justifications for their decision.

In the case of a natural cocoa and almond beverage, the quantity of emulsifier used is negligible, accounting for less than 3% of the product. As a result, the designers reasoned that their choice of emulsifier had minimal effects on the palm oil supply chain. They evaluated the relative impact of their decision and determined it to be negligible due to the tiny quantity requirements. In a different scenario, in which the palm oil content of a product was greater, they may have reconsidered their decision. They acknowledged that in such a scenario, the choice of ingredient would have a greater impact on the palm oil value chain, which could lead to a modification of their criteria or ingredient selection.

This decision illustrates the designers' pragmatic and context-sensitive approach to the selection of ingredients. It provides a nuanced perspective on sustainable product design by emphasizing the significance of contemplating the relative impact of ingredient choices based on the specific requirements and composition of a product.

One significant limitation encountered in this study pertained to the seamless integration of supply chain insights into the intricacies of the specific product design scenario. The

information gathered from stakeholders during the supply chain analysis phase yielded invaluable insights, enabling us to construct a comprehensive map of the palm oil supply chain and to identify overarching limitations and challenges.

However, where the study faced a notable challenge was in translating these high-level, systemic insights directly into actionable constraints and considerations for the product formulation task at hand. The design problem, in this case, focused on the selection of an emulsifier for a specific product. This narrow scope of the design task, while essential, was somewhat removed from the broader complexities of the palm oil supply chain.

Consequently, during the product design phase, it became evident that the knowledge gained from the supply chain analysis did not exert a significant influence on the decisions made by our panel of experts regarding ingredient selection. This divergence in influence can be attributed to the relative specificity of the design problem (emulsifier selection) compared to the broader and more systemic supply chain issues.

In summary, the integrated process of scenario approach, limitation evaluation, and ingredient definition provided a comprehensive platform for participants to investigate sustainable product design within the context of the palm oil value chain. This procedure emphasizes the significance of contextual awareness, stakeholder perspective, and a balance between sustainability and product requirements in product design. The results of this process not only provide valuable insights for the palm oil industry, but they also pave the way for future research into the value chains of other products.

5. Conclusions y recommendations

5.1 Conclusions

The integrated methodology for sustainable product design, with a focus on the palm oil supply chain, was successfully implemented using a product scenario approach with groups of chemical engineering students and seasoned food designers. The application provided significant insights into the ingredient selection decision-making processes, particularly when presented with information regarding the supply chain and sustainability factors. While qualitative research methods offer valuable insights and in-depth understanding of complex phenomena, it's important to acknowledge their inherent limitations, particularly in terms of generalizability. Unlike quantitative studies, which often involve large, statistically representative samples, qualitative research typically relies on smaller, purposive samples. As a result, the findings generated from this research may not be readily generalizable to broader populations or contexts.

The shift in ingredient selection among engineering students before and after the introduction of the supply chain context was a striking observation. Presumably, the students' initial decisions were influenced by their existing knowledge of process design. However, after acquiring knowledge of the palm oil supply chain, many consumers gravitated toward emulsifiers derived from sustainable palm oil, demonstrating an understanding and acceptance of the necessity of sustainable product design.

In contrast, accomplished food designers took a different approach. Instead of being substantially influenced by the introduction of palm oil supply chain aspects, they prioritized the product's natural characteristics and potential consumer expectations. They chose lecithin, an emulsifier not derived from palm oil, indicating a preference for aligning with consumers' perceptions of naturalness over the use of a more sustainable emulsifier derived from palm oil.

The experienced food designers also highlighted the limitations of the selected scenario, noting that the emulsifier content in a beverage product like the one in the scenario would not have a substantial impact on the product's overall sustainability. This insight emphasizes the significance of context and product specifics when employing sustainable product design criteria.

From this specific investigation, several fundamental conclusions can be drawn. First, the importance of contextual comprehension is highlighted. An in-depth understanding of the palm oil supply chain and its limitations has a significant impact on decision-making processes, as demonstrated by the results at each stage of the methodology. The changes in participants' decisions following the dissemination of information demonstrate the need for contextual awareness to be incorporated into the product design framework.

Second, the study graphically illustrates the importance of stakeholder perspectives on design decisions. The more technically oriented student groups, for instance, modified their emulsifier selection based on their newly acquired knowledge of the palm oil supply chain. On the other hand, industry designers, who were more focused on the market, stuck to their initial decisions, mindful of consumer preferences and market trends. This highlights the importance of incorporating a wide range of stakeholder perspectives in the pursuit of sustainable product design.

Thirdly, the delicate balance between sustainability factors, product specifications, and consumer preferences was a subtly recurring theme throughout the study. This further emphasizes the need for an all-encompassing approach to sustainable product design, one that integrates these various factors seamlessly.

To conclude it is necessary to remark that the findings of this study should be interpreted as exploratory rather than conclusive. While our research has provided initial insights into the inclusion of the supply chain requirements and sustainability criteria in the chemical product design, it is important to recognize that further research is needed to build upon and validate these findings. The proposed solutions for addressing the identified limitations in the palm oil supply chain present plenty of opportunities for improvement. The extensive array of recommendations, ranging from technological advancements and policy changes

to raising consumer awareness, provides a constructive road map for revamping the current supply chain.

5.2 Recommendations

The following recommendations for future work emerge from the present work:

1. Exploration of Alternative Raw Materials: Future research could explore the feasibility of using alternative raw materials for product design within the palm oil industry. Investigate the potential of utilizing other plant-based oils or non-edible oil sources to diversify the product range and reduce dependence on palm oil. Assess the environmental and economic implications of such alternatives to make informed decisions.

2. Development of Sustainable Product Applications: Focus on developing sustainable product applications using palm oil derivatives. Investigate innovative ways to create environmentally friendly and socially responsible products that align with consumer demands and sustainability criteria. Consider applications in various industries, such as cosmetics, pharmaceuticals, biofuels, and personal care, to enhance the value and demand for palm oil derivatives.

3. Integration of Circular Economy Principles: Explore the implementation of circular economy principles within the palm oil value chain. Investigate opportunities for recycling and reusing by-products, waste materials, and residues generated during palm oil processing. Develop circular supply chain models that promote resource efficiency and waste reduction, thus contributing to a more sustainable and circular palm oil industry.

4. Comparative Analysis with Other Vegetable Oils: Conduct a comparative analysis between palm oil and other vegetable oils in terms of their environmental impact, product performance, and economic viability. This study could help in identifying the strengths and weaknesses of different vegetable oils and inform decision-making processes for chemical product design.

5. Incorporating more quantitative elements and measurability: This research made an initial contribution by qualitatively exploring the integration of supply chain

considerations into chemical product design. However, a key limitation was the lack of quantitative data on sustainability factors and measurable impacts on decision-making. The opinions gathered from stakeholders were not quantifiable. As such, the influence of supply chain knowledge could not be conclusively verified.

6. Increase the number of groups to which the methodology is applied: larger sample sizes using surveys and experimental designs may yield generalizable results on how supply chain knowledge impacts decisions. The qualitative methodology was an important first step but integrating quantitative components in future work could strengthen validity and enhance measurability. For instance, combining surveys on ingredient preferences with discrete choice modeling could quantify willingness to pay for sustainable attributes. Overall, complementing the qualitative viewpoints with quantitative sustainability data and metrics could provide more tangible, measurable evidence on how supply chain considerations affect product design choices.

A. Annex: Material for the interview

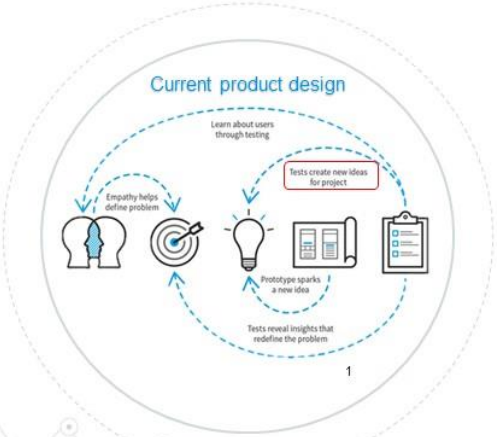
1. Presentation

Integrated methodology for product design including sustainability criteria and palm oil value chain requirements.

Mauro Montañez
Luisa Sánchez
Advisor: PhD. Juliana Serna
Advisor: PhD. Paulo César Narváez

UNIVERSITÉ DE LORRAINE
ERPI
UNIVERSIDAD NACIONAL DE COLOMBIA

Justification



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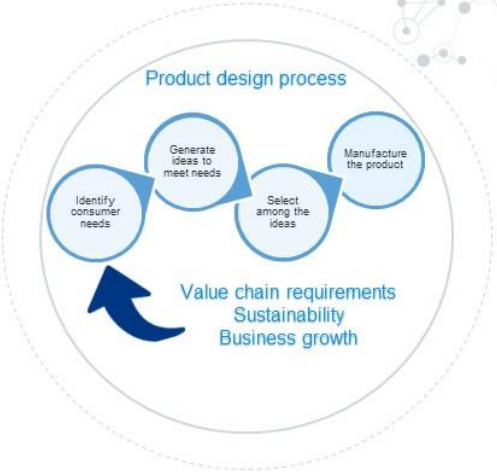
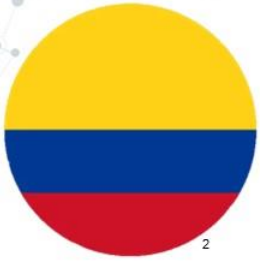


1. Fuente: https://www.interaction-design.org/literature/article/what-is-design-thinking-and-why-is-it-so-popular

2

Case of study: Palm Oil



2

4th in the world

Productor country of palm oil*

2,6% annual growth

Tons produced*

3

4

5

2. Source: https://www.countryflags.com/colombia-flag-icon/
3. Source: https://www.wedemain.fr/ralentir/deforestation-en-amazonie-18-arbre-sont-coupes-chaque-seconde/
4. Source: https://www.wrm.org.uy/es/articulos-del-boletin/expansion-de-las-plantaciones-de-palma-aceitera-como-politica-de-estado-en-centroamerica
5. Source: https://www.agronegocios.co/tecnologia/asi-fue-el-experimento-en-el-que-drones-hicieron-el-trabajo-de-500-agricultores-2934355
* Source: Fedepalma

3

Interview

Value chain diagnosis

1 2 3 4 5

6 7 8 9 10

Supply chain diagnosis

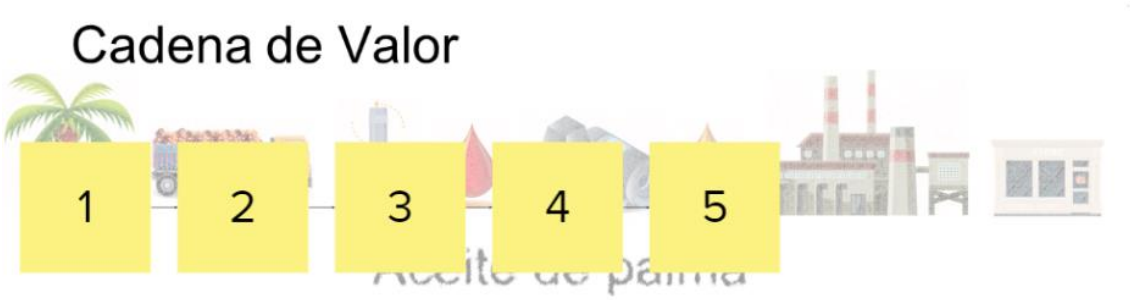
4

2. Questions guide

Stage	Questions
1. Interview presentation	
1.1. Interviewer presentation	
1.2. Introduction	
1.3. Activity description	
2. Interviewee information	
2.1. Interviewee data	• What is your profession? • What is your length of experience working in this value chain?
2.2. Description of the interviewee's company	• In which company do you work? • What is the size of the company you work for? • Where does the company have a presence? • What type of products does the company produce?
3. Value chain Diagnosis	
3.1. Value Chain Workshop	• What activities do you consider provide value in the palm oil value chain? • Which activity do you consider to be the most valuable and why? • What is the sequence of these value-generating activities?
3.2. Supply Chain Workshop	• What activities do you consider provide value in the palm oil value chain? • Which activity do you consider to be the most valuable and why? • What is the sequence of these value-generating activities? • According to the activities described in the previous exercise, what would be the chain of actors involved in the process of this product? • Which actor do you consider to be the most important in this chain and why? • Which actor plays a critical role in the sustainability of the chain and why?

	• What is the role of the organizations considered in the chain of actors? • Are there actors that coordinate activities in the value chain as a whole? • How do actors exchange information and learn about solutions to improve products and chain performance?
4. Closing the interview	
4.1. Conclusion	
4.2. Acknowledgement	

3. Value chain board



4. Supply chain board

B. Annex: Material for the Product Design Workshop

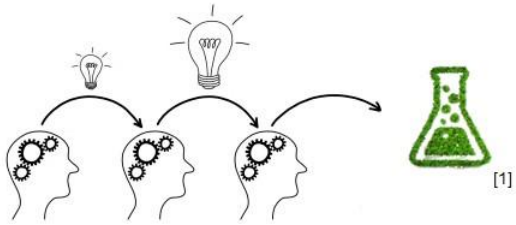
1. Presentation

What is product design?

Product design

Product design is the **process of creating products that meet user needs** and solve problems.

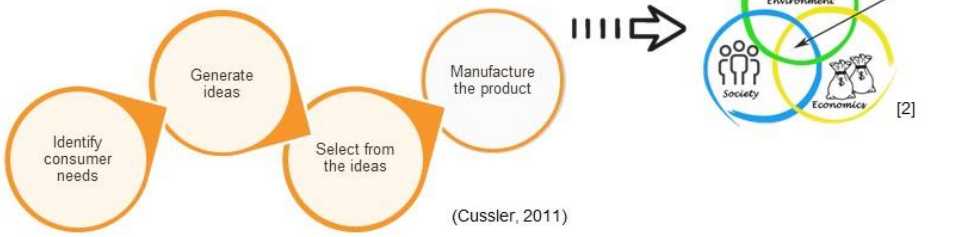
Chemical design is the process of **developing new chemical products with desired properties**. It is a multidisciplinary field that combines chemistry, engineering and economics.



[1]

Adapted from: https://ccs.org.co/quimica-sostenible-la-via-para-lograr-el-cumplimiento-de-los-ods/

Product design



(Cussler, 2011)

[2]

2. Adapted from: https://www.entrepreneur.com/en-in/growth-strategies/6-effective-ways-to-build-a-sustainable-business/252029

3. Adapted from: https://nutira.es/sustituto-de-leche/

INTRODUCTION

the trend to replace dairy products with non-dairy alternatives is driven by health, environmental and ethical concerns, as well as personal preferences. As a result, various non-dairy alternatives have been developed and popularized in the market.

4. Retrieved from: https://mejorconsalud.as.com/leche-de-almendras-beneficios/ [4]

01

DESIGN PRODUCT

DRINK WITH COCOA AND ALMONDS

Design of a plant-based beverage with no milk and no added sugars

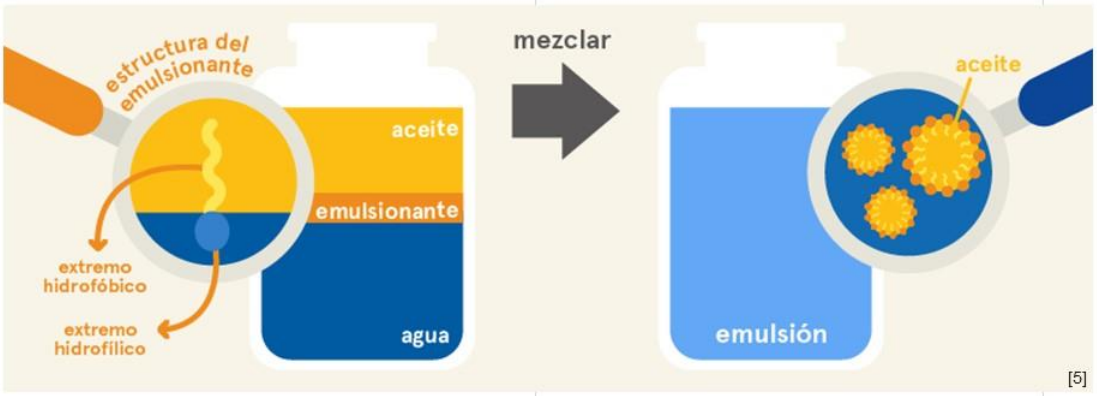
This drink will be perfect for those looking for a healthy and delicious alternative to dairy.

Ingredients

Water, cocoa powder, almond paste, natural flavors, emulsifier, natural identical flavor, salt, stabilizers, acidity regulator, natural sweetener.

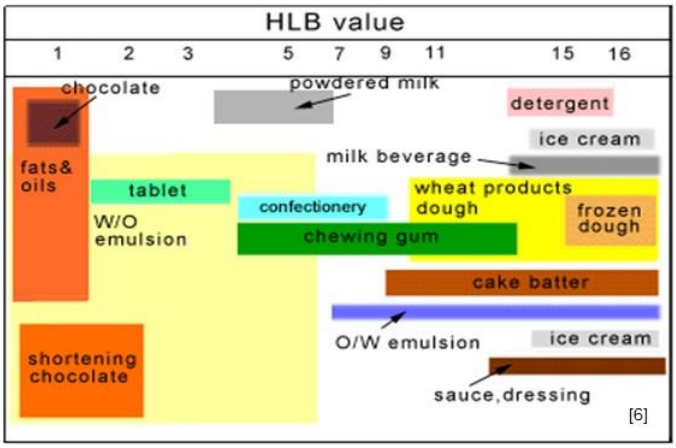
Origen vegetal | Cuidado = Disfrute | Alimentación consciente

Emulsifier



5. Retrieved from: https://www.eufic.org/es/que-contienen-los-alimentos/articulo/que-son-los-emulsionantes-y-cuales-son-algunos-de-los-que-se-utilizan-con-mayor-frecuencia-en-los-alimentos

HLB



6. Adapted from: https://www.m-chemical.co.jp/en/products/departments/mcc/food/product/1201443_9380.html

Emulsifiers

Glyceryl monostearate/sodium stearoyl-2-lactylate

HLB: 10

Polysorbate 80

HLB: 15

Lecithin

HLB: 9

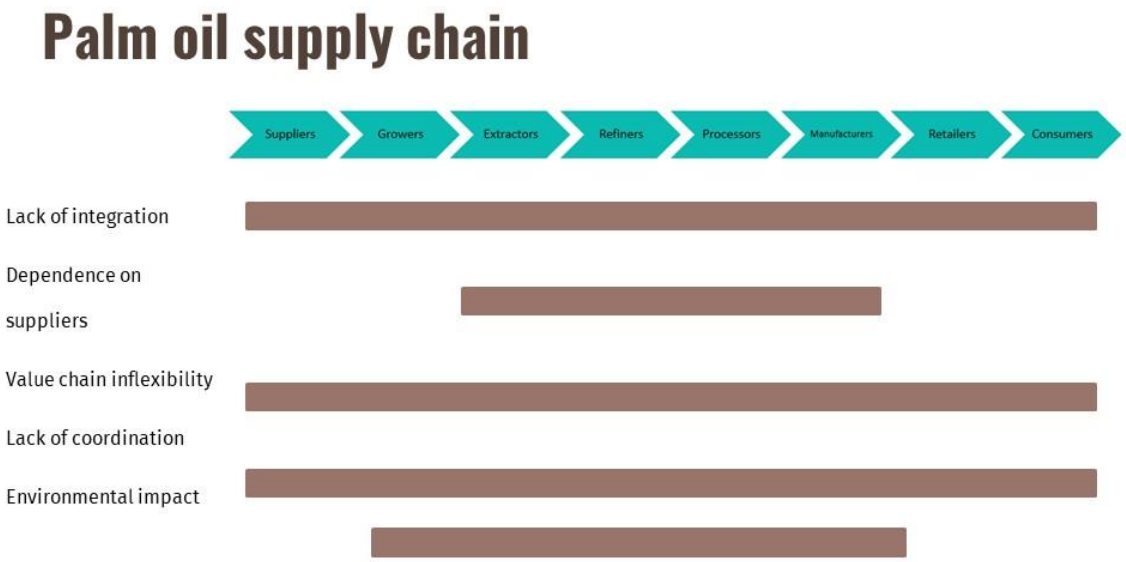
Criteria format

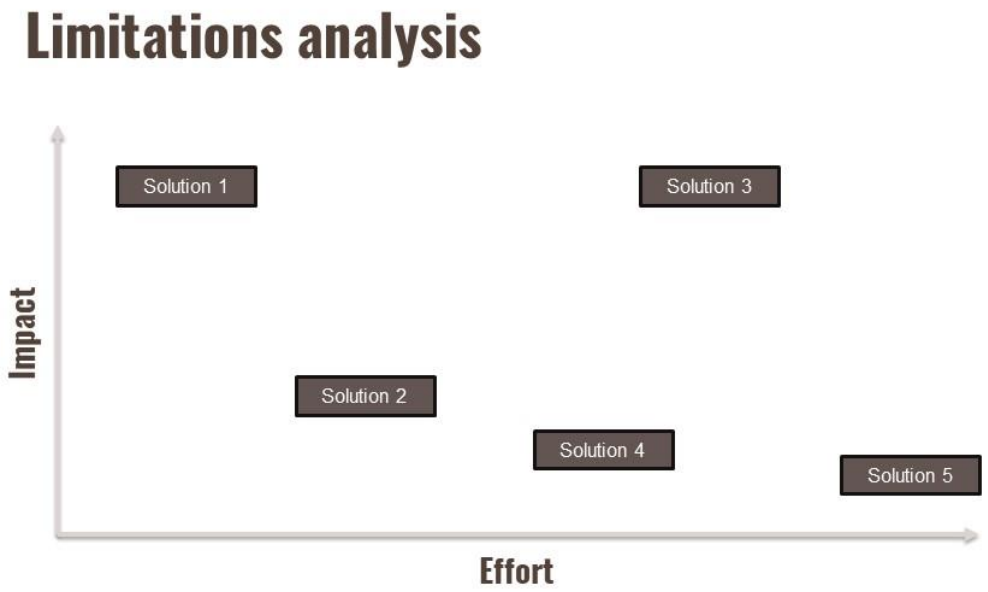
Emulsificante:

Explicación del emulsificante:

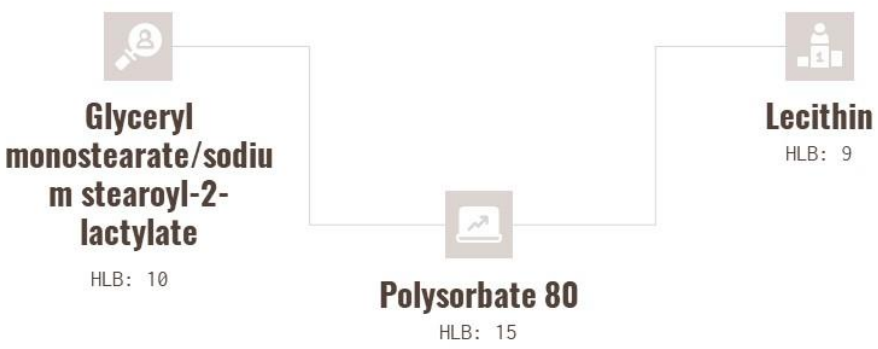
Criterio	Explicación

7. Retrieved from https://culturacientifica.com/2017/05/04/le-preocupa-aceite-palma-sea-las-razones-adecuadas


Palm oil supply chain
Suppliers
Growers
Extractors
Refiners
Processors
Manufacturers
Retailers
Consumers
Lack of integration
Dependence on suppliers
Value chain inflexibility
Lack of coordination
Environmental impact


Limitations analysis
Solution 1
Solution 3
Solution 2
Solution 4
Solution 5
Impact
Effort

Based on the information analyzed, would you change your initial design?



2. Ingredient Cards

Glyceryl monostearate

Applications

It is mainly used in the food industry as an emulsifier, thickener and preservative agent.

It can be mixed with sodium stearoyl-2-lactylate to increase its HLB.

It prevents the crystallization of fats and oils and improves the texture and mouthfeel of the product.

Helps to extend the shelf life of products, prevents oxidation and lipid degradation.

Price: 2.44 Usd/Kg

Composition: It is a mixture of mono, di and triacylglycerols.

Source: Soybean and palm oil

Reaction: Esterification of fatty acids

Molecular Formula: $C_{21}H_{42}O_4$

Molecular weight: 358 g/mol

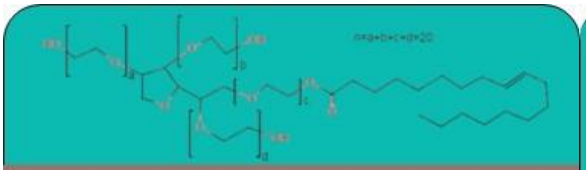
Melting point: 54 - 64 °c

HLB: 5 (11 blended) used in O/W emulsions

LD50 Oral: 5000 mg/Kg, mouse

Compatible with: starches, proteins, sugars and other emulsifiers and stabilizers.

Incompatible with: acidic components or those with a high mineral content.



Polysorbate 80

Applications

It is a nonionic surfactant, mainly used in the food industry as an emulsifier, stabilizer and preservative agent.

Can maintain its effectiveness at both high and low temperatures

Helps retain moisture in a product. This is useful in food products to keep them fresh for a longer period of time.

Price: 1.77 Usd/Kg

Composition: Polyoxyethylene sorbitan monooleate.

Source: Palm oil, sorbitol, ethylene oxide (petrochemical).

Reaction: Polyethoxylation of sorbitan esters

Molecular Formula: $C_{64}H_{124}O_{26}$

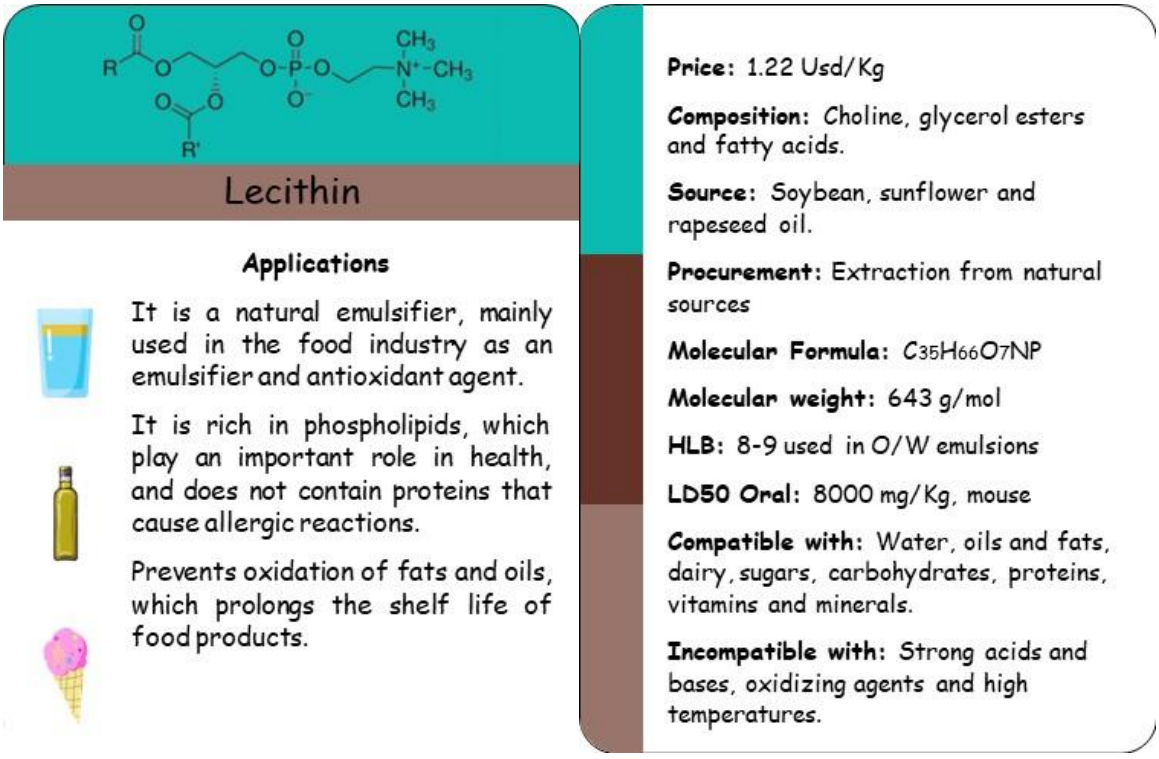
Molecular weight: 1309 g/mol

HLB: 15 used in O/W emulsions

LD50 Oral: 25 mg/Kg, mouse

Compatible with: oils and fats, dairy products, sugars and proteins.

Incompatible with: Strong acids and bases, heavy metal salts, tannins, phenols, tars and pitches.



3. Criteria format

Emulsifier:

Explanation of the emulsifier:

Criteria	Explanation

4. Cards of the limitations

Lack of integration in the palm oil value chain

Description

It refers to the disconnection and **disarticulation of activities**, communication and coordination between the various parties involved in the value chain.

Related problems

- fragmentation of activities along the value chain
- Poor communication among stakeholders
- Inadequate coordination between the different industry agents.

Consequences

- Inefficient processes
- Missed opportunities for collaboration
- Potential environmental and social impacts that could be avoided with better communication.

Actors involved

There are actors that have direct communication, but there are parts of the chain that are isolated.

Supportive statements

- "But we need to communicate from there to there and sell the idea to the people, but sell it with reality, with our Colombian reality, not with the reality of the gentlemen in Malaysia."
- "So, the role is to understand, that is, from the government, part of that lack of knowledge and that taboo that they are putting on oils, especially palm oil, which prevents you from using them."

Dependence on suppliers in the value chain

Description

It refers to an over-reliance on a **limited number of** key **suppliers for** palm oil supply.

Related problems

- Supply chain disruptions
- Scarce supply of local palm oil
- Lack of contingency plans

Consequences

- Cost increase
- Significant financial losses
- Disturbances in commercial operations

Actors involved

This dependence is present throughout the chain, as each actor is related to suppliers.

Supportive statements

- "In general, I think supply. Because price and supply also has its complexity, because of who we are competing for that. I mean, I hear a lot in my company, of the rise and fall of prices and availability."
- "There is a strong dependence there. In fact, one of the big criticisms of biodiesel production is that it enters into direct competition with food generation."

Inflexibility of the palm oil value chain

Description

This refers to the difficulty of chain actors in adapting to changes in market conditions, customer demands and regulatory changes.

Related problems

- Difficulty in adapting to change
- Rigidity in the value chain
- Lack of contingency plans
- Difficulty in responding to environmental challenges

Consequences

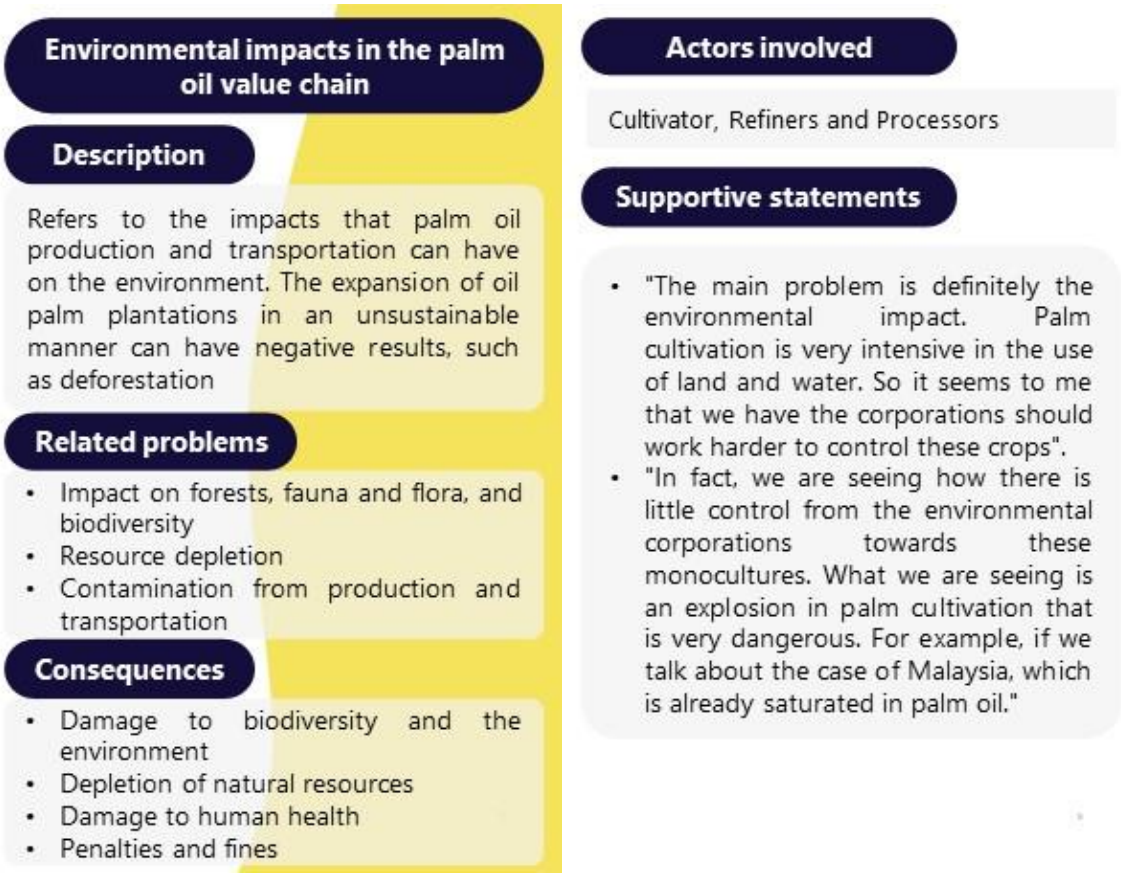
- Loss of market opportunities
- Customer dissatisfaction
- Potential for financial losses
- Decreased competitiveness
- Risk of regulatory non-compliance

Stakeholders involved

Inflexibility is present in all stakeholders, but mainly in the consumer.

Supportive statements

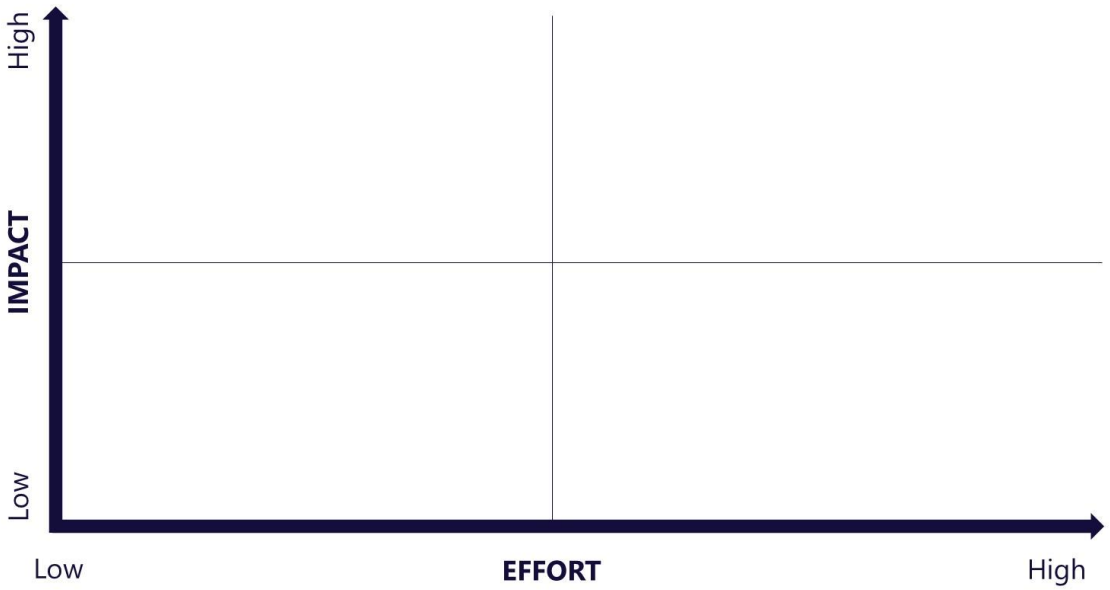
- "There are Colombian companies that prefer to sell their products abroad and not sell them here, because they do not value them here, they do not accept them.
- "Yes, we could improve some links in the chain, for example, it would be very nice to improve the harvesting process, to technify, but we lack research, research on the value chain of La Palma".



5. Brainstorm solution board

Solutions

Each proposed solution is evaluated in terms of its potential impact and the effort required to implement it, and then placed on the graph according to these two criteria.



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