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Life Cycle Assessment of frozen and chilled plant-based food: the case of Moroccan falafel produced by Gosh!

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Life Cycle Assessment of frozen and chilled plant-based food: the case of Moroccan falafel produced by Gosh!

Master dissertation

of

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Abstract

With the increase of available information on the environmental impacts arising from different diets, it has become increasingly important to apply environmental decision tools, such as Life Cycle Assessment (LCA), to food products, to promote sustainability and allow more conscious and informed decision-making about the food products consumed.

This tool has a crucial role in the development of the value chain of a given product since it identifies the critical phases of its life cycle, where the impacts are higher for the different categories. LCA also identifies opportunities for product improvement, being an essential methodology for sustainable innovation and development.

The main objective of this study is to compare the environmental performance of two plant-based food products: Frozen Moroccan Falafel and Chilled Moroccan Falafel. The selected functional unit was 100 kg of both products. The analysis was done considering the whole life cycle of the product, from obtaining the raw materials to the waste treatment of the packaging. The LCA study was prepared in the SimaPro software version 9.2.0.2, using the ReCiPe 2016 Midpoint (H) methodology that includes 17 environmental impact categories.

The inventory analysis was performed using data provided by the company. The databases used to model the inventory were Ecoinvent and AGRIBALYSE. After the inventory analysis, the impact categories were assessed and the results were interpreted. Firstly, comparing the two products, and then analysing each product individually to conclude on the critical stages in their life cycle. An analysis of ingredients only was also performed since this stage represents the largest impacts for almost all the impact categories.

A sensitivity analysis was performed by assessing the influence of four different cases on the final results. Firstly, sensitivity was tested to the ingredient present in the recipe with higher environmental impacts, the chickpea. The impact resulted from substituting 25% of chickpeas with either beetroot or sweet potato. The same methodology was adopted by replacing 25% of chickpeas with sweet potatoes. The third and fourth cases are characterised by the incorporation of a percentage (30% and 50%, respectively), of energy from renewable sources, namely solar power, in the total energy required for the Falafel production process.

The results obtained for the base case reveal a total carbon footprint of 10.7 kg CO_2 eq/kg for the chilled Moroccan falafel and 11.6 kg CO_2 eq/kg for the frozen Moroccan falafel. The similarity of results indicates that the critical points of the product life cycle are not related to the type of conservation but with the production of raw materials and manufacturing, stages that are common to both products.

Key words: Life Cycle Assessment, *Plant-based food*, Impact Assessment, Carbon Footprint, Sensitivity Analysis.

Resumo

Com o aumento da informação disponível relativa aos impactes ambientais decorrentes das diferentes dietas tornou-se cada vez mais preponderante a aplicação de ferramentas de decisão ambiental, como a Avaliação de Ciclo de Vida (ACV), a produtos alimentares, com o objetivo de promover a sustentabilidade e permitir a tomada de decisão mais consciente e informada sobre os produtos alimentares consumidos.

Este estudo tem como objetivo principal comparar o desempenho ambiental de dois produtos alimentares: Falafel Marroquino Congelado e Falafel Marroquino Refrigerado, a unidade funcional selecionada foram 100 kg de ambos os produtos. A análise foi feita considerando todo o ciclo de vida do produto, deste a obtenção das matérias-primas até ao tratamento de fim de vida da embalagem. O estudo de AVC foi elaborado no programa *Simapro* versão 9.2.0.2, utilizando a metodologia *ReCiPe* 2016 *Midpoint* (H) que inclui 17 categorias de impacto ambiental.

A análise de inventário foi feita através de dados fornecidos pela empresa. As bases de dados utilizadas para modelar o inventário foram *Ecoinvent* e *AGRIBALYSE*. Após esta etapa, foi realizada a interpretação dos resultados, procedendo-se primeiramente à comparação entre os dois produtos, e numa segunda fase, realizando-se uma análise individual de cada um dos produtos, de forma a concluir sobre quais as etapas críticas no seu ciclo de vida. Foi também realizada uma análise apenas incidindo sobre os ingredientes uma vez que esta fase representa as maiores emissões em quase todas as categorias de impacto.

Após a interpretação de resultados, foi feita uma análise de sensibilidade onde 4 cenários distintos foram avaliados. Primeiramente, estudou-se o impacte resultante da substituição de 25% de grão-de-bico por beterraba, criando assim um novo produto chamado Falafel Marroquino de Beterraba. A mesma metodologia foi adotado para a avaliação do cenário número dois, em que se substituiu 25% de grão de bico por batata doce. O terceiro e quarto cenário caracterizam-se pela incorporação de uma percentagem (30% e 50%, respetivamente), de energia proveniente de fontes renováveis no total de energia necessária para o processo de produção do Falafel.

Os resultados obtidos revelam um total de pegada de carbono de 10.7 kg CO_2 eq/kg falafel marroquino refrigerado e 11.6 kg CO_2 eq/kg falafel marroquino congelado. A similaridade de resultados, indica que os pontos críticos do ciclo de vida do produto, não estão relacionados com o tipo de conservação, mas sim com a produção das matérias-primas e manufactura, etapas essas que é comuns aos dois produtos.

Palavras-chave: Avaliação de Ciclo de vida, *Plant-based food*, Avaliação Impacto, Pegada de Carbono, Análise de Sensibilidade

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List of Acronyms

ACV - Avaliação de Ciclo de Vida
BB - Beyond Burger
CF - Carbon Footprint
EOFP - Photochemical Oxidant Formation Potential: Ecosystems
EOFH - Photochemical Oxidant Formation Potential: Human
FEP - Freshwater Eutrophication Potential
FETP - Freshwater Ecotoxicity Potential
FFP - Fossil Fuel Potential
FS - Fish Sticks
GWP - Global Warming Potential
HTPnc - Human non-carcinogenic Toxicity
HTPc – Human carcinogenic Toxicity
IB - Impossible Burger
ICN - Impossible Chicken Nuggets
LCA - Life Cycle Assessment
LCI - Life Cycle Inventory
LCIA - Life Cycle Impact Assessment
LOP - Agricultural Land Occupation Potential
MEP- Marine Eutrophication Potential
MFB - Moroccan Falafel Beetroot
MFC - Moroccan Falafel Chilled
MFF - Moroccan Falafel Frozen
MFO - Moroccan Falafel Original
MFS - Moroccan Falafel Sweet potato
ODP - Ozone Depletion Potential
PET - Polyethylene Terephthalate
PEF - Product Environmental Footprint
PMFP - Particulate Matter Formation
SDGs - Sustainable Development Goal
SOP – Surplus Ore Potential
TAP – Terrestrial Acidification Potential
TETP – Terrestrial Ecotoxicity Potential
VL - Vegan Lasagne
WCP - Water Consumption Potential

Chapter 1: Introduction

1.1. Background and work presentation

The paradigm of food production has changed over the years, starting with World War II and the Green Revolution. The Green Revolution, also known as the Third Agricultural Revolution, was a period that began in the mid-20th century. During this time, there significant agriculture development, primarily driven by the adoption of new agricultural practices and technologies that had a positive impact on crop yields and food production (John & Babu, 2021). These events led to the massive use of fertilisers, which significantly contributed to Earth pollution. More recently, due to population and economic growth coupled with technological development, consumer preferences have changed. Consumers are now looking for more sustainable alternatives for the consumption of food products since concerns about the environment have also started to play an important role in food demand decision-making (Morach et al., 2022a).

A recent study by Blue Horizon and BCG Customer Survey surveyed the food consumer preferences for alternative proteins, such as cell-cultured, microorganism-based and plant-based products (Witte et al., 2021). The study shows that 76% of consumers are already familiar with these types of food products. Consumers identified three crucial areas for improvement in these products: health, taste, and price. To increase demand for these products, they must guarantee the same nutritional value as animal-based products while also having as much as possible a similar taste and texture.

Although plant-based alternatives have become more popular, there are other alternatives protein sources that are starting to be more well-known, such as animal-cells-based products and microorganism-based products. The animal-cells-based products are made from animal proteins produced through in-vitro animal cells culture, using techniques similar to those used in generative medicine. They are still in the development stage, unlike the microorganism-based product that use traditional techniques and are already present in the food market, in products such as vinegar and beer. These products rely on microbiological cells culture as the predominant ingredient to replace the protein present in the animal-based product (Belderok et al., 2021).

While non-animal-based options are currently more expensive than animal protein, it is expected that with increased consumer demand, prices will decrease until they match or undercut animal products (Kraak, 2022). Figure 1 foresees the evolution of three alternative proteins compared to conventional animal protein in the United States and Europe. The cost of plant-based food products should be lower than animal-based proteins by 2023 (Witte et al., 2021; Zintinus & Bain & Company, 2022).

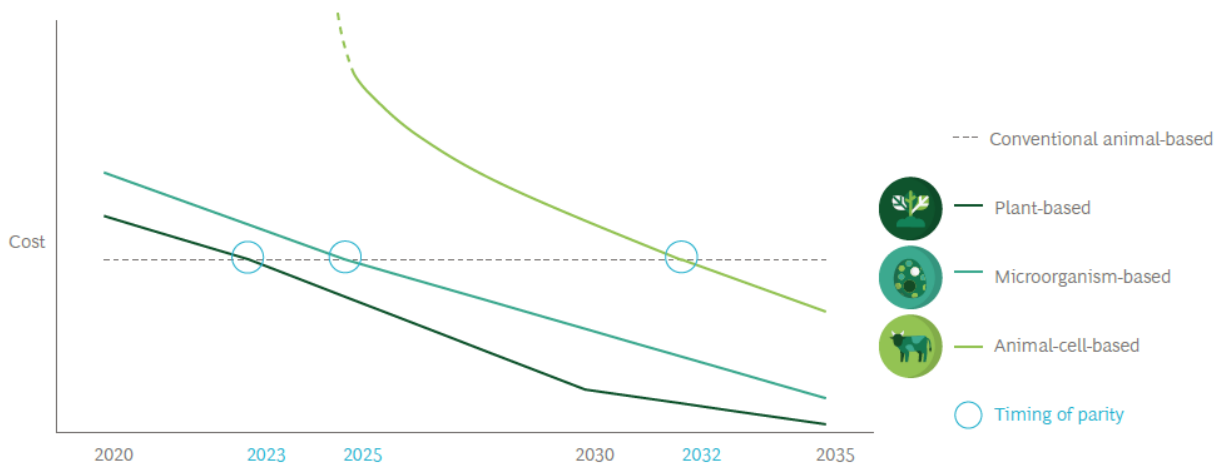

Figure 1. Evolution of cost for alternative proteins (plant-base, microorganism-based and animal-cell-based)(Zintinus & Bain & Company, 2022).

Although consumers are changing their food dietary, there are additional factors pressuring the industry to make adjustments. It is estimated that by 2050, the world population could increase by almost two billion people when compared to present days. Currently, 750 million people are already suffering from hunger worldwide, and with the projected population increase, more than 2 billion people will not have access to healthy diets (Zintinus & Bain & Company, 2022). Moreover, unhealthy diets increase the risk of micronutrient deficiencies, which can lead to diet-related obesity and related diseases, such as coronary heart disease, stroke, and diabetes (Witte et al., 2021).

Led by The Lancet in 2019 and followed by the Comission on the global Syndemic of obesity, undernutrition, and climate change, the EAT-Lancet Commission gathered 19 commissioners and 18 coauthors from 16 countries with the objective of developing global scientific goals based on the best evidence for healthy diets and sustainable food production, considering human health, agriculture, political sciences and environmental sustainability (Willett et al., 2019). The global targets defined ensure that both the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement are achieved. To achieve these objectives, the Commission presented an integrated framework that provides quantitative scientific goals for healthy diets and sustainable food production, which balance human health and environmental sustainability. The criteria for a healthy diet set by the authors consists largely of a diversity of plant-based foods, unsaturated rather that saturated fats, and limited amounts of refined grains, highly processed food, added sugars and animal source foods. Regarding sustainable food production, boundaries for four environmental impact categories, including climate change, land use, freshwater use and biodiversity loss, were proposed, beyond which food production risks irreversible damage to Earth systems. The study concludes that by adopting those developing goals, it will be possible to feed a global population of almost 10 billion people with a healthy diet within planetary boundaries for the selected production impact categories by 2050 (Willett et al., 2019).

LCA of food systems: meat-based *versus* plant-based

The food system accounts for almost 26% of the total greenhouse gas (GHG) emissions (Röös et al., 2018). Livestock and agriculture play the largest role being responsible for 15% of these emissions (Röös et al., 2018). Anthropogenic causes also contribute to approximately one-quarter of GHG emissions, leading to deforestation, biodiversity loss, freshwater use and water pollution (Röös et al., 2018).

The amount of GHG emissions is not constant from country to country as it depends on agricultural practices, climate, temperature, and soil properties. In Europe, it was estimated that the GHG emissions due to agriculture contribute to about 10% of the total emissions in 2022 (Bajan et al., 2022).

Figure 2 illustrates the global GHG emissions in 2010, by dividing the contribution of food systems and animal-related products into sub-categories, which provides a better understanding of the real impact of food systems (Carlsson Kanyama et al., 2021a; Morach et al., 2022b).

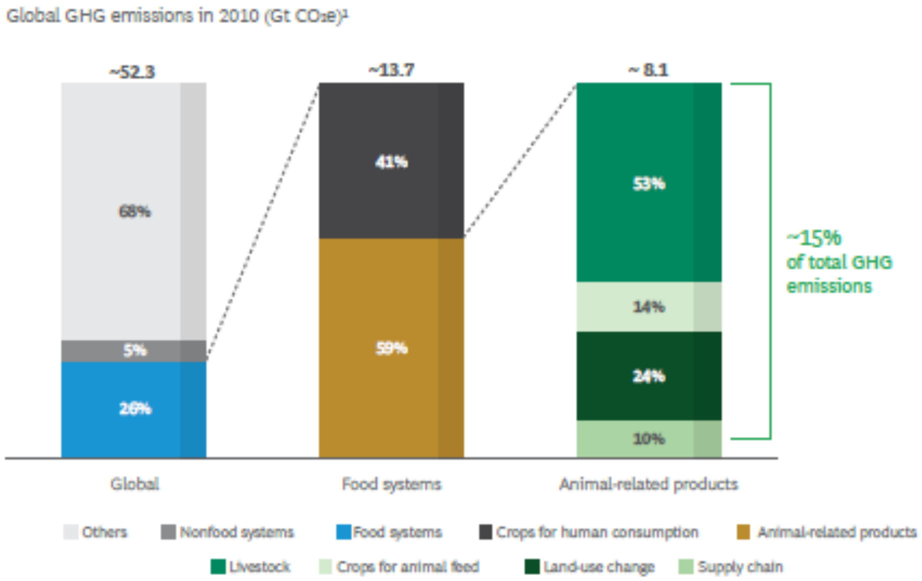

Figure 2. Global emissions of foods systems (Morach et al., 2022a).

According to a Blue Horizon study it is possible to save about 0.85 gigatons of CO_2 equivalent by 2030 only by adopting a plant-based diet and ending consumption of beef, pork, chicken, and eggs (Morach et al., 2022b). d bioSecon (Hunt et al., 1996). Figure 3 illustrates the potential savings from the substitution of animal-related products with alternative proteins.

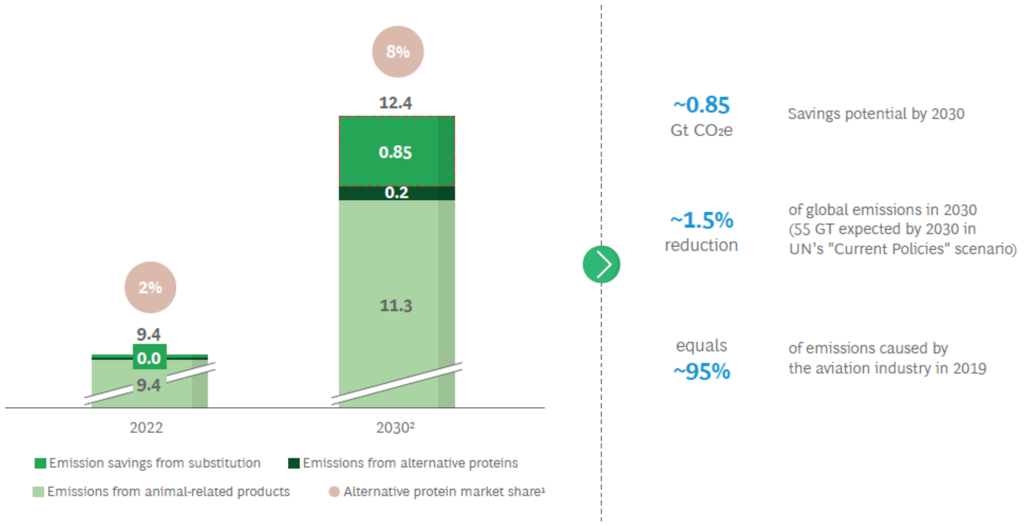

Figure 3. Potential CO2 emissions savings by substitute meat-based food with plant-based alternatives (Morach et al., 2022b).

Although there have been many studies related to mitigation measures that can be applied to the livestock and agriculture sectors, the most efficient way to reduce emissions from this sector is to decrease the demand for these products and thus reduce their production (Food and Agriculture Organization of the United Nations, 2023). Additionally, the current models of food production, that rely on the use of chemical fertilisers and pesticides to increase the crop yields, are insufficiently effective at feeding people and can lead to malnutrition in all its forms, including hunger, obesity and micronutrient deficiency. These problems affect about one-third of the world's population (Arwanto et al., 2022). Over the last two decades, many scientific studies have emphasized the importance of including more plant-based products in daily diets to decrease the stress on many ecosystems (John & Babu, 2021).

The transition towards a more sustainable food system is an opportunity for the food industry to adjust its practices. Animal protein production has resulted in negative impacts on the planet due to the scarcity of resources, including the use of land and water, as well as the emissions of GHG, as mentioned previously. However, alternative proteins, such as plant-based products, are integrating part of the food system. Producers are now converting high-value crop varieties into plant-based products that are adapted to local cuisines, resulting in the geolocation of the value chain and making it more resilient to global disruptions (Morach et al., 2022b; Witte et al., 2021; Zintinus & Bain & Company, 2022).

Studies have shown that adopting a plant-based diet or including plant-based foods in one's daily diet can contribute to a healthier life. This is because it can help avoid dairy allergies and intolerances from milk-based products and eliminate hormones and antibiotics present in meat-related products (Jaeger et al., 2023)

Although it has been proven that plant-based products have both nutritional and environmental advantages, there is still a lot of research to be done to optimise the production process and further reduce pressure on the environment.

LCA of food systems: meat-based *versus* plant-based

LCA is an internationally standardized method that can be applied to any service or product. This tool quantifies all the relevant environmental impacts, such as emissions and resources consumed, as well as the impact on human health associated with a certain product. LCA studies consider the entire product life cycle, from the extraction of raw materials to the disposal of remaining waste, the “cradle to grave” approach. These studies are crucial for creating an overview of the environmental impacts of a product and identifying the phases where mitigation is possible (JRC European Commision, 2010).

As mentioned previously mentioned, the shift towards a plant-based diet has direct positive impacts on the environment. However, more can be done to enhance these positive impacts.

The studies conducted by (Lacour et al., 2018) and (Heller et al., 2018) aimed to identify the key aspects to be addressed in the LCA of general food systems by comparing meat-based with plant-based food systems. The articles summarise the important factors that should be considered to achieve more environmentally friendly results in this sector. LCA, when applied to a specific food product, throughout its supply chain, can identify the specific life cycle stages with worst contribution to the environmental performance. The results obtained may contribute to define measures to improve the environmental performance of the product under study.

Although the studies have emphasized the need for detailed and rigorous data, as well as clear system boundaries definition and assumptions, it was possible to establish some trade-offs between the two systems under analysis. It has been possible to gather important conclusions from the studies related to the environmental benefits that can arise from the adoption of a plant-based diet. This diet usually has lower environmental impacts in the categories of, namely, GHG and land use. It was also possible to identify the stages of the two systems, meat-based and plant-based, which provide the largerst contribution to environmental impacts. For the meat-based system, the results showed that feed production and animal husbandry are the hotspots, mainly because of the necessity of water and land use, but also due to the use of fertilizer and pesticide and the quantities of GHG emissions produced during the raising of the livestock. For the plant-based food systems, the hotspots related to the plant-based food systems are, as expected, linked with its production. Even though the production stage requires less land than the animal-based food systems, the production of some products, such as soy and palm, can be associated with deforestation and habitat loss that increases this impact category.

In general, through the analysis of the studies mentioned above, it was possible to highlight that a plant-based food system can have significantly lower environmental impacts than meat-based food systems, with special attention to GHG emissions, land use, and resource consumption.

1.2. Curricular project at a company

This dissertation was developed at Sonae and refers to " Life Cycle Assessment of frozen and chilled plant-based food products: the case of Moroccan falafel produced by Gosh!" the product selected for this study was the Moroccan Falafel, produced by Gosh! Food and commercialized in the United Kingdom. The study focused on the Moroccan Falafel packed and sold in either frozen and chilled conservation methods.

Falafel is a typical dish from the Middle East, usually made from ground chickpeas or fava beans, mixed with herbs, spices and vegetables, like onions and garlic. This meal is a great source of protein, fiber and vitamins and minerals. All the ingredients are mixed and formed into a small ball that is usually baked or deep-fried (Raviv, 2003). The study focused on the Moroccan Falafel packed and sold in either frozen and chilled conservation methods.

The project consisted of two phases: the use of LCA, followed by a sensitivity analysis and the presentation of mitigation measures towards a product with lower environmental impacts.

The study was conducted in partnership with the manufacturing company (Gosh! Food). Gosh! is a leading producer of 100% natural plant-based food located in Milton Keynes, United Kingdom. Its products include vegan bites/falafel, burgers, and sausages made with high-quality raw materials and free from the top 14 allergens (SONAE, 2023). In the last seven years, Gosh! has increased its EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization), margins from 18.2% to over 24.6% and has experienced a 40% growth in sales. Aldi UK was their best-selling customer in 2022.

Sonae, a Portuguese multinational company with a diversified portfolio of businesses, recognised an opportunity to venture into the food-technology area. After analysing the market, Sonae decided to invest in alternative foods such as plant-based food and other alternatives to animal protein, and natural ingredients like natural extracts and active ingredients. (SONAE, 2023). With this strategic move, Sonae intends to become a major European supplier of alternative animal products and natural ingredients that can be incorporated into cosmetics, nutraceutical, and pharmaceutical companies. Sonae's first step on this space was the acquisition of the brand Gosh! Foods in the United Kingdom (SONAE, 2023).

1.3. Objective and Scope

The main goal of this study is to assess the environmental impacts of a food product - Moroccan Falafel, manufactured by Gosh! Food, and to relate those impacts to the various life cycle stages of the product, namely, origin and processing of raw materials, product manufacturing, product distribution, product consumption and packaging end-of-life treatment. With this, it will be feasible not only to identify mitigation measures to decrease the environmental pressure derived from the product, but also to highlight improvement opportunities within the supply chain, providing Sonae with information that supports decision. Consequently, two distinct LCAs were performed:

- LCA of chilled Moroccan Falafel, (MFC)
- LCA of frozen Moroccan Falafel, (MFF)

To accomplish these objectives, a LCA of the product was performed using the software SimaPro 9.2.0.2 with the Ecoinvent database version 3.7.1 and AGRIBALYSE version 3.0.1.

1.4. Dissertation Outline

This dissertation is organised into five main chapters.

Chapter 1 presents background information about the plant-based food market and the motivation for this study. This chapter also introduces the company where the study was performed. Finally, the objectives, scope, and dissertation outline are defined.

Chapter 2 contains a literature review on the carbon footprint and LCA of plant-based products.

Chapter 3 presents in detail the life cycle of the product under analysis, Moroccan Falafel- chilled and frozen, starting with a brief description of the products, followed by an overview of all the manufacturing stages, namely, production of raw materials, manufacturing, packaging, product storage, distribution, consumption, and packaging disposal.

Chapter 4 is dedicated to the LCA of the selected product. The goal and scope were defined (functional unit, boundaries of the system and environmental impact categories), as well the other stages of the LCA, Inventory Analysis and Impact Assessment. After this, the results were interpreted, and a sensitivity analysis performed.

In Chapter 5, the results of the study are discussed, conclusions are taken and suggestions for future work are made considering the results of the study.

Chapter 2: Literature Review

A total of six studies focusing on the LCA of plant-based meals were reviewed and summarised. Some of the studies were commissioned by brands that are major players in the plant-based food market. The main motivation behind the studies was to compare their products with animal-based food options in order to improve the supply chain of the product. The functional unit for all the studies was 1 kg of finished product allowing for a robust comparative analysis of the results.

The important aspects that should be addressed in an LCA study are the motivation and objective of the study, the functional unit, the details about the ingredients that compose the product, the software, databases and the impact assessment method used, the boundaries of the system under study, the life cycle stages of the product and the impact categories assessed. At the end, the results of the study are presented and analysed. Since the articles do not assess all the same environmental impact categories, it was important to relate the life cycle phases with the largest environmental impact and the ingredient or reason for that result. For each article studied, this information was organized in Table 1.

The articles cover different products, starting with burgers (two plant-based burgers from different brands), two plant-based chicken nuggets and fish sticks, a vegan lasagna and falafel. In the case of falafel the data was retrieved from the SimaPro software and from the:Ecoinvent 3, Agri-footprint 5, World Food LCA Database and AGRIBALYSE 3 databases. The studies assessed different impact categories, the most relevant of which are Global Warming potential (GWP), Agricultural Land Occupation potential (LOP), Water Consumption potential (WCP), Freshwater Eutrophication potential (FEP), Terrestrial Ecotoxicity potential (TETP), Freshwater Ecotoxicity potential (FETP), Human Non-carcinogenic Toxicity (HTPn) and Fossil Fuel potential (FFP).

Concerning the life cycle stages assessed the studies also varied from cradle-to-gate or cradle-to-distribution. They considered the origin of raw materials and transport from cultivation to the factory, the processing of ingredients, and packaging manufacturing and disposal. Some studies also included the distribution of the final product, although that information was not specified in detail. The results of the studies allowed us to identify for all products, which life cycle stages have the largest contribution to the environmental impact. In all the studies analysed, the first stage, extraction of raw materials, is the one with the largest contribution to the environmental impact. This is mainly due to the cultivation of food ingredients, which requires soil and water, but also chemical fertilisers and pesticides. The next life stages with larger contributions are the manufacturing and packaging due to their comparatively large energy consumption.

From the products analysed, the Beyond Burger (BB) and the Impossible Burger (IB) have higher carbon footprints (CF) compared to others. The BB has a CF of 3.4 kg CO_2 eq./kg, while the IB has a CF of 3.5 kg CO_2 eq./kg. This can be attributed to the use of canola oil and coconut oil in the BB recipe, and coconut oil and sunflower oil in the IB recipe. Unfortunately, it was not possible to assess to the percentages of these oils in each product. However, it is known that they constitute approximately 50% and 33% of the total ingredients in the BB and IB, respectively. When comparing the CF of any burger with the CF of falafel (0.853 kg CO_2 eq./kg), it is considerably lower. This difference can be justified by the use of olive oil in falafel, as well as the selection of different ingredients such as broad beans, chickpeas, and onions. In contrast, burgers contain processed ingredients like pea protein and soy protein. Additionally, for the Impossible Nuggets, the chosen ingredients are very similar to those used in the burgers, including sunflower oil and soybean oil. However, the CF for the nuggets is lower (2.19 kg CO_2 eq./kg), which may be due to the lower quantity of ingredients used in this recipe. The lowest CF value in the table corresponds to the vegan lasagna (0.26 kg CO_2 eq./kg). This value primarily reflects the impact of two ingredients: tomatoes and lentils. It is also important to note that this lasagna recipe does not include any kind of oil in its composition.

Through this examination it is possible to conclude that the oils (canola oil, coconut oil, olive oil and soybean oil) are those having the largest contribution to the total value of CO_2 eq emitted by product.

This analysis allows for the framing of the expected results in the development of this work.

Table 1. Review of the selected LCA studies focusing on similar products (plant-based food products) to the Moroccan Falafel by Gosh. GW- Global Warming Potential; FRS – Fossil Resource Scarcity; LU- Land Use; WC – Water consumption; AE - Aquatic Eutrophication

Study	(Heller & Keoleian, 2018)	(Khan et al., n.d.)	(Retrieved from SimaPro database Agribalyse, 2023)	(Canada, 2021)	(Meyer et al., 2022)	(Takacs et al., 2022)
Product	Beyond Burger (BB)	Impossible Burger (IB)	1 kg falafel at consumer	Impossible "chicken" nuggets (ICN)	Plant-Based "fish" sticks (FS)	Vegan Lasagne (VL)
Motivation	Acknowledge the environmental impact of plant-based protein (BB); Supply chain improvement; marketing	Compare the environmental impacts of a plant-based IB and a regular meat burger	_	Calculate the environmental impact of plant-based ICN with the meat-based option	Assess the environmental impact of a plant-based product under different impact categories	Compare the environmental impacts of individual meals and plant-based meals
Objectives	Calculate the environmental impact of plant-based protein (BB)	Assess the environmental impact of the product IB	_	Assess the environmental impact of plant-based ICN	Inform about the environmental impact of plant-based FS	Calculate the environmental impact of plant-based meals
Functional Unit	1/4 pound (0.113kg) of uncooked (BB)	1 kg of final product of IB	1 kg of falafel	1 kg of product (ICN), manufactured and delivered in the US in 2021	100g of plant-based FS	One single meal
Ingredients	Water; Pea protein; Canola Oil; Coconut Oil	Potato protein; Coconut oil; LegH protein; Sunflower oil; Soy protein; Flavor mix	Broad beans; Chickpeas; Coriander; Olive oil; Onion; Water; Wheat flour	Water; Soy protein; Sunflower oil; Salt; Wheat flour; Potato starch; Corn flour; Sugar; Soybean oil;	Not provided	Pasta lasagne sheets; Tomato; Cauliflower; Pepper; Lentils; Aubergine; Curgette; Onion; Spinach
Software and Databases	SimaPro 8 (Databases: Ecoinvent, Agrifootprint)	SimaPro 8.4 (Databases: Ecoinvent, World Food Lifecycle)	Simprapro (Agribalyse)	Gabi	Not provided	SimaPro
Impact assessment method	ReCiPe 2009 Midpoint	ReCiPe 2006 Midpoint	ReCiPe	ReCiPe 2018 Midpoint	Not provided	Not provided
Boundaries	Cradle-to-distribution	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-distribution	Cradle-to-plate

Table 1 (cont.). Review of the selected LCA studies focusing on (plant-based food products). GW- Global Warming Potential; FRS – Fossil Resource Scarcity; LU- Land Use; WC – Water Consumption; AE - Aquatic Eutrophication; TE- Terrestrial Ecotoxicity; FE – Freshwater ecotoxicity; HNT- Human Non-carcinogenic Toxicity.

Study	(Heller & Keoleian, 2018)	(Khan et al., n.d.)	(Retrieved from SimaPro database Agribalyse, 2023)	(Canada, 2021)	(Meyer et al., 2022)	(Takacs et al., 2022)
Life Cycle Stages assessed	Origin of raw materials (ingredients and packaging); processing, packaging, lighting; transport (ingredients and packaging); cold storage; distribution; and packaging disposal	Raw material manufacturing; Heme production (plant-base protein); IB production; and packaging	Raw ingredients extraction and manufacturing process; distribution; consumption; and packaging end-of-life	Base "meat" production (raw materials production and transport from site to facility); processing (ICN bulk formation, transport to finishing and cooking facility, finishing and cooking); packaging	Plant cultivation; processing; packaging and transportation	Agricultural produce and ingredient production; distribution; storage and meal preparation.
Impact Categories	GW; FRS; LU and WC	AE; GW; LU and WU.	GW; TE; FE; HNCT; LU and FRS	GW; AE; LU and WU	WU; FRS; LU and GW	GW; WU; AE and FE
Hotspots	GW: ingredients and packaging; FRS: ingredients and packaging; LU: ingredients and packaging; WC: processing, packaging, and ingredients	AE; GW; LU, WC: ingredient manufacturing. The packaging had negligible contributions.	The stage of the life cycle with larger negative contribution is the ingredients production followed by the incineration of the wasted packaging of polypropylene.	GW: processing with larger value; for the remaining categories, the stage with larger impact is the base “meat” production	Plant cultivation and processing	Ingredient production stage
Product Carbon Footprint	3.4 kg CO_2 eq./kg of BB	3.5 kg CO_2 eq/IB	0.853 kg CO_2 eq/kg falafel	2.19 CO_2 eq./kg ICN	_	0.26 kg CO_2 eq/kg vegan lasagne

Study	(Heller & Keoleian, 2018)	(Khan et al., n.d.)	(Retrieved from SimaPro database Agribalyse, 2023)	(Canada, 2021)	(Meyer et al., 2022)	(Takacs et al., 2022)
Conclusion	CF ingredients 1.94 kg CO_2 eq (36% pea production and 12% canola oil)	LU: 2.5 m^2. y (coconut oil, soy protein); WC: 106.8 l and AE 1.3 g PO_4^- eq (potato protein)	Land use 0.2496 m^2 eq	AE 3.13 g P-eq (base meat production); LU 2.60 m^2 crop eq (base meat production); WC 0.15 m^3 (base meat production)	The process stages with the largest impacts are ingredients extraction and product processing.	CF: 0.26 kg CO_2 eq (tomato and lentil)

Chapter 3: Gosh! Products

The Moroccan Falafel was chosen as the subject of this study due to its high sales in 2022, being one of the best seller product of the company. Figure 4 presents the refrigerated product, while Figure 5 represents the frozen product. These images aim to illustrate the difference between the two packaging options depending on the preservation method. The analysis will include the phases from the production and transportation of the raw materials to the factory, to ingredient processing and product manufacturing, product storage, distribution, consumption, and treatment of packaging waste. These stages define the boundaries of this study and will be further explained.

Figure 4. Moroccan Falafel Chilled.

Figure 5. Moroccan Falafel Frozen (illustrative example).

Additionally, a detailed flowchart of all the processes, including all the production stages, is presented in Figure 6, to support this information.

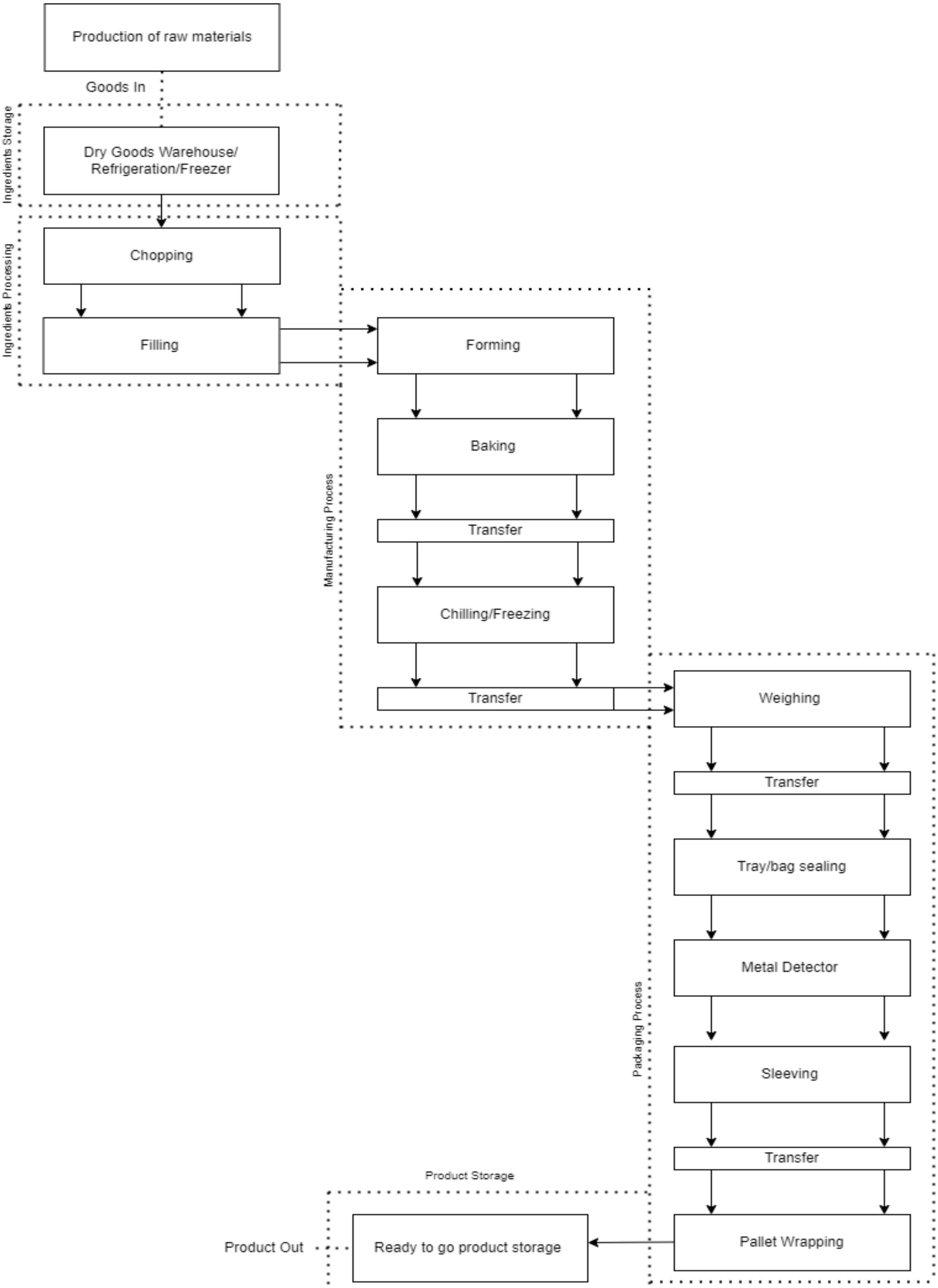

Figure 6. Product processing flowchart.

3.1. Raw Materials

Table 2 provides a description of the ingredients required to produce the functional unit, one batch (100 kg) of Moroccan Falafel. Chickpeas are the primary ingredient, summing up approximately 49% of the total ingredients. This is followed by red pepper at 15%, white onion and rapeseed oil at around 8%, potato flake at 5.6%, dried apricots at 4.7%, and dehydrated dates at 3.7%. The remaining ingredients are present in the recipe with very low percentages (below 1%), varying from garlic granules (0.9%) to chilli accounting for just 0.04% of the total.

Table 2. List of ingredients of the Moroccan Falafel by Gosh!

Ingredients	For 100 kg of Moroccan Falafel (kg)	For 100 kg of Moroccan Falafel (%)
Chickpeas	48.67	49%
Red Peppers	14.98	15%
White Onion	7.49	7.50%
Rapeseed Oil	7.49	7.50%
Potato Flakes	5.6	5.60%
Apricots Dried	4.68	4.70%
Dates Dehydrated	3.74	3.70%
Water	3.74	3.70%
Garlic Granules	0.9	0.90%
Salt	0.7	0.70%
Sod Bicarb Fine	0.45	0.45%
Cumin Seed	0.38	0.38%
Coriander Seed	0.38	0.38%
Parsley Leaf	0.32	0.32%
Cinnamon Ground	0.25	0.25%
White Pepper Ground	0.16	0.16%
Crushed Chilli	0.04	0.04%
Total:	100	100%

All the data concerning the product was provided by Gosh!. After analysing the data, it was possible to identify different alternative suppliers for the ingredients. Although the ingredient suppliers are all located in the UK, it does not necessarily mean that the production of those ingredients is based in the UK. Therefore, it was necessary to gather additional information regarding the agricultural production of such materials. Later in Chapter 4 it will be discussed the assumptions made to address this information gap.

Another aspect to consider regarding the ingredients and the suppliers is that the same ingredient can be sourced from various distributors. In other words, the same ingredient can be imported from different geographies across the world. However, for the purpose of this study, only the suppliers that provide the largest amount of each ingredient worldwide will be considered. Table C. 2 (Annex C) will provide detailed information about the different suppliers for each ingredient, along with the quantities they supply to Gosh!. Table C. 2 also highlights, in bold, the suppliers that were selected for this study.

3.2. Manufacturing, Packaging and Storage

The production process of Moroccan Falafel begins with the goods arriving at the factory warehouse, where an inspection is conducted. The ingredients and packaging materials are then divided and stored according to their respective conservation methods, which can be refrigerated, frozen or kept in the ambient area.

The production operations involve a combination of manual, semi-automated, and fully automated lines. Production of Moroccan Falafel occurs in two continuous lines. The operations manager's team is responsible for production planning and scheduling, which depends on the sales plans and forecasts. The production process is based on a recipe-driven system called Stevens, which controls each Stock Keeping Unit, (SKU) used for the batch.

The first stage is the weighing and mixing area. Here, the raw materials are transferred to containers with the assistance of a filling machine. The production area is divided into three distinct sections: one for chickpea rehydration, another for spices and dry ingredients, and finally, a weighing area for the remaining raw materials. In the second area, the spices and smaller ingredients are weighed and then transferred to smaller containers. This part of the process requires operator control to ensure that the correct ingredients are selected for each recipe.

Afterwards, all the ingredients are transferred to the batching area, which consists of three bowl choppers and takes approximately five minutes. Here, all the ingredients are mixed, and the liquids are added. This process occurs in three chopping machines, and it is controlled by operators who ensure the proper level of mixing. After the bowl chopping, the batches are transferred to tote bins and then placed in the cooking lines. The first stage in the cooking line is the forming machine, where the products are deposited and shaped into the appropriate size. For Moroccan Falafel, the product is formed into small balls. The forming process takes around 6 minutes. The falafel balls then proceed to the oven, which has been preheated to 250°C.

Next, the product needs to be cooled down, which is done in the spiral chiller. There are two spiral chillers available, one serving as both a freezer and chiller, while the other is functioning solely as a chiller. These machines transport the product around a rotating drum on a conveyor belt with a rapid linear airflow. The objective is to decrease the product temperature to around 19 °C, and this process takes around 50 minutes. For frozen falafel, the process occurs in a special frozen spiral chiller.

The next step is the packaging lines, which consist of a Modified Atmosphere Packaging (MAP) process. The choice of packaging option depends on whether the product is chilled or frozen. In the MAP line, the packaging materials are conveyed from the storage area via an ultraviolet tunnel to the packaging area. The falafel balls are deposited into trays and pass through one of the two MAP packaging machines. These machines utilize a combination of nitrogen and carbon dioxide gases to enhance the shelf life of the product. After MAP packaging, the product is almost ready for storage. The final steps involve metal detection and weighing check. The product passes through a metal detection system to ensure its quality, and then it goes through a check weighing mechanism, namely the Ishida equipment, to verify correct product weights. Prior to storage, the packed products are conveyed through a wall into the sleeving and boxing area. There, the products are sleeved, date coded, and labeled. The finished packed and palletized products are then transferred to a chill storage for quarantine time before dispatch. The quarantine time occurs while samples of finished product are analysed at an outside laboratory. If the results are satisfactory, the quarantine time is over and the products are dispatched. The storage temperature is approximately 5°C. For frozen falafel, the product is packed in bags made of 100% Polyethylene terephthalate (PET). Figure 7 describes all the phases from ingredients processing to manufacturing and packaging necessary to produce Moroccan Falafel, as described previously.

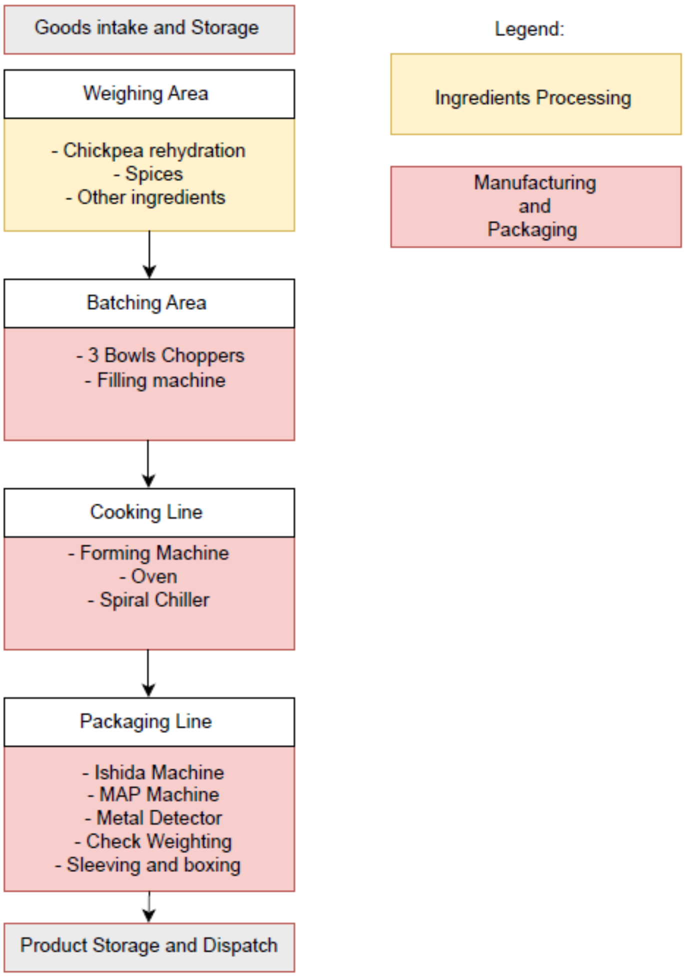

Figure 7. Detailed aspects of the production process of the Moroccan Falafel.

In 2022, the total production of Moroccan Falafel summed up around 932 tons. Table 3 illustrates the mass in tons produced monthly in 2022. The months with larger production volumes were June, August, and May.

Table 3. Total Moroccan Falafel produced in the year of 2022.

Months	Total Tons Produced
1	801
2	658
3	756
4	828
5	851
6	937
7	793

8	901
9	710
10	757
11	732
12	594
Total for 2022	**932**

3.3. Distribution

After the dispatch of the goods, the distribution phase is carried out by external logistics companies. As a result, and also considering that retailers purchases and delivery are centralized, it was not possible to assess the quantities of products distributed to each final supermarket store. Therefore, the evaluation only took into consideration the distance between the factory, distributors, supermarkets' warehouses, and the final supermarket, rather than considering the only the distance between the factory and the supermarket that receives the largest amount of product. There are three companies that collect the products from Gosh!'s warehouse: CML Distribution, Culina, and Chiltern Food. Chiltern Food is specifically responsible for handling the frozen products. Once the goods are picked up by the transporter, the chain of events remains the same, regardless of which distributor's service is being used.

The distributor collects the products from the Ready Goods Warehouse at Gosh! and transfers them to its own storage facility. When requested by the supermarkets, the distributor then transfers the products to the supermarkets' depot storage, there are several depots location concerning the same supermarket brand. Finally, when necessary, the supermarkets collect the goods from their respective depot and transport them to the stores.

Within the framework of this work, CML Distributor and LIDL supermarket were selected as a case study for the distribution of the product. CML Distributor provides its services to two Gosh! customers, namely LIDL and ALDI supermarkets. The selection between LIDL and ALDI was based on their sales performance. LIDL leaded the sales when compared to ALDI in the previous year, 2022. Figure 8, presents the event chain that was previously mentioned, specifically related to CML distribution.

For the LCA study it was considered the LIDL Regional Distribution Center (RDC) that is the one located at the farthest place from the Gosh! factory.

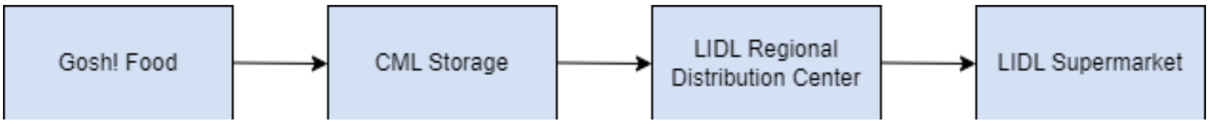

Figure 8.Distribution event chain.

Google Earth software was used to calculate the distance between the CML storage and all the LIDL RDC.

Annex D provides details on the geographical locations of the various LIDL RDCs and the distances between the Gosh! factory and the CML distribution center. It also includes the distances between CML's distribution center and the different LIDL RDCs.

The LIDL RDC located in Motherwell is the farthest location, being 452 km away from the CML Storage. Therefore, to this, this location was selected for the calculations regarding the product distribution

3.4. Consumption and Packaging disposal

Regarding the consumption stage, only the energy consumption of the equipment used to prepare the product will be considered. As for the end-of-life stage, the study will focus only on the packaging, as foodwaste will not be considered. Only one option for packaging disposal will be evaluated, namely, incineration.

Chapter 4: LCA of Moroccan Falafel – chilled and frozen

4.1. Introduction to the LCA Methodology

The original purpose of LCA was to develop a framework to support decision-making and simplify the distinction between two similar products, product systems, or services in the environmental field. Some examples of the application of this methodology are listed below (Carlsson Kanyama et al., 2021b).

- Industrial application of LCA for developing or improving new products.
- Application of LCA in strategic planning or policies to support decisions in industries and services.
- Marketing purposes.
- Governmental policy in the areas of ecolabelling, green procurement, and waste management.

LCA was performed in the USA for The Coca-Cola Company due to environmental issues that the scientific community started to highlight in the late 1960s (Hunt et al., 1996). The concept emerged when Henry E. Teasley Jr. was managing the packaging system of the company. He was searching for a methodology that could assess the number of materials and energy needed for production, considering all stages from the extraction of raw materials to the packaging disposal to quantify the environmental consequences (Hunt et al., 1996).

LCA is an environmental tool that allows consumers, investors, and stakeholders to make decisions based on the environmental performance of a service, process, or product throughout its life cycle, also known as “from cradle to grave” analysis (Santos da Silva, 2021). This methodology is a crucial tool that can warn of environmental degradation and can influence the decisions made by legislative bodies to promote better policies for conscience development in many fields, such as agriculture and industrial food production (Roy et al., 2009). It can identify the stages of the life cycle that present the most negative environmental impact in specific categories (Santos da Silva, 2021). ISO 14040:2006 describes the concept and framework that should be followed to apply for LCA. This methodology can also be complemented with ISO 14044:2010 (ISO, 2006). The LCA framework is divided into four main parts: Goal and Scope definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Life Cycle Interpretation (Berlin & Sund, 2010).

The first step is the <u>Scope and Goal Definition</u>. Here the study purpose, target market, functional unit, boundaries of the system and impact categories should be defined (Roy et al., 2009). The **functional unit** (FU) enables the comparison between different products, but also the relation with the inventory data. The definition of a FU will be based on the impact categories that were chosen. It can be the mass of the product under study, or expressed in terms of economic and nutritional values, or even land use (Corrado, 2015). The **system boundaries** are chosen usually reflecting the limits between the natural and the technical part of the system under study, starting with the extraction of the raw materials and ending with some waste treatment option such as landfill or incineration. This analysis is usually called a “cradle to grave”. Some studies can just consider from the extraction of the raw materials up to the manufacturer, in which case, it's called a” cradle to gate” analysis (Berlin & Sund, 2010; European Commissions, 2023). In this first stage it is equally important to define which **impact categories** will be considered and the limitations and assumptions that can be made further in the study (ISO, 2006). The next step is the <u>Inventory Analysis</u>, and the main goal is to perform a Life Cycle Inventory (LCI) of the selected product. This phase consumes the most time and requires extensive work, as it involves gathering detailed data about resource use, energy consumption, emissions, and products from all activities in the production chain - from product design to transport, raw material extraction, ingredient processing, product production, packaging, product distribution, retailing, consumption, and packaging end-of-life. The more detailed the inventory analysis, the more realistic the results of the study (ISO, 2006; Roy et al., 2009). The Inventory Analysis is followed by the <u>Impact Assessment</u>, and the goal here is to estimate the Life Cycle Impact Assessment (LCIA) of the product by evaluating environmental impacts based on the inventory analysis and the defined goal and scope. The inventory results are linked with the chosen impact categories. This evaluation typically consists in four sub-steps, including mandatory ones such as classification and characterization and optional ones such as normalisation and weighting (ISO, 2006; Jensen et al., 1997). The first sub-step of LCIA is **classification**, where data from the LCI, such as materials and energy inputs and outputs, are assigned to their respective impact category. For example, all inputs/outputs that result in GHG emissions are linked to the Climate Change Impact category (Roy et al., 2009). Next is **characterisation**, which involves calculating the magnitude of each input and output classified in different impact categories. For climate change impacts, all the GHG emissions previously accounted for are weighted in terms of impact intensity relative to CO_2 and expressed as kg of CO_2 equivalents. **Normalisation** is not mandatory, but many studies include it. This phase involves multiplying the LCIA results by a normalization factor to compare the magnitude of their contribution to impact categories in only one reference unit. The European Commission created the Product Environmental Footprint (PEF) to create a common baseline for measuring environmental performance. For example, the PEF defined the value of $8.1x10^3$ kg CO_2eq/person for climate change. These factors are expressed as impact per capita, related to a global value. PEF is used to assess the overall environmental impact of a product throughout its entire life cycle. It considers a broad range of environmental indicators, such as greenhouse gas emissions, resource depletion, water use, and other environmental impacts associated with the product's life cycle stages (from raw material extraction to production, distribution, use, and end-of-life). And provides a standardized framework to quantify and compare the environmental performance of products in the same category, allowing companies and consumers to make more informed decisions regarding the environmental impacts of their choices. **Weighting** is also a non-mandatory stage but important for better understanding and communicating the results. Here, the results from the previous phase are multiplied by a group of weighting factors (in %) to better illustrate the contribution and importance of each impact category considered. According to PEF, the weighting factor for climate change is 21%, indicating its importance compared to other categories, with resource use following at 8.3% (European Commission, 2023; Jensen et al., 1997; Roy et al., 2009). Finally, in the Interpretation phase, the results of the LCI and LCIA are discussed, and significant environmental problems are identified. This step also includes a sensitivity analysis, as well as qualitative and quantitative measures to mitigate or improve any of the life cycle steps of the product (Jensen et al., 1997).

Figure 9, illustrate all the phases that are part of a Life Cycle Assessment study, as well the direct application that can resulted from this evaluation.

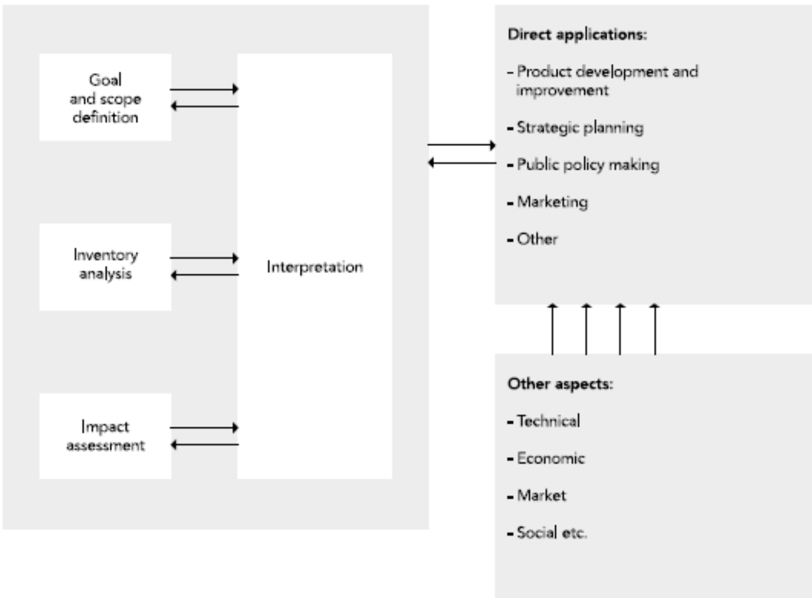

Figure 9. Life Cycle Assessment phases and direct applications (Jensen et al., 1997)(ISO, 2006).

Environmental Impact Indicators – ReCiPe

The LCA methodology selected was the ReCiPe 2016 Midpoint (H). This method is one of the most upgraded and modern impact assessment methods available to LCA users. The method considers 18 environmental categories at the midpoint level and then gathers the midpoint into a set of three endpoints categories. The endpoint characterization models the impact from midpoint into Areas of Protection, that are separated in “Damage to human health”, “Damage to ecosystems”, and “Damage to resource availability” (Figure 10) (European Commissions, 2021) .

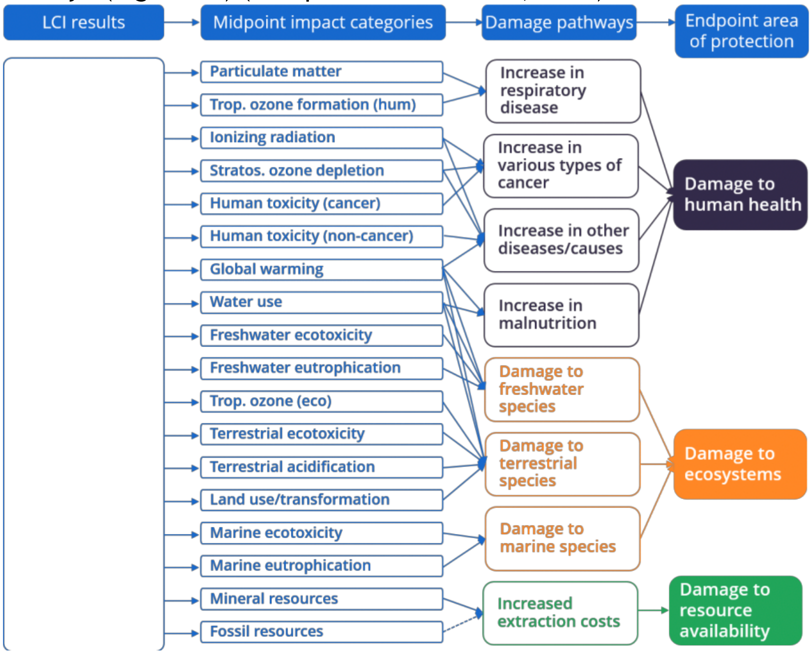

Figure 10. Impact categories covered in ReCiPe 2016 method and their relation to areas of protection (European Commissions, 2021).

It is possible to understand the relation between the midpoint impact categories and the endpoint areas of protection, as it represents a cause-effect pathway (Huijbregts et al., 2017).The endpoint approach evaluates the damage in three different areas of protection, such as: damage to human health, damage to ecosystem and damage to resource availability. On the other hand, the midpoint approach considers a list of environmental indicators to measure the different environmental impacts before the damage occurred to one of the endpoint areas of protection (Dong & Ng, 2014). The present study was applied at the midpoint level since it aims to identify and prevent the environmental damages from a product within the different environmental categories.

This methodology provides characterization factors, which are representative for a global scale, and enables the implementation of impact characterization factors at country or continental scale, creating consistency in the development of midpoint and endpoint models or frameworks, with the same time horizon. Thus, the main objective is to gather the data from the Inventory analysis into a certain number of indicators that express the severity of a certain environmental impact category (Huijbregts et al., 2016).

Environmental Impact Categories

The environmental impact categories considered in ReCiPe and the indicators are present in Table 4. Since this study is a pioneer in the LCA field, the results will consider all the environmental impact categories present in the methodology presented.

Table 4. The 18 impact categories of the ReCiPe 2016 Midpoint methodology (Huijbregts et al., 2016).

Midpoint impact category Characterisation factor	Indicator	Unit
Global Warming (GW)	Infrared radiative forcing increase	kg CO_2 eq to air
Ozone Depletion (OD)	Stratospheric ozone decrease	kg CFC-11 to air
Particulate Matter Formation (PMF)	PM2.5 population intake	kg PM2.5-eq to air
Photochemical Oxidant Formation Potential: Ecosystems (EOFP)	Tropospheric ozone increase	kg NO_x-eq to air
Photochemical Oxidant Formation Potential: Humans (EOFH)	Tropospheric ozone population intake increase	kg NO_x-eq to air
Terrestrial Acidification (TA)	Proton increases in natural soils	kg SO_2-eq to air
Freshwater Eutrophication (FE)	Phosphorus increases in freshwater	kg P-eq to freshwater
Marine Eutrophication (ME)	Dissolved inorganic nitrogen increase in marine water	kg N to marine water
Human Toxicity (HTPc)	Risk increases of cancer disease incidence	kg 1,4-DCB-eq to urban air
Human Toxicity Potential (HTPnc)	Risk increases of non-cancer disease incidence	kg 1,4-DCB-eq to urban air
Terrestrial Ecotoxicity (TET)	Hazard-weighted increase in natural soils	kg 1,4-DCB-eq to industrial soils
Freshwater Ecotoxicity (FET)	Hazard-weighted increase in fresh waters	kg 1,4-DCB-eq to fresh water
Marine Ecotoxicity (MET)	Hazard-weighted increase in marine waters	kg 1,4-DCB-eq to marine water
Agricultural Land Occupation (LO)	Occupation and time-integrated transformation	$m^2 \times yr$ annual crop land-eq
Water Consumption (WC)	Increases of water consumption	m^3 water consumed
Mineral Resources (MR)	Mineral resources consumption	kg Cu
Fossil Fuel (FF)	Upper heating value	kg oil

4.2. Goal and Scope Definition

The main objective of this LCA study is to compare the environmental impacts of different conservation methods (chilled and frozen) and packaging options for a specific food product, Moroccan Falafel. The conservation methods being evaluated include both chilled and frozen options, while the packaging options are a PET tray and a PET bag. This analysis will help calculate the environmental impacts of the selected product and identify areas, within its production, where changes can be made to enhance its overall environmental performance.

The study will be divided into two parts: first the LCA of chilled and frozen Moroccan Falafel until the end of the manufacturing process. Here, the objective is to conduct an analysis from the origin of raw materials to the manufacturing process. The second phase involves conducting an LCA of the chilled/frozen packed product, during its entire life cycle. The overall analysis will capture the packaging materials, as well as the distribution of the product, consumption, and options for packaging disposal.

Functional Unit

The functional unit for this study is one batch of product, corresponding to 100 kg of Moroccan Falafel. Two separate LCAs were conducted to account for the variations in the production stage, while the functional unit is maintaining the same across all the studies.

System Boundaries

The system boundaries aim to identify unit processes that will be considered in the LCA. Two LCA studies will be carried out. The functional unit is 100 kg of Moroccan Falafel either Chilled (MFC) or Frozen (MFF) that follow a cradle-to-grave perspective. The product life cycle phases include 1) Production of raw materials, 2) Transport of raw materials to Gosh! factory (including the transportation from the origin country to the suppliers, and from the suppliers to the final factory), 3) Goods Storage, 4) Ingredients Processing, 5) Manufacturing Process, 6) Packaging Process, 7) Product Storage, 8) Product Distribution, 9) Product Consumption, and finally, 10) Packaging disposal (incineration).

It is important to note that this analysis excluded the consideration of infrastructure and equipment used in the production of Moroccan Falafel. This decision was made based on the understanding that both infrastructure and equipment have a longer lifetime and are utilized for the production of larger quantities and various products. Therefore, their impact can be disregarded for this specific study.

It is worth mentioning that both Falafels are manufactured in the same location, and the distinction is in the final step of production (namely, spiral chiller and spiral frozen), but also the packaging process and product storage

Figure 11 represents the boundaries of the system chosen for this study. Both LCAs will consider all the steps represented

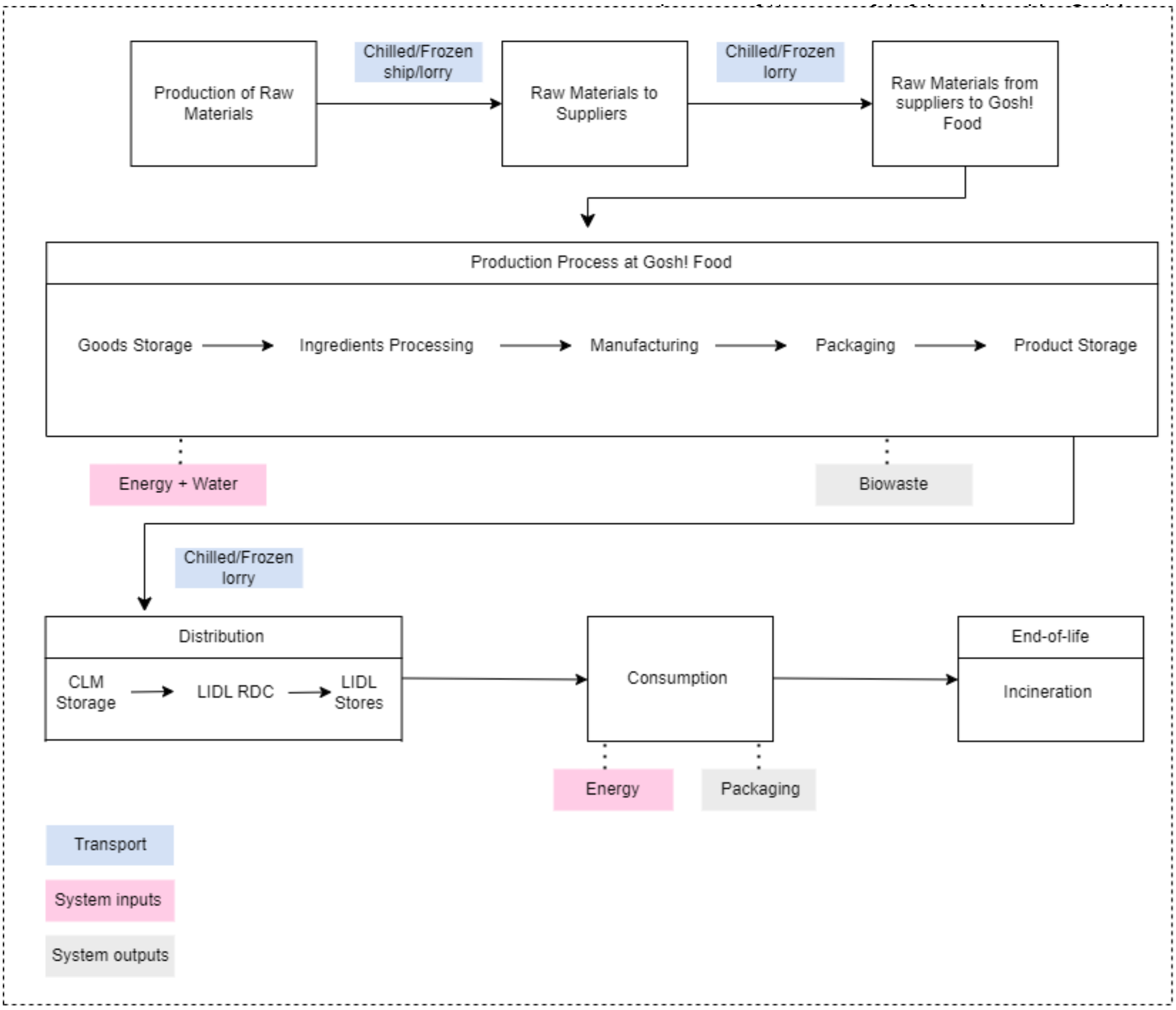

Figure 11. System boundaries for MFC and MFF.

4.3. Inventory Analysis

The company provided the primary data used for this inventory analysis, specifically the quantities of raw materials used, the type and characteristics of equipment and processing times. In some cases, more data was necessary, and assumptions were made using the data available in the SimaPro databases. The two databases used were AGRIBALYSE and Ecoinvent. AGRIBALYSE provided in general all the information about the ingredients used, while Ecoinvent was used to model the transportation and electricity used.

4.3.1. Production of raw materials

Regarding the origin of the raw materials, some assumptions were made to fill data gaps. AGRIBALYSE is a French database and was the only one available with the required information about the ingredients. Although the actual origin of the ingredients might not be France, it was not possible to obtain that information. Therefore, the study was conducted using the available data. Table 5 shows all the ingredients and the quantities needed to produce 100 kg of Moroccan Falafel.

Table 5. Inventory for the ingredients used to produce 100 kg of Moroccan Falafel.

Input	Quantity	Unit
Potato flakes, dehydrated, plain, processed in FR | Chilled | Cardboard | at packaging/FR	5.6	kg
Salt, white, for human consumption (sea, igneous or rock), iodine added, no other enrichment, processed in FR | Ambient (long) | PVC | at packaging/FR	0.7	kg
Sodium bicarbonate, processed in FR | Ambient (long) | Cardboard | at packaging/FR	0.4	kg
White pepper, powder, processed in FR | Ambient (long) | Glass | at packaging/FR	0.2	kg
Chili pepper, raw, processed in FR | Ambient (average) | No packaging | at distribution/FR	0.04	kg
Cumin, seed, processed in FR | Ambient (long) | Glass | at packaging/FR	0.4	kg
coriander {IN}| coriander production | Cut-off, U	0.4	kg
Cinnamon (canella), consumption mix/FR U	0.3	kg
Parsley, fresh, processed in FR | Ambient (long) | LDPE | at packaging/FR	0.3	kg
Onion {CN}| onion production | Cut-off, U	7.5	kg
Apricot, pitted, raw, processed in FR | Ambient (average) | LDPE | at packaging/FR	4.7	kg
Date, pulp and peel, dried, processed in FR | Ambient (average) | LDPE | at packaging/FR	3.7	kg
bell pepper {RoW}| bell pepper production, open field | Cut-off, U	15	kg
Garlic, powder, dried, processed in FR | Ambient (long) | Glass | at packaging/FR	0.9	kg
Rapeseed oil, processed in FR | Ambient (long) | PET | at packaging/FR	7.5	kg
Chickpea {IN}| chickpea production | Cut-off, U	48.7	kg
Tap water {Europe without Switzerland}| market for | Cut-off, U	3.7	kg

4.3.2. Transportation of raw materials

The transportation of raw materials to the factory occurs in two stages. First, the raw materials are transported from their country of origin, where they are produced, to the distributor warehouse. In the second stage, the materials are transported from the distributor warehouse to the factory. Since it was not possible to analyse specific information about the origin of the raw materials and the distributors, two distinct assumptions were made.

First, it was assumed that all the production of the ingredients occurs in France because the available database, AGRIBALYSE, only provided information for ingredients produced in France. However, it was possible to obtain information about the production country for the main ingredients, and the distance between that country and the suppliers was accounted for. For ingredients imported from Argentina, China, Turkey and India, transportation by ship was considered, from the origin country to the Port of Felixstowe, as this is the most frequently used port in the UK. From the port to the suppliers the transportation was assumed to be carried out by a specific type of lorry, namely a lorry with refrigeration machine weighing 7.5-16 tons. Out of the 15 ingredients listed before, only two, namely onion and red pepper, are transported in the frozen stage. Since these specific ingredients are imported from China, they require two different vehicles for transportation: freezer ship containers and freezer lorry. The vehicle was selected taking into consideration the Euro 5 Regulation, that since 2009, proposes the adoption of new limits for the emissions of particles and NOx (European Commission, 2006).

Annex C presents all the information regarding the different distances calculated using Google Earth, as well as the unit conversion according to the functional unit. Since there are 23 ingredients that require two vehicles to arrive at Gosh! (for example, the case of the onion), it was necessary to divide the analysis in order to account for the environmental impacts of both the freezer ship and the freezer lorry. The same reasoning was applied to all the ingredients. These calculations were first made by converting the individual quantity of each ingredient into tons and then multiplying this value by the total distance traveled by each vehicle. All the calculations are also presented in Annex C.

Table 6 presents the inventory regarding the distribution of raw materials.

Table 6. Inventory for the goods transportation from country of origin (considered France) to suppliers.

Inputs	Total mass of ingredients being transported (ton)	Total km	Distance modelled (tkm)
Lorry with refrigeration machine. 7.5-16 tons cooling	0.0791	1719	14.3
Lorry with refrigeration machine. 7.5-16 tons freezing	0.0172	2032	8.53
Container ship cooling	0.0593	54670	614.9
Container ship freezing	0.0225	14638	164.67

After the goods arrive at the suppliers' warehouses, they need to be transported to the factory. For this purpose, the same vehicles as before, namely lorries with cooling and freezing capabilities, were used. The distances between the suppliers' warehouses and the factory are described in Annex C. Table 7 presents the total distance in tonne-kilometers (tkm).

Table 7. Inventory for the goods transportation from suppliers to Gosh! factory.

Inputs	Total mass of ingredients being transported (ton)	Total km	Distance modelled (tkm)
Lorry with refrigeration machine. 7.5-16 tons cooling	0.074	1512	116.8
Lorry with refrigeration machine. 7.5-16 tons freezing	0.023	83	1.87

4.3.3. Production Process at Gosh!

Goods Storage

When the ingredients arrive at Gosh! storage, they are separated into frozen and chilled goods. At this stage, only the power of the equipment and the storage duration of the goods are taken into consideration. Table 8 summarises this information for chilled and frozen ingredients, the total values of energy consumption were converted to the Unit Functional (UF).

The calculations were made by multiplying the processing time, in hours, with the power of each equipment, both values provided by the company. However, only 22.5% of the total goods need to be frozen, while the remaining 73.8% (excluding 3.7% of water) need to be stored in a chilled refrigerator. Therefore, the calculations were made taking into account the amount of ingredients that are imported in the frozen and chilled state.

In Annex B are presented all the calculations made regarding the energy consumption of each equipment since the goods storage stage until the final product storage.

Table 8. Inventory about the storage of chilled and frozen raw materials.

Input	Consumption per FU	Unit
Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	366.5	kWh

Ingredients Preparation

This stage follows the same principles as the previous one, considering only the power of the equipment and the timing of each step to calculate energy consumption. The ingredient preparation process is the same for both chilled and frozen products. Table 9 shows the various equipment utilized during this stage, along with the final energy consumption according with the UF selected.

Table 9. Inventory about the energy consumption of the ingredients preparation stage.

Input	Consumption per FU	Unit
Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	8.3	kWh

Manufacturing Process

The manufacturing process consists of three phases: forming machine, oven, and cooling mechanism. The first two steps are the same for both chilled and frozen products, with the only difference occurring during the cooling stage. For chilled falafel, a spiral chiller is used, whereas for frozen falafel, a spiral freezer with higher power is required. Table 10 represents the energy consumption data for the manufacturing process of both products. The first two sub-stages (forming machine and travelling oven) are common for both products. All the values are reported to the FU selected. In this step is also added water to the recipe. The water quantity is the same for both chilled and frozen product and it is detailed below.

Table 10. Energy consumption on the manufacturing stage for chilled products.

	Input	Consumption per FU	Unit
MFC	Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	22.5	kWh
	Tap water {Europe without Switzerland}| market for | Cut-off, U	3.7	kg
MFF	Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	155.8	kWh
	Tap water {Europe without Switzerland}| market for | Cut-off, U	3.7	kg

After this stage, a total of 2.5 kg of biowaste is generated as an output of the process.

Packaging Process

Gosh! is responsible for packing the product, but it does not manufacture the packaging material in-house. It buys the trays and bags from a different manufacturer. The packaging process, which occurs in-house, is divided into two stages: tray sealing and sleeving machine. The process remains the same for both packaging options, whether it is tray or bag. Table 12 provides an overview of the energy consumption inventory for the packaging stage. The packaging material used is polythene, with the only difference being the quantity required to pack the functional unit. The data regarding the weight of clear polyethylene required is also presented in Table 11. All the data was adapted depending on the UF of the study.

Table 11. Energy consumption and packaging material.

	Input	Consumption per FU	Unit
MFC	Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	5.6	kWh
	Packaging film, low density polyethylene {GLO}|market | Cut-off, U	9.5	kg
MFF	Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	5.6	kWh
	Packaging film, low density polyethylene {GLO}|market | Cut-off, U	1.2	kg

Product Storage

After the manufacturing process, the goods are stored at the factory warehouse as ready products. In terms of inventory for this particular stage of the life cycle, the worst-case scenario was considered regarding the storage time before the pick-up by the distribution company. This worst-case scenario assumed a storage time of 12 hours. Additionally, the energy consumption of the refrigeration and freezer units used for the final product was evaluated. The information concerning the energy consumption of the assets was resumed in Table 12 for both Moroccan Falafel Chilled (MFC) and Moroccan Falafel Frozen (MFF).

Table 12. Inventory about the finished product storage.

	Input	Consumption per FU	Unit
MFC	Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	50.4	kWh
MFF	Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	279	kWh

4.3.4. Distribution

Table 13 represents the distances that the products travel from the moment they are picked up at Gosh! to their delivery at the supermarket. The distances were calculated using Google Earth software and converted to tkm. In this life cycle stage, the worst-case scenario was also considered. All the LIDL Depots were taken into consideration, and the one farthest to the factory was selected. The vehicle chosen was the same as the one mentioned earlier for the transportation of raw materials, namely the lorry with a refrigeration machine,7.5-16 tons cooling/ freezing, depending on the type of product being transported. The information about the type of vehicle and distance is presented in Table 14.

Table 13. Total distance travelled since from Gosh! to the LIDL Supermarket.

	Distance	Units
Gosh! Food to CML	138	km
CML to LIDL Depot	399	km
LIDL Depot to LIDL Supermarket	50	km
Total:	587	km

Table 14. Transportation distances about the product transportation for MFC and MFF.

Inputs	Total mass of product being transported (ton)	Total km:	UF (tkm)
Lorry with refrigeration machine. 7.5-16 tons cooling	0.1	587	58.7
Lorry with refrigeration machine. 7.5-16 tons freezing	0.1	587	58.7

4.3.5. Product Consumption

For the consumption stage, only the energy consumption of the equipment used to cook the product was analysed. A conventional oven was used for this purpose. The data regarding this stage is presented in Table 15 for MFC and MFF. The baking time depends on the conservation stage of the product. It was assumed to be 5 minutes for MFC and 15 minutes for MFF, based on the recommendations on the label. Again, the UF was considered in the calculations. For the power of the equipment, it was considered a standard oven with a power of 2400 kW (Fisher, 2023).

Table 15. Inventory for the consumption stage.

	Input	Consumption per FU	Unit
MFC	Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	0.2	kWh
MFF	Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U	0.6	kWh

4.3.6. Packaging disposal

For the modeling of this last stage of the product life cycle, it was measured the weight of the packaging used to pack the functional unit considering the two options most common to treat municipal waste: landfilling and incineration. According to the bibliography, waste incineration has been increasing in the past years and is expected to continue to increase (Amutha Rani et al., 2008). In line with this, waste treatment incineration was selected to evaluate the environmental impact of the packaging disposal. Table 16 resumes the quantity of material used in both products.

Table 16.Inventory of the packaging disposal.

	Output	Quantity	Unit
MFC	Municipal solid waste {GB}|treatment of, incineration | Cut-off, U	9.5	kWh
MFF	Municipal solid waste {GB}|treatment of, incineration | Cut-off, U	1.2	kWh

4.4. LCA Results

The environmental impact assessment of both MFC and MFF was performed using the software SimaPro 9.2.0.2. Two databases, Ecoinvent version 3.7.1 and AGRIBALYSE version 3.7.1, were used for the assessment. The selected impact method was ReCiPe 2016 Midpoint (H), which assesses 17 environmental impact categories.

This chapter will present and discuss the environmental results for all life cycle phases of each product. First, the focus will be on comparing the two products, Moroccan Falafel Chilled and Moroccan Falafel Frozen. Following this analysis, a detailed evaluation will be conducted for each product, specifically highlighting the life cycle stages with larger environmental impacts.

The life cycle stages assessed were the following:

1. Production of raw materials
2. Transportation of raw materials
3. Production process at Gosh! (including goods storage and ingredients preparation, which are the same for both products). This step also includes the phases of manufacturing process and packaging, which differ depending on whether the product is chilled or frozen.
4. Distribution
5. Product consumption
6. Packaging disposal

For the last three steps (distribution, product consumption, and packaging disposal), the inventory data differs between MFC and MFF.

4.4.1. Comparison between the two Moroccan Falafel (Chilled *vs* Frozen)

Figure 11 displays the overall environmental impact results for both products across the 17 assessed environmental categories. The results indicate similarity on the contribution to the overall environmental impact.

However, for MFF the contribution is slightly larger for 13 out of the 17 total categories, with special attention for the categories such as: Global Warming Potential, Freshwater Eutrophication Potential, Human Toxicity Potential, Agricultural Land Occupation Potential and Fossil Fuel Potential.

The environmental impact for the MFC is larger than 50% for the categories of Marine Ecotoxicity Potential and Freshwater Ecotoxicity Potential.

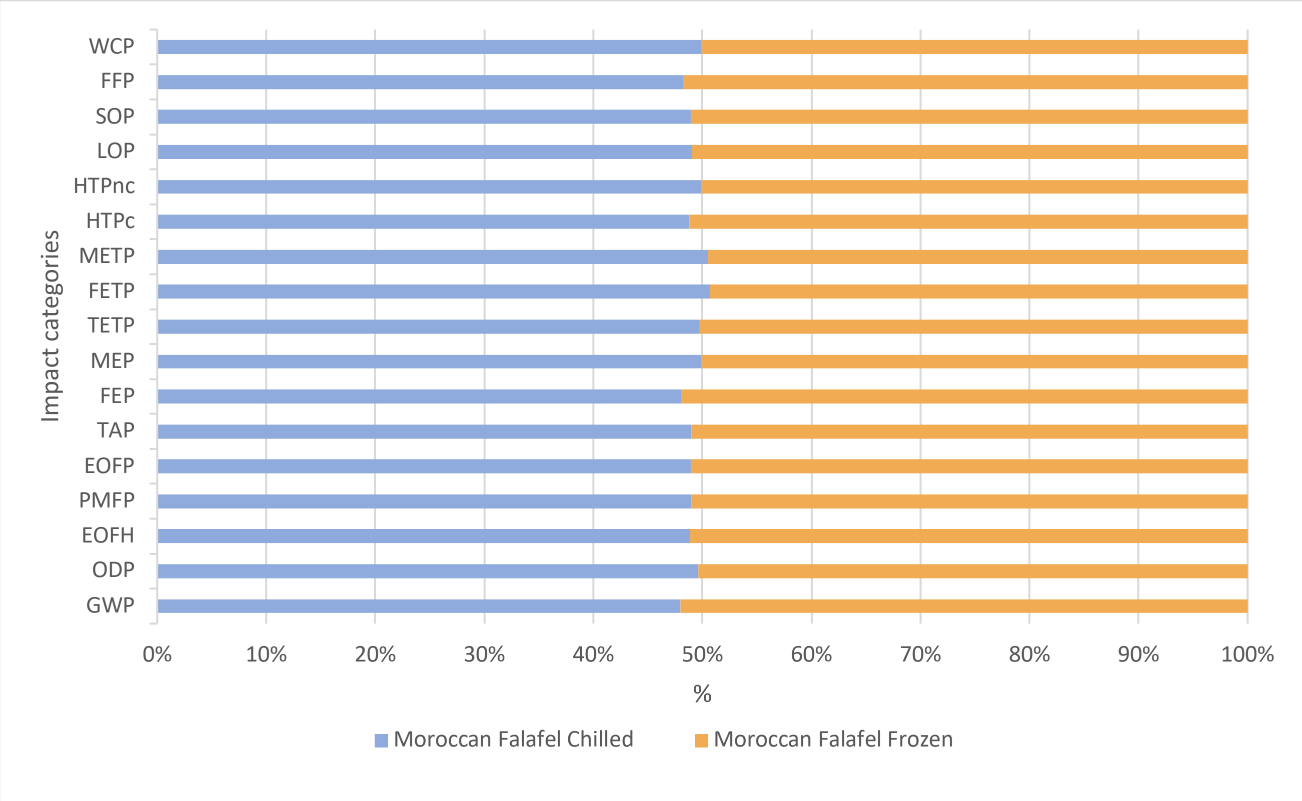

Figure 11. Comparison between MFC and MFC for all environmental impact categories (GW- Global Warming; OD-Ozone Depletion; EOFH-Photochemical Oxidant Formation: Humans ; PMFP- Particulate Matter Formation; EOFP-Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; MED- Marine Eutrophication; TETP- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTPc- Human Toxicity (cancer incidence disease); HTPnc- Human Toxicity (non-cancer incidence disease); LOP- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WCP- Water Consumption).

4.4.2. Moroccan Falafel Chilled

Figure 12 illustrates the results of the environmental impacts for all the evaluated life cycle stages. The production of raw materials emerges as the primary contributor across all environmental impact categories. The impact is larger than 70% for all the following categories: Water Consumption Potential, Human Toxicity Potential (both cancer and non-cancer diseases), Marine Eutrophication Potential and Ozone Depletion Potential.

These results align with expectations, as agricultural practices, particularly the use of fertilisers, have a large contribution to the overall impacts. These emissions not only affect the ozone layer depletion but also have implications on water sources pollution, leading to potential impacts negative on human health. Furthermore, the substantial water and land requirements associated with the ingredients production process contribute to an increase in values within the water consumption and land occupation categories. In this study, a further analysis will be conducted to evaluate the raw materials integrated in the falafel recipe. The objective is to quantify the individual contribution of each raw material used in terms of environmental impact.

The third stage with the highest impact is the transportation of raw materials from the origin country to the Gosh! factory. This is a result of the various kinds of vehicles required for distribution, powered by fossil fuels, and the long distances that the raw materials need to travel before arriving at the factory.

The production process at Gosh! Don´t represent a significant impact. The major impact categories affected are: Fossil Fuel Potential, Freshwater Eutrophication Potential and Global Warming Potential. Although these categories have the largest contributions.

The distribution stage exhibits significant environmental impacts, with more than 50% contribution in three distinct categories: Freshwater Ecotoxicity Potential, Terrestrial Ecotoxicity Potential and Marine Ecotoxicity Potential. These results can be attributed to the type of fuel used for product distribution, which was assumed to be fossil fuel. It is important to note that the distribution stage considered the transportation of the functional unit (100 kg of MFC) to the farthest LIDL RDC. This may lead to an overestimation of the average impact results.

Among the other two stages (transport of raw materials, product consumption, and end-of-life), transportation has the most significant contribution. The largest value is observed for the category of Photochemical Oxidant Formation Potential (EOFH). The packaging disposal stage only exhibits relevant impact of around 7% for the categories of Freshwater Ecotoxicity Potential and Marine Ecotoxicity Potential. Product consumption has a negligible contribution across all the analysed categories.

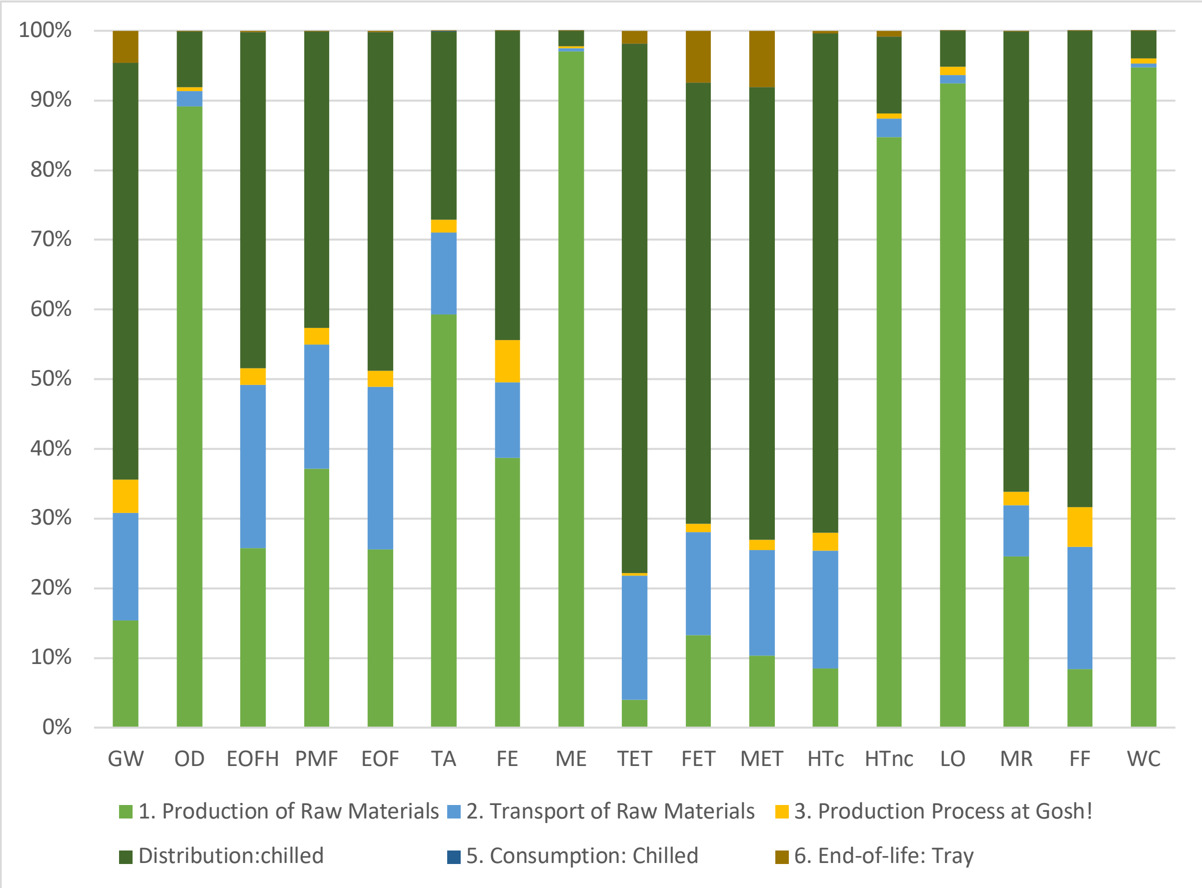

Figure 12. Contribution of each life cycle stage evaluated of MFC to the environmental categories (GW- Global Warming; OD- Ozone Depletion; EOFH -Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

Annex D (Table D-1) presents the total impact contribution of the Moroccan Falafel Chilled production, considering all the life cycle stages evaluated. The results are presented to emphasize the significance of each stage in relation to the assessed environmental impact categories. The relative percentage contribution was calculated by dividing the individual value of each stage in each category (e.g., GWP for the production of raw materials) by the total value for that category. This methodology was consistently applied across all life cycle phases. The largest contributions within each life cycle phase are indicated in bold.

4.4.3. Moroccan Falafel Frozen

Figure 13 presents the results of the inventory analysis specifically for the product Moroccan Falafel Frozen. The results for the stages of production and transportation of the raw materials remain unchanged from the previously analysed results since these stages are similar for both products.

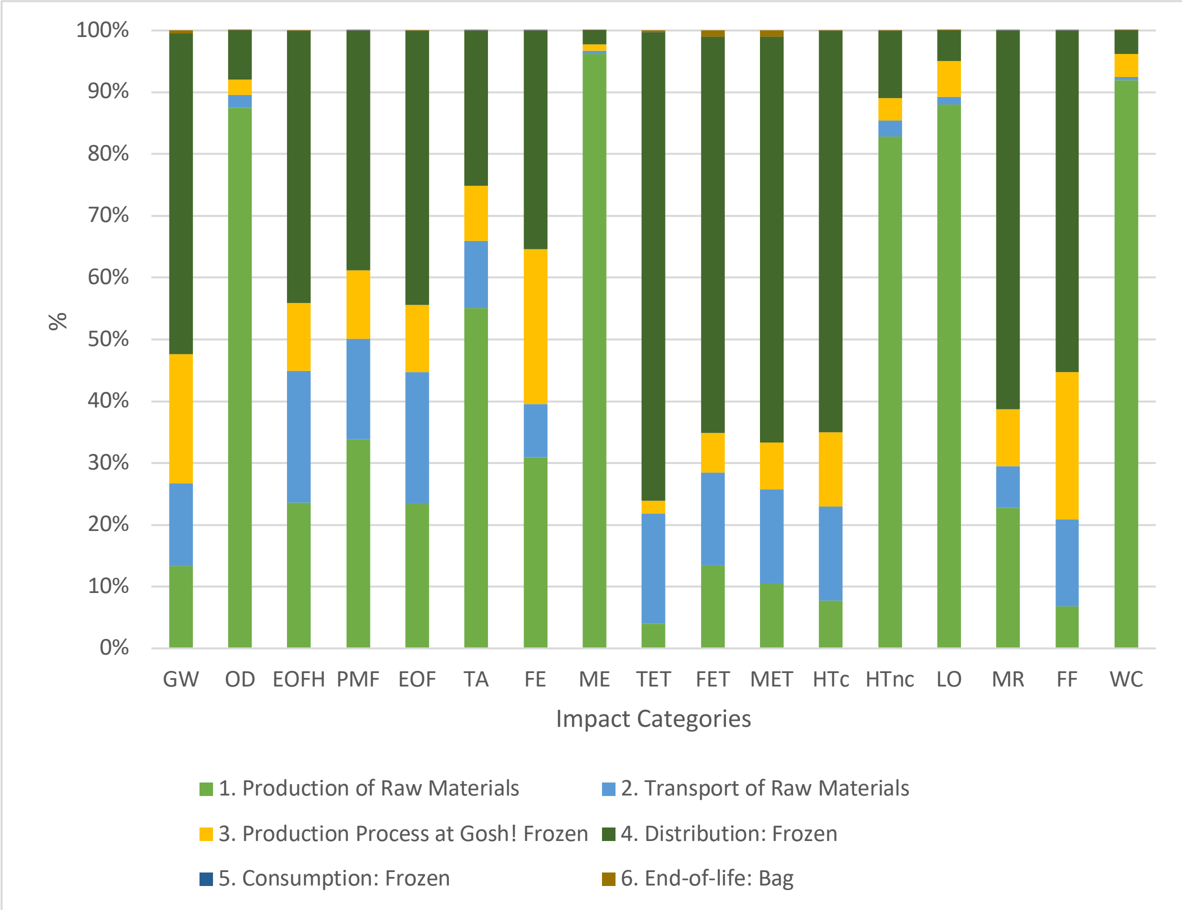

Figure 13. Contribution of each life cycle stage evaluated of MFF to the environmental categories (GW- Global Warming; OD- Ozone Depletion; EOFH -Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

The production of raw materials continues to have the most significant contribution to the environmental impact across all categories. The distribution stage had very similar results when compared with the same stage for the MFC, with Terrestrial Ecotoxicity Potential being the category with the worst environmental impact results. This is followed by the production process at Gosh! stage, where the results show a similar trend to MFC but with an overall increase in environmental impact for all categories. Specifically, there is a notable increase in impact for the categories of Marine Ecotoxicity, Freshwater Ecotoxicity, and Global Warming. In the case of MFF, the percentage values for these categories have increased by almost 4%. These values reflect the higher energy consumption requirements due to the power needed for the spiral freezer used in the freezing process of the Moroccan Falafel Frozen product. The increased energy consumption in the freezing stage contributes to the higher environmental impact observed in the categories mentioned.

The transportation of raw materials was modeled in the same way for both products, so the results are the same as the ones already analysed.

Finally, when comparing the packaging disposal, there is a notable decrease in the impact values across all categories for the MFF. This decrease is particularly highlighted in the categories of Marine Ecotoxicity Potential and Freshwater Ecotoxicity Potential, where a significant reduction was observed (4%). This decrease was expected since the quantity of materials needed to pack 100 kg of MFF is significantly lower than the quantity of materials required to pack the same amount of MFC.

Annex D (Table D-2) presents the individual data for each life cycle stage and the assessed environmental impact categories. It provides a detailed analysis of the environmental impacts associated with each stage and category.

4.4.4. Production of Raw Materials

Since the stage that results in the largest environmental impacts in all analysed impact categories is the raw materials production, it is important to analyse all the ingredients used in the Moroccan Falafel recipe and ascertain which contribute to the largest impacts. Figure 14 shows the environmental results for all the ingredients used.

The analysis of the ingredients is limited to those that make up more than 95% of the total ingredients in the Moroccan Falafel recipe, including, chickpeas, red peppers, rapeseed oil, dates, apricots, potato flakes, onions and water.

Among the ingredients considered, chickpeas contribute with the largest impact to all the analysed categories. They contribute to more than 50% of the total impact in six categories: Water Consumption Potential, Marine Ecotoxicity Potential, Terrestrial Ecotoxicity Potential, Human Toxicity Potential (cancer and non-cancer incidence) and Ozone Depletion Potential. Chickpeas also have the largest contribution to the Global Warming category, accounting for 41% of the total emissions in this category. The significant impacts associated with chickpeas are due to their comparatively larger amount used in the falafel recipe (49 kg). The second largest contributor to the impact is red pepper, with the most significant contributions in the and Freshwater Eutrophication Potential, where it exceeds 47% in both cases. Rapeseed oil also has a relevant contribution to the impact in Land Occupation Potential, with 38% of impact in this category. The contributions of the other ingredients can be considered negligible, as they do not exceed 6% in any of the evaluated categories. However, dates have a considerable contribution to the Ozone Depletion potential category, accounting for more than 46%. Annex D (Table D.3) presents the absolute values and percentages obtained in this analysis.

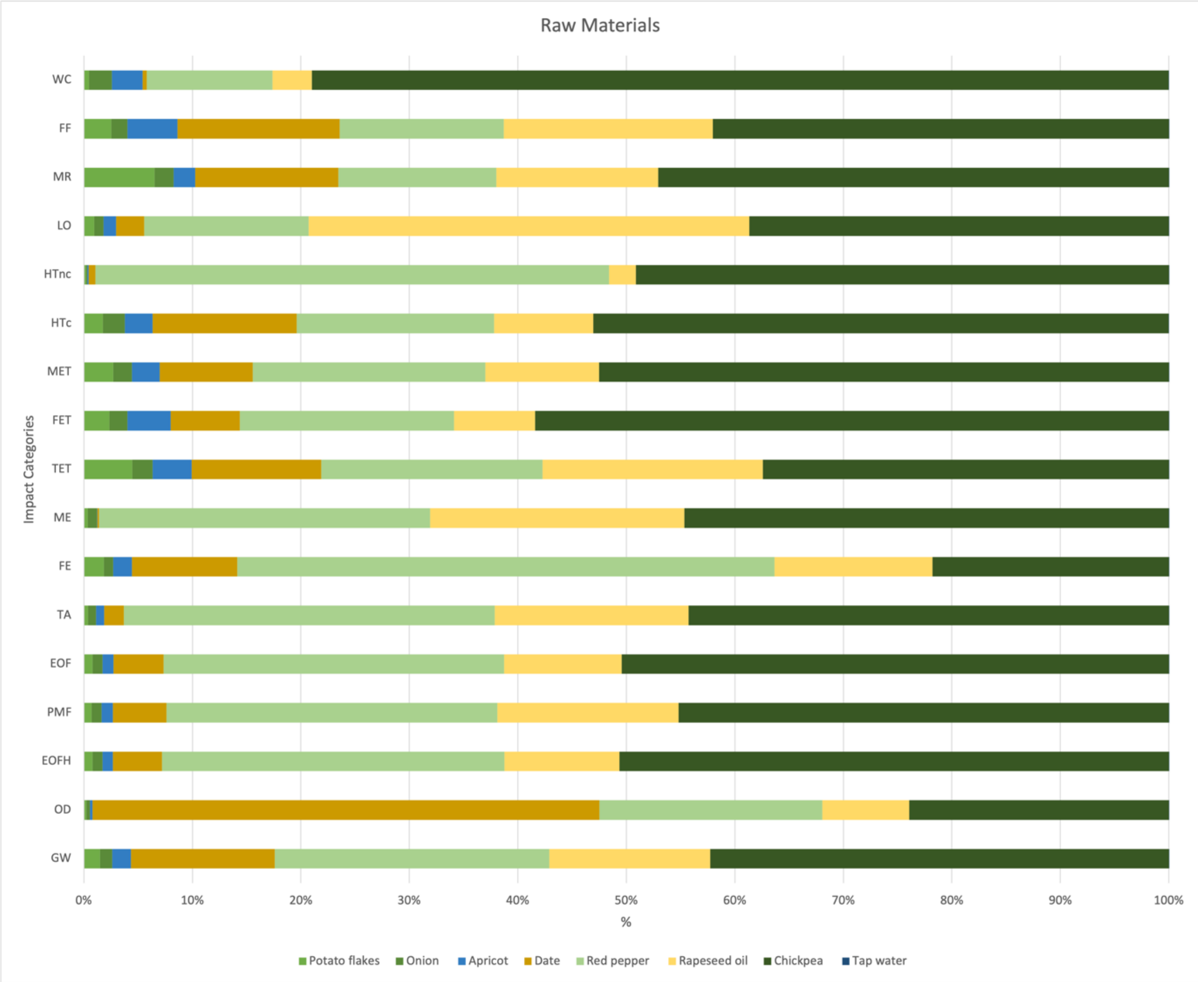

Figure 14. Contribution of each life cycle stage evaluated of the Raw Materials Production to the environmental categories (GW- Global Warming; OD– Ozone Depletion; EOFH -Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

4.4.5. Sensitivity Analysis

According to ISO 14040:2006, sensitivity analysis is a procedure used to test how the results of a life cycle assessment (LCA) change when specific parameters are altered (ISO, 2006).

This is a very important tool that enables the study of the robustness of the results obtained and their sensitivity to uncertainty factors or alteration that can be made within the product's life cycle. This method consists of varying the input parameters, which provides information that makes it possible to identify which factor or factors have the most significant influence on the LCA results. In addition to a better understanding of the sensitivity of the parameters, it also contributes to the reliability of the results, which is especially important for decision making.

In this work, two types of analyses were performed. The first focused on the main ingredient present in the product (chickpea) by replacing half of it by either beetroot and sweet potato. The second considered the type of energy used in the manufacture of falafel, (including goods storage, ingredient preparation, product manufacturing, packaging and product storage), and replaced it by electricity from renewable sources (30% and 50%). All comparisons will be made between the Moroccan Falafel Chilled and the evaluated product. To simplify the nomenclature, the Moroccan Falafel Chilled (MFC) will now be referred to as Moroccan Falafel Original. The chilled product was chosen as the basis of comparison in this study because it represents higher sales compared to the other product.

All the calculations were made using the software SimaPro and the Ecoinvent version 3.7.1. The databases used for the sensitivity analysis are presented in Table 17.

Table 17. Inventory used for the Sensitivity Analysis by considering as reference the Energy consumption for the Moroccan Falafel Chilled.

Input	Quantity	Units
Beetroot, raw, process in FR | Ambient (average) | No packaging | No preparation | at consumer	24.5	kg
Sweet potato, raw, process in FR | Ambient (average) | No packaging | No preparation | at consumer	24.5	kg
Electricity, medium voltage (GB)| electricity production, photovoltaic, 3 kWp slanted roof, multi-Si | Cut-off, U	43.4*	kWh
Electricity, medium voltage (GB)| electricity production, photovoltaic, 3 kWp slanted roof, multi-Si | Cut-off, U	26.1 **	kWh

*Value corresponding to 30% of the total energy consumption coming from photovoltaic electricity production. The remaining electricity consumption was modelled as Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U and is equal to 43.4 kWh.
** Value corresponding to 50% of the total energy consumption coming from photovoltaic electricity production. The remaining electricity consumption was modelled as Electricity, medium voltage {GB}|electricity voltage transformation from high to medium voltage | Cut-off, U and is equal to 60.76 kWh.

4.5.1. Replacement of the main ingredient: Beetroot and Sweet potato

Chickpeas are the ingredient used in the greatest quantity, accounting for approximately 49% of the total ingredients in the recipe. Therefore, this analysis aims to evaluate the results obtained when the quantity of chickpeas in the recipe is reduced and replaced by another ingredient. Specifically, the analysis will focus on replacing 24.5 kg of chickpeas with an equal quantity of two alternative ingredients, beetroot and sweet potato, already used in other falafel recipes prepared by Gosh!. The goal is to assess the environmental impacts resulting from this substitution and compare them to the original recipe. This analysis aimed to investigate the environmental impact of the final product if the main ingredient used in the Moroccan Falafel recipe is replaced by another vegetable option. In this way, this analysis reflect an hypothetical product and not a real product manufactured by Gosh!.

Table E.1 to E.6 (Annex F) presents the absolute and percentage values for all the sensitivity analyses conducted in this chapter.

Moroccan Falafel Original *versus* Moroccan Falafel Beetroot

First, the raw materials production stage will be evaluated for two scenarios: MFO (Moroccan Falafel Original), which represents the original selection of raw materials with chickpeas, and MFB (Moroccan Falafel Beetroots), which includes the same quantity of chickpeas and beetroot as a replacement.

Figure 15 illustrates the percentage differences that occurred in the production of raw materials stage as a result of this substitution. The difference between the two bars in terms of percentage represents the decrease resulting from the substitution.

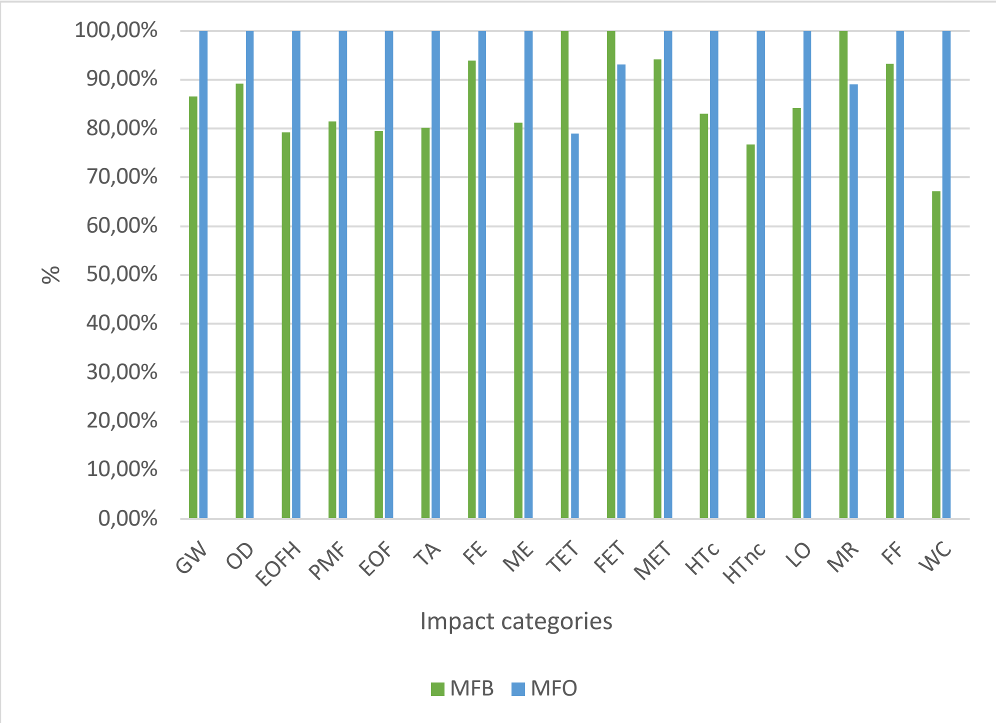

Figure 15. Sensitivity Analysis: MFO vs MFB (GW- Global Warming; OD– Ozone Depletion; EOFH -Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

The difference is higher for the categories of Water Consumption Potential and Human Toxicity Potential (non-cancer incident) in which the values decrease by 19.5% and 13.1%, respectively.
There was only one category, Terrestrial Ecotoxicity Potential, where the values were higher for MFB compared to MFO. In this category, the substitution of chickpeas with beetroot resulted in an increase of 11% in environmental impact.

Chickpea *versus* Beetroot

Regarding the comparison between the two ingredients, it is notable, as shown in Figure 16, that the selected ingredient has a lower impact in almost all the analysed categories, except for Terrestrial Ecotoxicity, Freshwater Ecotoxicity and Mineral Resources. The categories where the decrease was most pronounced were Human Toxicity (non-cancer incidence) with a decrease of less than 93% compared to the same category for MFO. The same trend was observed for the category of Ozone Depletion, with a decrease of less than 88%. It is also important to highlight the difference between the two ingredients in terms of GWP, with beetroots emitting less than 53% compared to the same mass of chickpeas in this category.

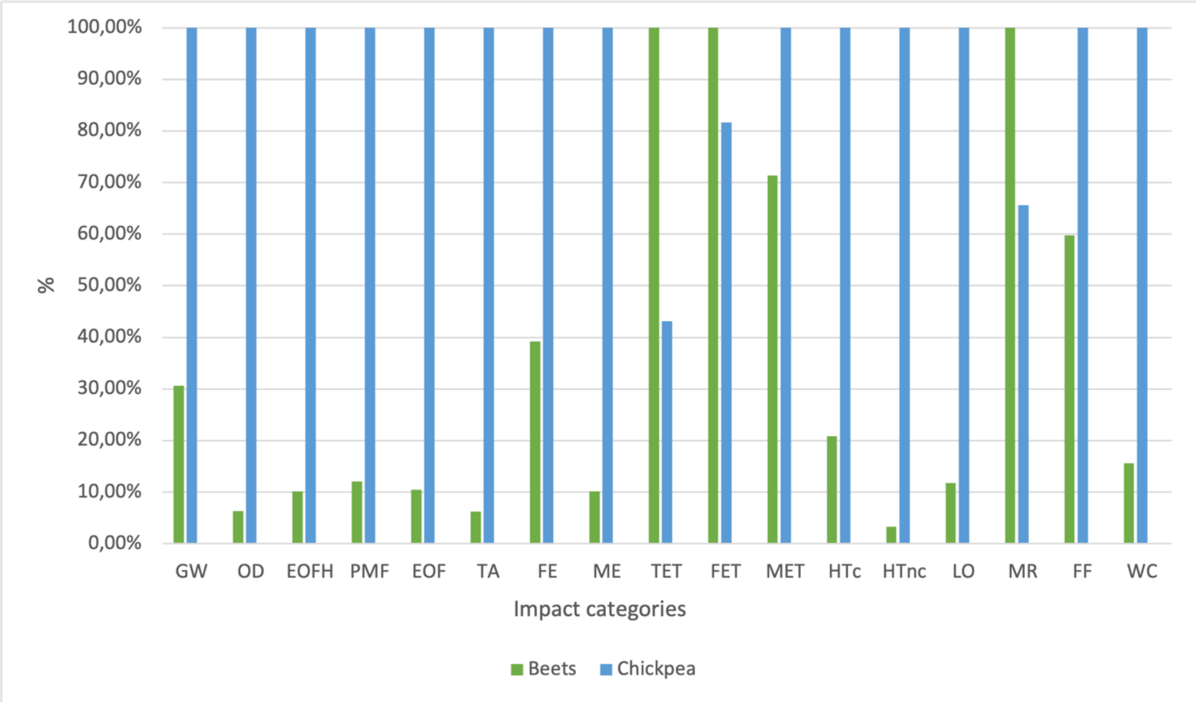

Figure 16. Comparison of impacts: Chickpea vs Beetroot (GW- Global Warming; OD- Ozone Depletion; EOFH - Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

Moroccan Falafel Original *versus* Moroccan Falafel Sweet Potato

This analysis follows a similar approach to the evaluation between MFO and MFB. However, in this case, the objective is to assess the variation in environmental impacts when half of the mass of chickpeas is replaced by sweet potato, resulting in a new product called Moroccan Falafel Sweet Potato (MFS). The MFS has 24.5 kg of chickpeas and 24.5 kg of sweet potato to produce 100 kg of MFO.

Figure 17 displays the results of this evaluation.

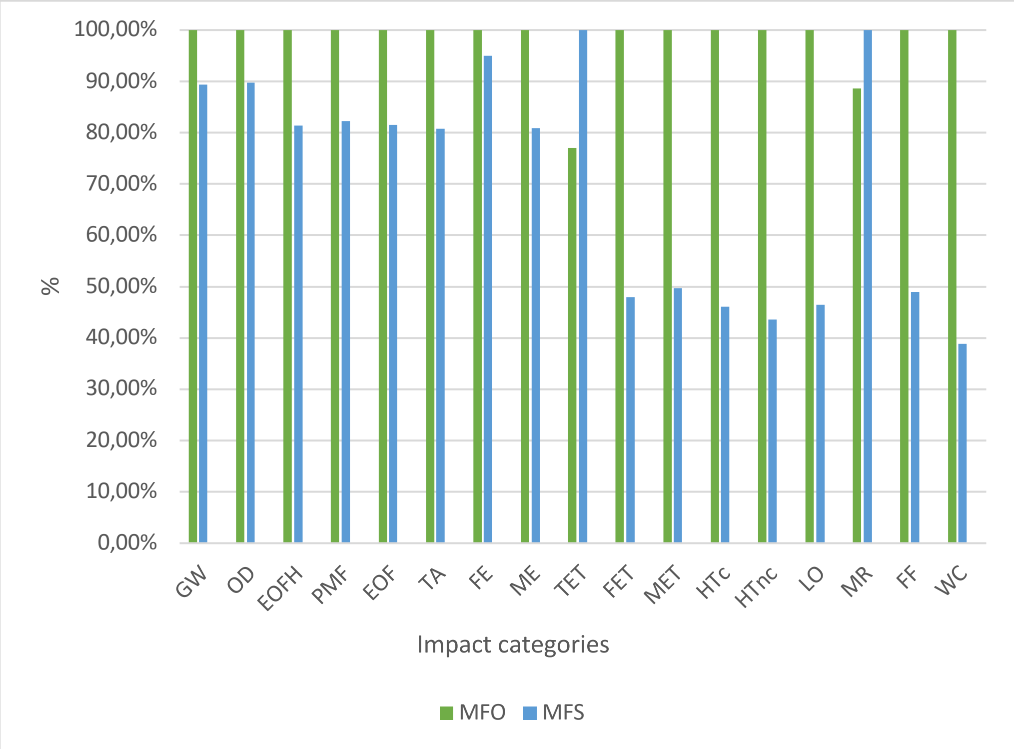

Figure 17. Sensitivity Analysis: MFO vs MFS (GW- Global Warming; OD- Ozone Depletion; EOFH -Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

The major difference is observed in the category of Water Consumption Potential, where the impact can be reduced by more than 22% simply by replacing that quantity of chickpeas with sweet potato. Similarly, to the case of MFB, the adoption of sweet potato leads to a 12% decrease in emissions in the category of Human Toxicity (non-cancer incidence) Across all other environmental categories, the results consistently show that MFP has the lower values. The exception to this trend is seen in the categories of Terrestrial Ecotoxicity and Mineral Resource, where was observed an increase of the values by adding the sweet potato.

Chickpea *versus* Sweet Potato

This analysis will directly compare the two ingredients across the 17 environmental impact categories. The results obtained are presented in Table 18. The findings are similar to the previous comparison between beetroots and chickpeas. Sweet potato shows emissions of less than 80% compared to chickpeas in four categories: OD, TA, MET, and WC. Notably, sweet potato has a 38% lower impact than chickpeas in the category of GW. However, in two categories, namely FET and MR, chickpeas still demonstrate better environmental results.

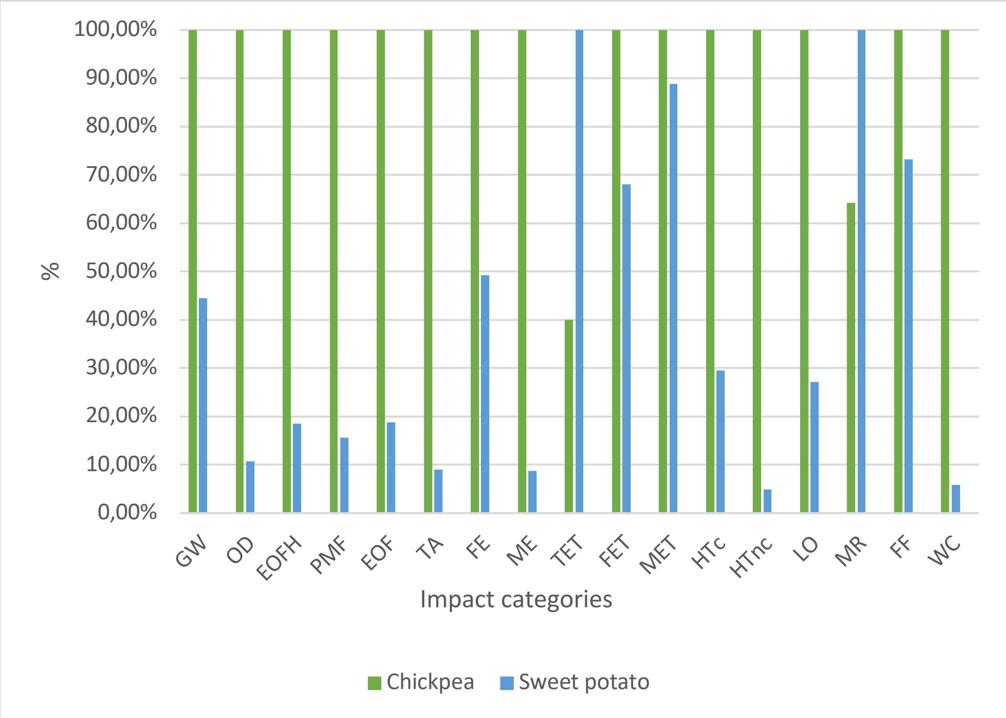

Figure 18. Sensitivity Analysis: Chickpea vs Sweet potato (GW- Global Warming; OD– Ozone Depletion; EOFH - Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

MF Original *versus* MF Beetroot *versus* MF Sweet Potato

Table 16 shows the results obtained when comparing the two new ingredients with the original (chickpeas) used in the recipe. As observed before, the two new ingredients lead to decreases in almost all the environmental categories, with the category of water consumption showing the highest reduction, followed by the category of fossil fuel. Despite the positive results achieved, there are two categories where the use of chickpeas contributes to an environmental benefit, those being Terrestrial Ecotoxicity and Mineral Resources.

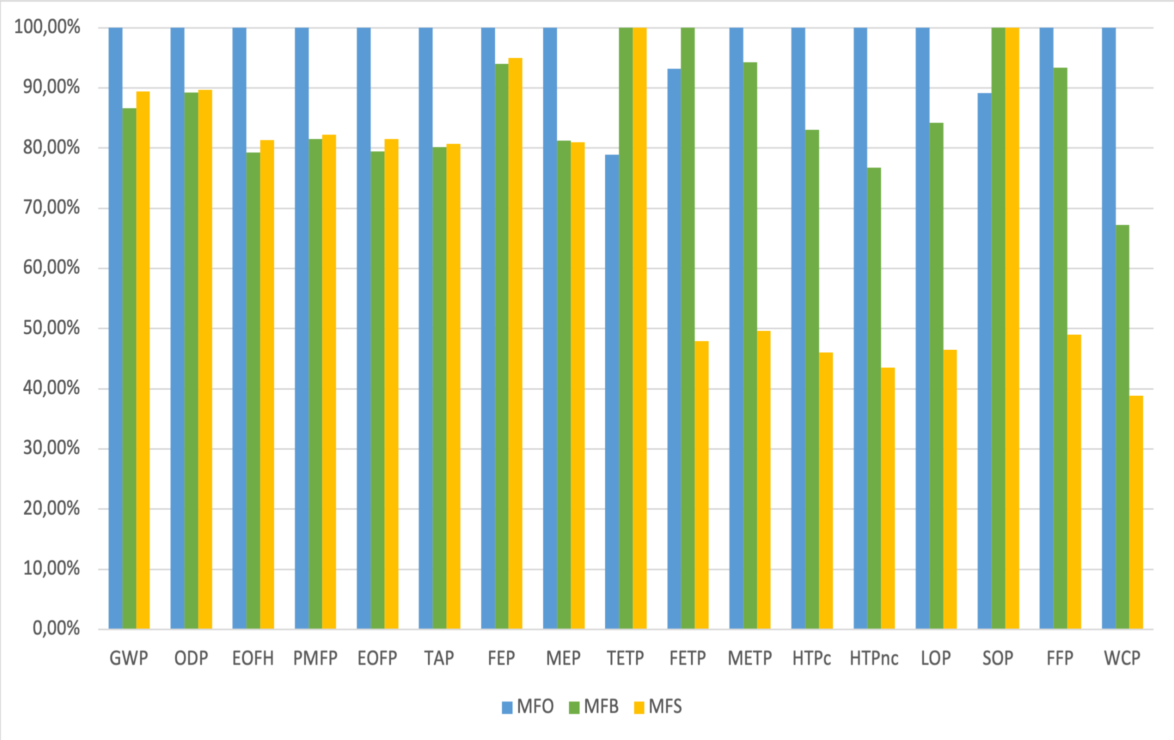

Figure 19. Sensitivity Analysis: MFO vs MFB vs MFS. (GW- Global Warming; OD- Ozone Depletion; EOFH - Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

4.5.2. Incorporation of Renewable Energy

The objective of this section was to evaluate the environmental benefits or disadvantages resulting from the incorporation of a certain percentage (initially 30% and then 50%) of electricity from renewable sources, specifically solar energy. In the year of 2021, the United Kingdom's national grid was generated with 79,70% coming from fossil fuels, 16,76% coming from nuclear and biomass and 3,34% generated by renewable energies (with wind power leading the renewables energies production) and the rest coming from nuclear and biomass (IEA, 2023).

The calculations made for the energy consumption achieved a value of 86.8 kWh used during the Moroccan Falafel Chilled production (since the goods storage, ingredients processing, manufacturing process, packaging and finally, the product storage). In this chapter, a part of the total energy consumption will the replaced by a percentage of energy coming from solar power.

The case of 70/30

The analysis considered the manufacturing stage, which includes all phases at the factory where energy is consumed. The MFO represents the manufacturing stage for the production of the original falafel, utilizing 100% electrical energy from the national electrical grid. On the other hand, MFO 70/30 represents the manufacturing process that includes 30% of electricity derived from renewable sources, specifically solar power. The results are presented in Figure 19.

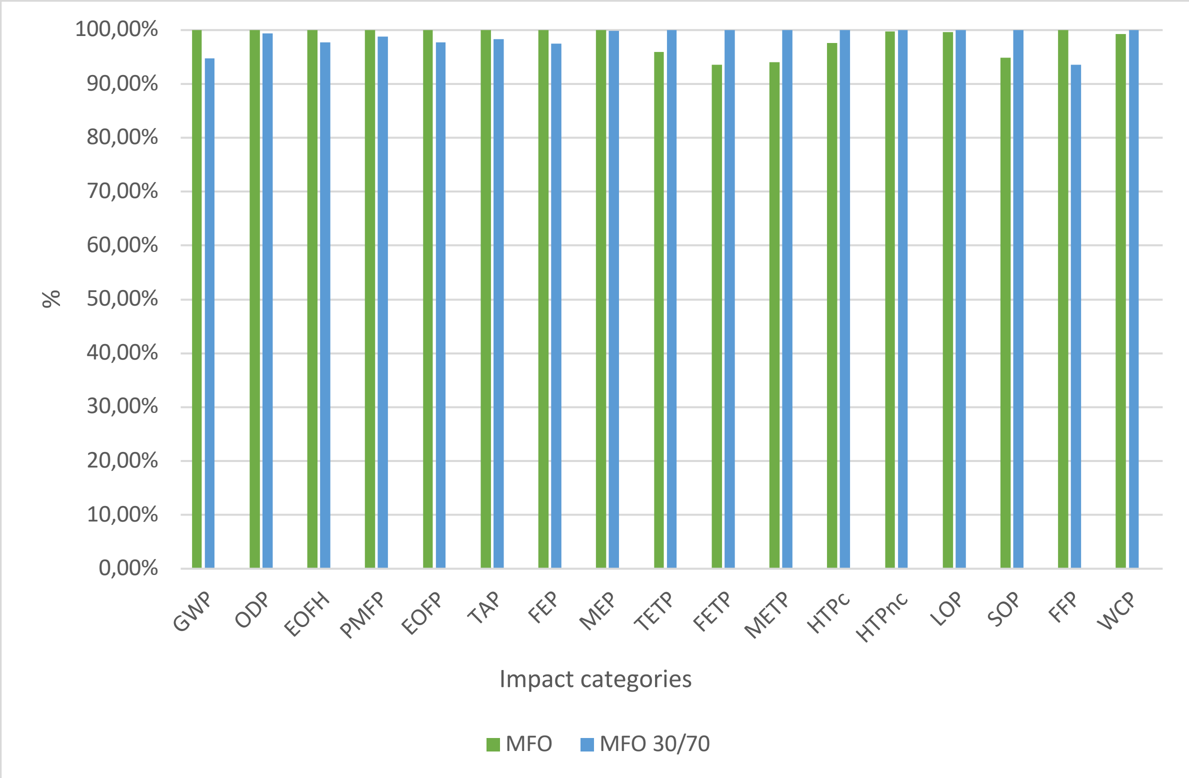

Figure 20. Sensitivity Analysis: MFO vs MF 70/30 (GW- Global Warming; OD- Ozone Depletion; EOFH - Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

Although there is a slight decrease in emissions in certain categories, such as GW and FU, the reduction is less than 5%. Furthermore, it is noticeable that in most categories, the incorporation of 30% electricity from renewable sources increases in impact. This is evident in categories such as Terrestrial Ecotoxicity and Marine Ecotoxicity.

The case of 50/50

For this analysis, the same approach was followed, but with around a 20% increase in renewable energy. As a result, the national grid now contributes an equal amount of energy as the renewable source.

The results of this evaluation are presented in Figure 20.

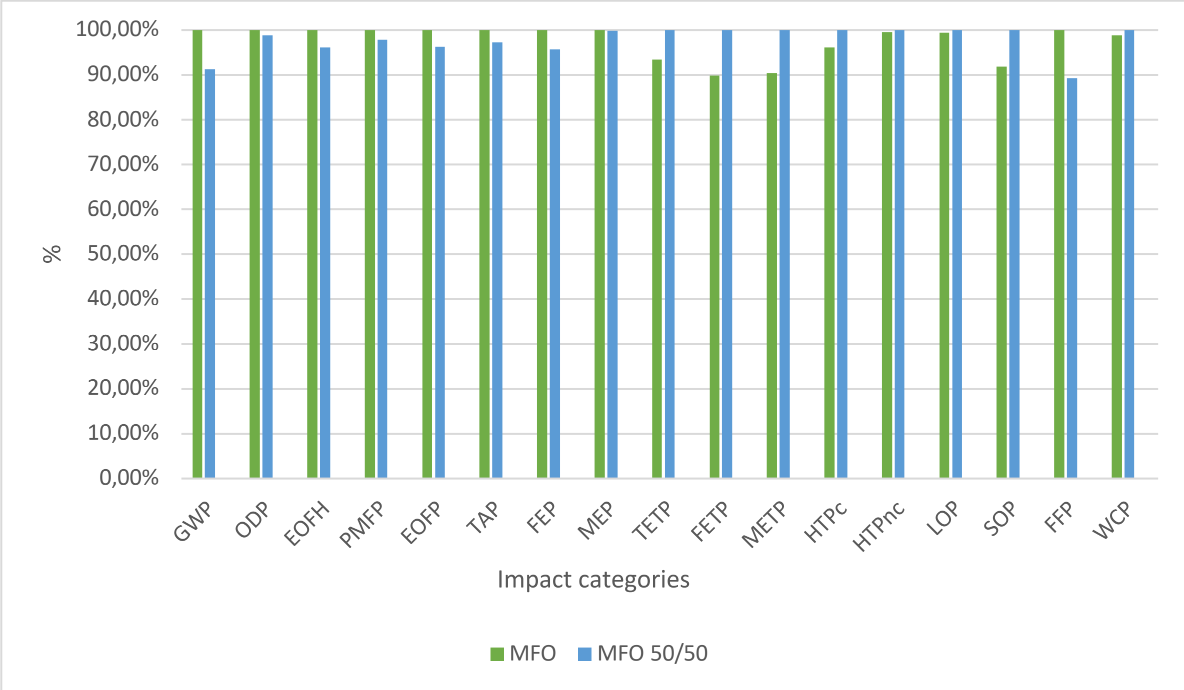

Figure 21. Sensitivity Analysis: MFO vs MFO 50/50 (GW- Global Warming; OD- Ozone Depletion; EOFH - Photochemical Oxidant Formation: Humans ; PMF- Particulate Matter Formation; EOF- Photochemical Oxidant Formationl: Ecosystems; TA- Terrestrial Acidification; FE- Freshwater Eutrophication; ME- Marine Eutrophication; TET- Terrestrial Ecotoxicity; FET- Freshwater Ecotoxicity; MET- Marine Ecotoxicity; HTc- Human Toxicity (cancer incidence disease); HTnc- Human Toxicity (non-cancer incidence disease); LO- Agricultural Land Occupation; MR- Mineral Resources; FF- Fossil Fuel; WC- Water Consumption).

It is evident that even with a 50% replacement of the national grid with renewable energy sources, the environmental results are not significantly different from those obtained without any renewable energy source.

The categories with the lowest impact as analysed before, are still Global Warming and Fossil Fuel. However, even with a 20% increase in renewable energy used to produce the falafel, the results only change by 2% when compared to the results obtained with 20% of renewable energy. Similarly to the previous analysis, there are certain categories where the MFO (without renewable energy) shows better environmental results, such in the categories of Terrestrial Ecotoxicity and Marine Ecotoxicity. This can be explained, due to the release of chemicals used in the photovoltaic cells that could be emitted to air, surface water, and groundwater. There are different type of chemicals used to produce photovoltaics cells, namely, acetone, ammonia and methanol (Klugmann-Radziemska, n.d.). The release of chemicals from the photovoltaic cells can have a negative impact on the terrestrial and marine ecosystems. Contributing in this way to an increase of the values in the TET and MET categories.

Chapter 5: Discussion, Future Work and Conclusions

Discussion

After analysing the results obtained for all the categories, it can be concluded that it was not necessary to extend the evaluation to all 17 categories, as some are less relevant to the subject of this study. Considering that the study focuses on a food product, Moroccan Falafel, it is crucial to analyze the categories that reflect agricultural methods and fertilizers used, as well as transportation, production, and distribution of the product. Therefore, the categories of higher importance are Water Consumption, Land Occupation, Human Toxicity (cancer and non-cancer incidence), Terrestrial, Freshwater, and Marine Ecotoxicity, Terrestrial Acidification, Freshwater and Marine Eutrophication, Ozone Depletion, and Global Warming.The carbon footprint values obtained for the MFC were 622 kg CO_2 eq/UF, and for the MFF, 717 kg CO_2 eq/UF. To simplify the comparison with the results obtained in the bibliography, these values were converted to 1 kg of MFC and MFF. This conversion resulted in a carbon footprint of 6.2 kg CO_2 eq/kg for MFC and 7.2 kg CO_2 eq/kg for MFF.

After analysing the bibliography, a carbon footprint value was found for plant-based products similar to the falafel being studied. These values ranged between 3.4 kg CO_2 eq/kg product and 3.5 kg CO_2 eq/kg product. When comparing these values with the carbon footprint values obtained for falafel, it is evident that the life cycle of falafel results in more than double the emissions in comparison to these products.

This difference can be explained by the fact that Moroccan Falafel uses a greater variety of ingredients in its recipe compared to the ingredients used in the plant-based products reviewed in the bibliography. The two evaluated products, BB and IB, only consist of water, pea protein, canola oil, coconut oil, potato protein, LegH protein, sunflower oil, soy protein, and flavour mix, while Moroccan Falafel requires 17 different ingredients, all of which are vegetables (except for water). As observed before, the production of raw materials is the stage of the product life cycle with higher impacts, so the larger number of ingredients will lead to a higher environmental impact at that stage, contributing to a higher negative environmental impact of the final product. The higher carbon footprint value of the Moroccan Falafel product may also be explained by the use of of rapeseed oil instead of canola oil, coconut oil, sunflower oil, or olive oil. Although the carbon footprint values were lower for the other plant-based products, it was not possible to assess the individual quantities of ingredients used in the recipes of the studies reviewed, making it impossible to directly compare the two recipes.

Based on the literature review, it was found that the production of raw materials had the largest environmental impacts in terms of GW, FE, and LO. This was followed by the manufacturing process, which had impacts in the category of WC, and the disposal of packaging, which impacted GW, FE, LO, and WC. In line with the literature, the results obtained in this study also showed that the stage of production of raw materials for Moroccan Falafel had the highest impacts, as expected. However, the impacts were not primarily in the category of GW but rather in MET and WC. The production of raw materials accounted for a contribution of 95 kg CO_2 eq/kg to the total carbon footprint of both chilled and frozen falafel products, considering that the ingredients were the same for both variants. The higher values obtained for the production of ingredients stage can be attributed to agricultural activities including the use of fertilisers, water and land. In this study, an assumption was made that all ingredients were produced in France due to the lack of alternative data. However, it is reasonable to expect that agricultural practices in France may differ from those in countries like Argentina or China. Therefore, if an appropriate database accounting for specific country practices were used, the results would likely differ from the findings obtained in this study.

After analysing all the ingredients used in the recipe, it is possible to ascertain that the chickpea contributes the most to the product's carbon footprint, with 39.5 kg CO_2 eq/UF. This high contribution is primarily due to the quantity of chickpeas used in the recipe, which is 49 kg. However, the red pepper is the second highest source of emissions, 23.6 CO_2 eq/UF, although it represents only 15% of the total ingredients. This suggests that, individually, the red pepper has a larger contribution to the environmental impacts than the chickpea. This illustrates the necessity of considering the individual ingredient contribution to the overall carbon footprint. Since raw material production had the largest impacts, a sensitivity analysis was performed. This analysis examined the environmental results obtained by replacing half the quantity of chickpeas with the same amount of other ingredients, specifically beetroots and sweet potatoes. The results for Moroccan Falafel Beetroot showed a decrease in emissions in more than 88% of the categories, with a significant reduction in the Water Consumption, Human Toxicity (non-cancer incidence), Terrestrial Acidification and Photochemical Oxidant Formation. The only categories where a decrease wasn't observed were TET and FET. These results coincide with those observed when comparing chickpea and beetroot, where the beetroot had lower environmental impacts than the chickpea for all categories excluding TET, FET and MR.

The same reduction was observed in the case of Moroccan Falafel Sweet Potato, where the sensitivity analysis resulted in emissions decrease for almost all categories compared to Moroccan Falafel Original. Similarly to the previous case, the reduction of emissions was more pronounced in the category of Water Consumption and Human Toxicity (non-cancer incidence), The categories where no reduction of the impacts was observed were Mineral Resources and Terrestrial Ecotoxicity. The results obtained for the comparation between MFO and MFS align with the ones obtained for the comparation between the two ingredients, chickpea and sweet potato, being observed a large decrease of impact for the categories of Water Consumption and Marine Eutrophication when compared to the production of sweet potato and chickpea. However, for the category of Mineral Resources and Terrestrial Ecotoxicity, the results are more favorable for the chickpea.

With this analysis is it possible to conclude that replacing a percentage of chickpeas in the recipe can lead to better environmental results for the majority of environmental categories, as demonstrated by the adoption of beetroots and sweet potato.

According to the bibliography, the next life cycle stage with higher impacts is expected to be the production process, which aligns with the results obtained in the case under study. This stage contributes 29.47 kg CO_2 eq/kg for the MFC and 150.3 kg CO_2 eq/kg for the MFF. The carbon footprint value in this stage is a result of the energy consumption throughout all the production stages, including goods storage, ingredient preparation, manufacturing, packaging, and product storage. In total, these steps account for 86.8 kWh consumed for the MFC and 445.7 kWh for the MFF. The increase in energy consumption between the two products is due to the use of a freezer in goods and product storage, as well as the use of a spiral chiller in the manufacturing process. The impact categories with higher emissions are TET and GW while the impact in the category of WC is not as significant, representing only 13% of the total product life cycle. The sensitivity analysis performed envisaged the inclusion of a percentage of an electricity coming from renewable sources, namely, solar power, in the company's energy mix. The results of the sensitivity analysis showed a decrease in emissions across more than half of the impact categories. However, the reduction observed was not significant.

The increase of impacts in the categories of Terrestrial, Freshwater, Marine Ecotoxicity and Eutrophication with the use of renewable energy can be attributed to the chemical emissions released during the manufacturing and installation of photovoltaic cells on the roof. The materials used for the production of the cells are minerals such as quartz, which are manipulated to obtain silicon, the major material present in the cells. Consequently, a high amount of energy is required to produce the cells and panels, with the majority of this energy coming from non-renewable sources such as natural gas and nuclear power. The processing of the raw materials present in the photovoltaic panels releases emissions into the air, such as benzene and arsenic, as well as emissions into water resources

Nonetheless, a slight decrease in the category of GWP was observed, demonstrating that the adoption of renewable energy contributes to the reduction of GHG emissions. This allows us to interpret the results obtained when a percentage of energy consumption is substituted by energy coming from renewable sources.

To calculate the most realistic value of energy consumption during the production process at Gosh!, the energy consumption used for ingredients storage was not considered. This assumption was made because the majority of the ingredients (76%) used for the Moroccan Falafel are stored in chilled and ambient conditions for a maximum of 3 days, while the remaining ingredients are stored in a freezer for a maximum of 3 weeks. It was considered that accounting for this energy consumption would lead to an overestimation of the results, as it was not feasible to directly relate the total energy consumption of the equipment with the specific ingredients that were stored.

The next stage with a higher negative impact in the life cycle of the product is the distribution stage. The impacts in this stage are motivated by the distance travelled from the factory to the supermarket and the choice of transportation vehicle. In this study, the distribution to the LIDL RDC was analysed as the worst-case scenario. The distances between the factory and the CML warehouse, as well as between the CML warehouse and the LIDL RDC, were taken into account. However, there was one assumption made regarding this stage. It was considered that there is no contribution from the storage equipment used in both the CML warehouse and the LIDL RDC. Only the contribution from the transportation vehicle and the distance in km travelled were accounted for in this analysis. The distribution stage contributes 371.8 k kg CO_2 eq/UF for both the MFC and MFF. Despite the selection of different vehicles for transportation, the carbon footprint values obtained are the same for both products.

The transportation of raw materials to the factory is a life cycle stage that is not explicitly mentioned in the bibliography, likely because it may not have significant contributions compared to the previous stages. However, in this study, it was found that the carbon footprint for this transportation stage represents 96.5 kg CO_2 eq/UF, which is nearly the same amount as the production of raw materials, what can suggest that the same amount of fossil fuel is used to produce and to transport the raw materials from the origin country until the factory. Although France was assumed to be the country of origin for the ingredients, the transportation stage takes into account the distance between the import country and the factory, as well as the type of vehicle typically used for long-distance transportation of ingredients.

Contrary to the expectations based on the literature research, the packaging disposal stage does not significantly contribute to the overall emissions of the product being studied. This may be attributed to the type of plastic used (polyethylene low density) and the quantity of packaging material used. In this study, the waste treatment method of incineration was considered. The impact results indicate that the carbon footprint is higher for the MFC compared to the MFF, as the former uses a greater quantity of packaging material. The carbon footprint calculated for the MFC was 5 kg CO_2 eq/UF, while for the MFF it was 0.62 kg CO_2 eq/UF. Regarding the product distribution, it is important to note that a limitation of this study is the exclusion of energy consumption by storage equipment during the product's storage period.

Future Work

Future work developments to mitigate the environmental impact of the product may include the exploration of new ingredients for the development of new products with a lower percentage of chickpea in its constitution, since it was proven that this ingredient contributes with higher impacts in all categories within the recipe of Moroccan Falafel. However, it is important to study the ingredients individuality before making any choice. It is recommended to investigate the possibility of using ingredients sourced from suppliers located closer to the factory. This would help to understand the agricultural methods used (since this is the stage with worst environmental performance across all the life cycle stage of the product). The adoption of closer suppliers will also decrease the impacted derived from the transportation of the raw materials to the factory.

Concerning the production process at Gosh! and since this stage is the one with higher levels of energy consumption, and consequently, the second one with worst environmental impact. It is important to deep investigate the creation of a solar power plant at the factory location, with different energy voltage and energy production from the ones evaluated in this study. Including a study where is evaluated the area available for the installation of the solar power plant and the power that can be produced. It is also recommended for Gosh! to perform an energy audit to evaluate the equipment and make recommendations to improve energy efficiency at the factory.

Furthermore, future work should assess emission values associated with transportation of raw materials to the factory and distribution of the final product, done by companies using hybrid or electric trucks to provide comparison between different transport companies.

In terms of packaging, future efforts should focus on reducing the amount of material used, especially in the case of PET trays, considering that the packaging used for the frozen product has lower environmental impacts. These actions can contribute to a more sustainable and environmentally friendly production and distribution process for the analysed products.

Conclusion

The objective of this study was to compare the Life Cycle Assessment (LCA) of two products: Moroccan Falafel Chilled (MFC) and Frozen (MFF). Both products had a functional unit of 100kg. Since the preservation method differed between the two products, the life cycle stages also varied. The evaluated system boundaries included the production of raw materials, transportation of raw materials, production process at the factory, downstream distribution, consumption, and packaging disposal. The first two stages are common to both products, with subsequent stages varying depending on whether the product is chilled or frozen.

Inventory data for all system inputs and outputs was collected, and the LCA methodology was applied using SimaPro 9.2.0.2 software with the Ecoinvent database version 3.7.1 and AGRIBALYSE version 3.0.1. The environmental categories were assessed using the ReCiPe Midpoint (H) methodology, which includes 17 impact categories. The impact assessment was conducted in four different forms.

In the initial global comparison of MFC and MFF, the results showed that the environmental impact was similar for both products. It was determined that the type of preservation (chilled or frozen) did not have a significant influence on the overall environmental impact.

The second and third parts of the study aimed to identify the life cycle stages that have the greatest contribution to the environmental performance of the product. All life cycle stages of the product were analyzed for both MFC and MFF. The results revealed that the production of raw materials played the most significant role in terms of emissions. It was found to have higher emissions for most impact categories, accounting for 93% of total contributions for the category of Marine Eutrophication Potential and 82% for Water Consumption Potential. The production of raw materials contributed 95 kg CO_2 eq/UF to the carbon footprint.

Based on these findings, an analysis of the ingredients used was undertaken to identify their individual contribution to the results. As expected, the analysis identified chickpeas as the major contributor, considering its higher quantity in the recipe. The second ingredient with the largest contribution was red pepper, despite being present in a much smaller quantity than chickpeas. When comparing the carbon footprint of these two ingredients, it was observed that red pepper had higher emissions. Thus, the analysis of each ingredient individually was crucial, not only considering their quantity in the overall recipe but also taking into account their individual contribution to environmental impact categories.

The second stage with the most significant environmental impact was the production process at the factory, primarily due to energy consumption. It resulted in a carbon footprint of e, representing 47% of the total carbon dioxide emissions. To explore potential improvements, a sensitivity analysis was conducted by incorporating 30% and 50% of energy from renewable sources. The results of the sensitivity analysis showed a decrease in emissions across more than half of the impact categories. However, the reduction observed was not considered significant.

The distribution stage of the product also contributes significantly to environmental impacts, primarily due to the type of vehicles used for transportation to the final destination. Currently, the distribution stage contributes approximately 372 kg CO_2 eq/UF in terms of emissions for both MFC and MFF.

The environmental impacts related to the transportation of raw materials to the factory, product consumption, and packaging disposal were found to be relatively minor compared to the emissions from other life cycle stages.

In conclusion, this study successfully achieved its objectives of quantifying the environmental impact of the two products. The total carbon footprint was estimated at 1,077 kg CO_2 eq/UF for the MFC and 1,167 kg CO_2 eq/UF for the MFF, with significant contributions to Global Warming Potential, Water Consumption Potential (21.2 m^3 WC), and Fossil Fuel Depletion (351 kg oil eq for MFC and 377 kg oil eq for MFF).

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Annex A: Ingredients information

Table A.1 - Raw materials information.

INGREDIENT	100 kg	2022 purchases (kg)	SUPPLIERS	%	Country of origin
Potato Flake	5,6	303800	**J L Priestley & Co Ltd**	100	Netherlands
Salt	0,7	45326,96	**UNIVAR**	100	UK
Sod Bicarb Fine	0,4	_	**UNIVAR**	_	UK
White Pepper Ground	0,2	4200	**H.j. Langdon & co (UK) Ltd**	**90**	India
			Virani Food Products Ltd	10	
Crushed Chilli	0,04	_	_	_	India
Cumin Seed Ground	0,4	29100	**H.j. Langdon & co (UK) Ltd**	71	India
			Sleaford Quality Foods Ltd	23	
			Virani Food Products Ltd	6	
Coriander Ground	0,4	23350	**H.j. Langdon & co (UK) Ltd**	81	India
			Virani Food Products Ltd	9	
Cinnamon Ground	0,3	2600	H.j. Langdon & co (UK) Ltd	_	India
Parsley Leaf 3mm	0,3	12760	Rosemary & Thyme Ltd	_	UK
White Onion Diced	7,5	388030	**ARDO UK Limited**	50	India
			Foodnet Ltd	50	
Apricots Dried	4,7	64000	First Grade International Ltd	_	Turkey
Dates Chopped Dehydrated	3,7	36000	First Grade International Ltd	_	Turkey
Red Peppers Diced	15,0	376430	**Foodnet Ltd**	58	India
			ARDO UK Limited	41	
Garlic granules	0,9	246867	Sleaford Quality Foods Ltd	_	China
Rapeseed Oil IBC	7,5	442000	Olympic Oils Ltd	_	France
SR Rehydrated Chick Peas	48,7	1058125	**Wherry and Sons Ltd**	69	Argentina/ Canada
			A.Poortman (London) Ltd	31	
Water	3,7	not applicable	not applicable	_	_

Annex B: Calculation for the UF

	Mass (kg) of ingredients
Frozen	22.2
Chilled	73,6

Table B. 1. Energy consumption.

3. Goods Storage				
Type of equipment	Power of the equipment (kW)	Process timing (h) per UF (100 kg MF)	Energy consumption UF (kWh)	
Chiller for raw materials	2,2	72	116	
Freezer for raw materials	23	336	250.0	
Total energy consumptio:			366.0	
4. Ingredients Preparation				
Type of equipment	Power of the equipment (kW)	Process timing (h) per UF (100 kg MF)	Energy consumption UF (kWh)	
Bowl Chopper Line 1	40	0.08	3.33	
Volumetric Filler Line 1 + Line 2	15	0.33	5	
Total energy consumption:			8.3	
5. Manufacturing Process				
Type of equipment	Power of the equipment (kW)	Process timing (h) per UF (100 kg MF)	Energy consumption MFC (kWh)	Energy consumption MFC (kWh)
Multiheaded Diaphragm Forming Machine Line 1	12	0,33	4	4
Travelling Oven Line 1	18	0,33	6	6
Spiral Chiller	15	0,83	12.5	__
Spiral Freezer	175	0,83	__	145.8
Total energy consumption:			22.5	155.8
6. Packaging Process				

Type of equipment	Power of the equipment (kW)	Process timing (h) per UF (100 kg MF)	Energy consumption MFC (kWh)	Energy consumption MFC (kWh)
Set of Modular Conveyors Spiral to Ishida Line 1	1,1	0,33	0.36	0.36
Ishida (Multiheaded Weigher) Line 1	3	0,33	0.99	0.99
Peg & Chain Conveyors Line 1	0.37	0,33	0.12	0.12
Traysealer Line 1	25	0,33	8.25	__
Metal Detector Line 1	0.012	0,33	0.0396	0.0396
Sleeving Machine 1	1,1	0,33	0.363	0.363
Bagging Line 1	25	0,33	__	8.25
Set of Conveyors Line 1	0.48	0,33	0.1386	0.1386
Wrapping Machine Line 1	11.00	0,33	0.91	0.91
Total:			5.6	5.6
Type of material			Quantity of material MFC (kg)	Quantity of material MFF (kg)
Low density Polyethylene			9.5	1.2
7. Product Storage				
Type of equipment	Power of the equipment (kW)	Process timing (h) per UF (100 kg MF)	Energy consumption MFC (kWh)	Energy consumption MFC (kWh)
Refrigerator	4.2	12	50.4	__
Freezer	23	12	__	276

Annex C: Raw materials distribution

Table C. 1- Raw materials distribution calculations- type of vehicles.

Ingredients	**Type of vehicle and distance**			
	Lorry with refrigeration machine. 7,5-16 tons cooling	Lorry with refrigeration machine. 7,5-16 tons freezing	Container ship cooling	Container ship freezing
Potato flake	401	__	__	__
Salt	246	__	__	__
Sodium Bicarbonate	246	__	__	__
Parsley	246	__	__	__
White peper	__	181	7319	__
Cumin seed	__	181	7319	__
Coriander	__	181	7319	__
Cinnamon	__	181	7319	__
White Onion	181	__	__	7319
Red pepper	181	__	__	7319
Garlic	63	__	7682	__
Chickpea	155	__	11778	__
Rapessed oil	__	850		__
Apricots dried	__	229	2967	__
Dates	__	229	2967	__

Table C. 2- Raw materials distribution calculations- distance between country of origin and suppliers.

Country	Ingredients	**Type of vehicle and distance** (km)				Supplier
		Lorry with refrigeration machine. 7,5-16 tons cooling	Lorry with refrigeration machine. 7,5-16 tons freezing	Container ship cooling	Container ship freezing	
Netherlands	Potato flake	401	__	__	__	J L Priestley & Co Ltd
UK	Salt	60	__	__	__	UNIVAR; Rosemary & Thyme Ltd
	Sodium Bicarbonate	60	__	__	__	
	Parsley	60	__	__	__	
India	White peper	__	181	7319	__	H.J. Langfon & co (UK) Ltd; ARDO UK Limited; Foodnet LTD
	Cumin seed	__	181	7319	__	
	Coriander	__	181	7319	__	
	Cinnamon	__	181	7319	__	
	White Onion	181	__	__	7319	
	Red pepper	181	__	__	7319	
China	Garlic	63	__	7682	__	Sleaford Quality Foods Ltd
Argentina	Chickpea	155	__	11778	__	Wherry and Sons Ltd; A.Poortman (London) Ltd
France	Rapessed oil	__	850		__	Olympic Oils Ltd
Turkey	Apricots dried	__	229	2967	__	First Grade International Ltd
	Dates	__	229	2967	__	
Total:		1719	2032	54670	14638	

Table C. 3- Raw materials distribution since suppliers to Gosh! factory.

	Type of vehicle and distance (km)			
SUPPLIERS	Lorry with refrigeration machine. 7,5-16 tons cooling	Lorry with refrigeration machine. 7,5-16 tons freezing	Mass transported (ton)	UF (tkm)
H.j. Langdon & co (UK) Ltd	__	83	0.022	1.867
J L Priestley & Co Ltd	146	__	0.073	116.7
UNIVAR	246	__		
Sleaford Quality Foods Ltd	151	__		
Rosemary & Thyme Ltd	151	__		
Wherry and Sons Ltd	121	__		
A.Poortman (London) Ltd	83	__		
ARDO UK Limited	177	__		
Foodnet Ltd	58	__		
Olympic Oils Ltd	251	__		
First Grade International Ltd	129	__		
Total distance (km):	1512	83		

Table C. 4- Inventory calculations for Lorry with refrigeration machine, cooling.

Ingredient:	Potato flake	Salt	Sodium Bicarbonate	Parsley	White Onion	Red pepper	Garlic	Chickpea	Total:
Quantity (ton)	0.0056	0.0007	0.0004	0.0003	0.0075	0.015	0.0009	0.0487	0.0791
Lorry with refrigeration machine. 7,5-16 tons cooling	401	246	246	246	181	181	63	155	1719
Total (tkm):	2.245	0.172	0.098	0.074	1.358	2.715	0.057	7.548	14.26

Table C. 5- Inventory calculations for Lorry with refrigeration machine, freezing.

Ingredients	White peper	Cumin seed	Coriander	Cinnamon	Rapessed oil	Apricots dried	Dates	Total:
Quantity (ton)	0.0002	0.0004	0.0004	0.0003	0.0075	0.0047	0.0037	0.0172
Lorry with refrigeration machine. 7,5-16 tons freezing	181	181	181	181	850	229	229	2032
Total (tkm):	0.036	0.072	0,072	0,054	6,375	1,076	0,847	8,534

Table C. 6- Inventory calculations for Container ship, cooling.

Ingredient:	White peper	Cumin seed	Coriander	Cinnamon	Garlic	Chickpea	Apricots dried	Dates	Total
Quantity (ton)	0,0002	0,0004	0,0004	0,0003	0,0009	0,0487	0,0047	0,0037	0,0593
Container ship cooling	7319	7319	7319	7319	7682	11778	2967	2967	54670
Total (tkm):	1.46	2.93	2.93	2.19	6.91	573.59	13.95	10.98	614.94

Table C. 7- Inventory calculations for Container ship, freezing.

Ingredient:	White Onion	Red pepper	Total:
Quantity (ton)	0.0075	0.015	0.0225

Container ship freezing	7319	7319	14638
Total (tkm):	54.89	109.78	164.67

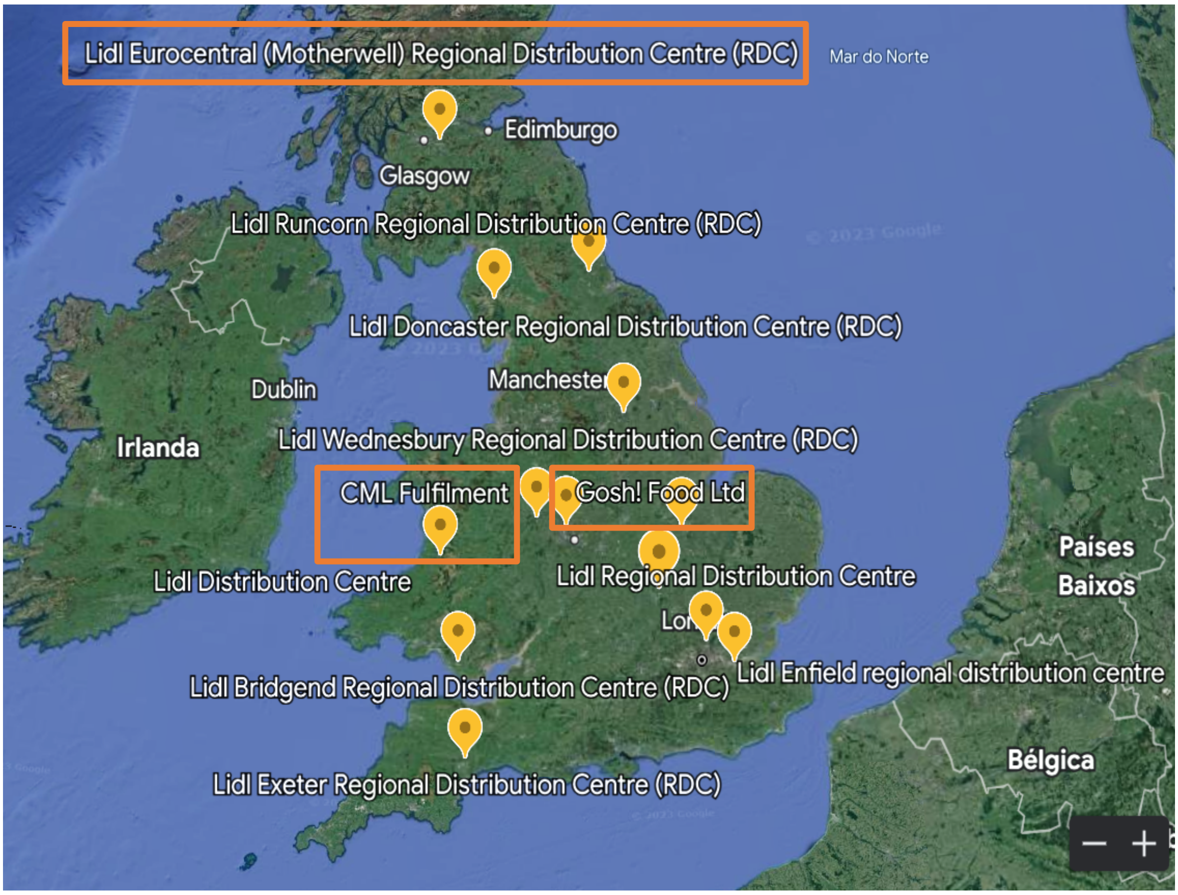

Figure C. 1- Geographic locations (Gosh! Food; CML Fulfilment; Lidl RDC)

Table C. 8- Distances between CML Fulfilment and Lidl RDC.

Warehouse	Distance (km)	Warehouse	Distance (km)
LIDL Motherwell RDC	452	LIDL Bridgend RDC	216
LIDL New Aycliffe RDC	298	LIDL Peterborough RDC	175
LIDL Exeter RDC	296	LIDL Doncaster RDC	164
LIDL Southampton RDC	277	LIDL Avonmouth RDC	160
LIDL Northfleet RDC	283	LIDL Runcorn RDC	128
LIDL Belvedere RDC	282	LIDL Wednesbury RDC	39
LIDL Enfield RDC	237	LIDL Peterborough RDC	175
LIDL Bridgend RDC	216		

Annex D: Impact Assessment results

Table D. 1- Absolute and percentage results of each stage of 100 kg of MFC.

Categoria de impacte	Unidade	Totalt	1. Production of Raw Materials	2. Transport of Raw Materials	3. Production Process at Gosh! Chilled	Distribution:chilled	5. Consumption: Chilled	6. End-of-life: Tray
GW	kg CO2 eq	621.71078	95.33952	96.473844	29.274152	371.8102	0.067451962	28.745605
OD	kg CFC11 eq	0.0030723805	0.002740085	0.000067174874	0.000015094314	0.00024790369	0.000000034779526	0.0000020877901
EOFH	kg NOx eq	2.1456668	0.55307012	0.50315559	0.049949592	1.0349508	0.00011509123	0.0044256536
PMF	kg PM2.5 eq	0.88737431	0.3295281	0.15849336	0.020849252	0.3778339	0.000048039752	0.00062165514
EOF	kg NOx eq	2.1874551	0.5585982	0.51152003	0.050465645	1.062319	0.00011628029	0.0044359498
TA	kg SO2 eq	3.2760647	1.9427835	0.3835393	0.060778625	0.88693012	0.00014004292	0.001893144
FE	kg P eq	0.084041235	0.032510246	0.0091175743	0.0051235699	0.037249717	0.000011805461	0.000028323095
ME	kg N eq	0.31567781	0.30626986	0.0016478534	0.00067500895	0.0070399875	0.0000015553202	0.000043546721
TET	kg 1.4-DCB	4434.2551	176.015	790.40092	18.668315	3365.3449	0.04301455	83.782979
FET	kg 1.4-DCB	27.461742	3.6504213	4.0531373	0.34138626	17.374684	0.00078660428	2.0413261
MET	kg 1.4-DCB	36.221117	3.7304422	5.4978277	0.52503821	23.526763	0.0012097655	2.9398358
HTc	kg 1.4-DCB	39.9361	3.3888898	6.7370847	1.0286295	28.626083	0.0023701142	0.15304223
HTnc	kg 1.4-DCB	1929.925	1634.6801	51.967214	13.906487	212.93811	0.032042596	16.400985
LO	m2a crop eq	178.62592	165.06985	2.1929597	2.136673	9.2182354	0.0049232097	0.0032855033
MR	kg Cu eq	1.5889266	0.39006	0.11638852	0.030738448	1.0499714	0.000070825918	0.0016974765
FF	kg oil eq	177.31409	14.931002	30.99124	10.161413	121.13681	0.023413393	0.070208561
WC	m3	18.489407	17.524829	0.096817951	0.13625397	0.72857922	0.00031394924	0.0026126444

Table D. 2 - Absolute and percentage results of each stage of 100 kg of MFF.

Categoria de impacte	Unidade	Totalt	1. Production of Raw Materials	2. Transport of Raw Materials	**3. Production Process at Gosh! Frozen**	4. Distribution: Frozen	5. Consumption: Frozen	6. End-of-life: Bag
GW	kg CO2 eq	717.77365	95.33952	96.473844	150.3167	371.8102	0.20235589	3.6310238
OD	kg CFC11 eq	0.0031330378	0.002740085	0.000067174874	0.000077506173	0.00024790369	0.00000010433858	0.00000026372085
EOFH	kg NOx eq	2.3485616	0.55307012	0.50315559	0.2564808	1.0349508	0.00034527368	0.00055902993
PMF	kg PM2.5 eq	0.9731346	0.3295281	0.15849336	0.10705659	0.3778339	0.00014411926	0.000078524859
EOF	kg NOx eq	2.392477	0.5585982	0.51152003	0.25913062	1.062319	0.00034884087	0.0005603305
TA	kg SO2 eq	3.5259978	1.9427835	0.3835393	0.31208564	0.88693012	0.00042012875	0.00023913398
FE	kg P eq	0.105225	0.032510246	0.0091175744	0.026308469	0.037249716	0.000035416382	0.0000035776541
ME	kg N eq	0.3184339	0.30626986	0.0016478534	0.003466031	0.0070399874	0.0000046659605	0.0000055006385
TET	kg 1.4-DCB	4438.3309	176.015	790.40092	95.857926	3365.3449	0.12904365	10.583113
FET	kg 1.4-DCB	27.091402	3.6504213	4.0531373	1.7529476	17.374684	0.0023598128	0.25785172
MET	kg 1.4-DCB	35.825973	3.7304422	5.4978277	2.6959623	23.526763	0.0036292964	0.37134769
HTc	kg 1.4-DCB	44.060299	3.3888898	6.7370847	5.2817994	28.626083	0.0071103425	0.019331651
HTnc	kg 1.4-DCB	1973.1602	1634.6801	51.967214	71.406925	212.93811	0.096127788	2.0717034
LO	m2a crop eq	187.4676	165.06985	2.1929597	10.971373	9.2182354	0.014769629	0.00041501094
MR	kg Cu eq	1.7146823	0.39006	0.11638853	0.15783556	1.0499713	0.00021247775	0.00021441809
FF	kg oil eq	219.31491	14.931002	30.99124	52.176747	121.13681	0.07024018	0.0088684497
WC	m3	19.051134	17.524829	0.096817952	0.69963588	0.72857922	0.00094184772	0.00033001824

Table D.3- Absolute and percentage results of each impact category for the Raw Materials.

Impact category	Unit	Total	Potato flakes		Onion		Apricot		Date	
GW	kg CO2 eq	95.34	1.4	1.47%	1.06	1.11%	1.59	1.67%	12.4	13,00%
OD	kg CFC11 eq	0.00274	0.00000598	0.22%	0.00000905	0.33%	0.00000688	0.25%	0.00127	46.51%
EOFH	kg NOx eq	0.553	0.00433	0.78%	0.00508	0.92%	0.00514	0.93%	0.0249	4.5%
PMF	kg PM2.5 eq	0.33	0.00235	0.71%	0.00298	0.9%	0.00335	1.02%	0.016	4.86%
EOF	kg NOx eq	0.559	0.0044	0.79%	0.00516	0.92%	0.00551	0.99%	0.0256	4.58%
TA	kg SO2 eq	1.94	0.00747	0.38%	0.0142	0.73%	0.0144	0.74%	0.0351	1.8%
FE	kg P eq	0.0325	0.000573	1.76%	0.000261	0.8%	0.000543	1.67%	0.003	9.24%
ME	kg N eq	0.306	0.00106	0.34%	0.0025	0.82%	0.0000891	0.03%	0.000392	0.13%
TET	kg 1.4-DCB	176.02	7.37	4.19%	3.09	1.75%	5.97	3.39%	19.75	11.22%
FET	kg 1.4-DCB	3.65	0.0832	2.28%	0.0596	1.63%	0.143	3.92%	0.227	6.22%
MET	kg 1.4-DCB	3.73	0.0974	2.61%	0.0631	1.69%	0.0928	2.49%	0.31	8.3%
HTc	kg 1.4-DCB	3.39	0.058	1.71%	0.0668	1.97%	0.0849	2.51%	0.438	12.93%
HTnc	kg 1.4-DCB	1634.68	3.53	0.22%	1.76	0.11%	1.71	0.1%	10.37	0.63%
LO	m2a crop eq	165.07	1.48	0.89%	1.34	0.81%	1.83	1.11%	4.05	2.45%
MR	kg Cu eq	0.39	0.0246	6.3%	0.00655	1.68%	0.00753	1.93%	0.0497	12.75%
FF	kg oil eq	14.93	0.362	2.43%	0.215	1.44%	0.663	4.44%	2.15	14.37%
WC	m3	17.52	0.0844	0.48%	0.362	2.07%	0.493	2.81%	0.0671	0.38%

Table D.3.1 - Absolute and percentage results of each impact category for the Raw Materials (cont.)

Impact category	Unit	Total	Red pepper		Rapeseed oil		Chickpea		Tap water	
GW	kg CO2 eq	95.34	23.66	24.82%	13.87	14.55%	39.52	41.45%	0.00128	0,00%
OD	kg CFC11 eq	0.00274	0.00056	20.43%	0.000218	7.97%	0.000653	23.83%	0.000000000553	0,00%
EOFH	kg NOx eq	0.553	0.172	31.18%	0.0579	10.47%	0.277	50.06%	0.00000302	0,00%
PMF	kg PM2.5 eq	0.33	0.0991	30.06%	0.0543	16.49%	0.147	44.54%	0.00000214	0,00%
EOF	kg NOx eq	0.559	0.173	30.99%	0.0599	10.72%	0.278	49.83%	0.0000031	0,00%
TA	kg SO2 eq	1.94	0.659	33.91%	0.345	17.75%	0.853	43.91%	0.00000474	0,00%
FE	kg P eq	0.0325	0.0154	47.23%	0.00451	13.88%	0.00675	20.77%	0.000000927	0,00%
ME	kg N eq	0.306	0.0893	29.15%	0.0685	22.36%	0.131	42.61%	0.0000000883	0,00%
TET	kg 1.4-DCB	176.02	33.71	19.15%	33.56	19.07%	61.87	35.15%	0.00291	0,00%
FET	kg 1.4-DCB	3.65	0.704	19.28%	0.267	7.3%	2.08	57.1%	0.0000654	0,00%
MET	kg 1.4-DCB	3.73	0.775	20.79%	0.379	10.15%	1.9	50.9%	0.0000898	0,00%
HTc	kg 1.4-DCB	3.39	0.601	17.72%	0.301	8.89%	1.75	51.68%	0.001	0.03%
HTnc	kg 1.4-DCB	1634.68	772.78	47.27%	40.23	2.46%	801.79	49.05%	0.00155	0,00%
LO	m2a crop eq	165.07	23.61	14.31%	63.3	38.35%	60.29	36.53%	0.0000329	0,00%
MR	kg Cu eq	0.39	0.0548	14.06%	0.0562	14.4%	0.177	45.44%	0.0000148	0,00%
FF	kg oil eq	14.93	2.17	14.54%	2.77	18.53%	6.04	40.44%	0.000338	0,00%
WC	m3	17.52	2.01	11.48%	0.63	3.59%	13.72	78.26%	0.00376	0.02%

Annex E: Sensitivity Analysis results

Tabel E. 1- Absolute vales and percentage of Moroccan Falafel original vs Moroccan Falafel Beetroot sensitivity analysis.

Impact category	Unit	Total	Beetroot		Original	
GW	kg CO2 eq	89.5	41.53	**46.41%**	47.96	53.59%
OD	kg CFC11 eq	0.00262	0.00124	47.14%	0.00139	52.86%
EOFH	kg NOx eq	0.497	0.22	44.22%	0.277	55.78%
PMF	kg PM2.5 eq	0.301	0.135	44.89%	0.166	55.11%
EOF	kg NOx eq	0.503	0.223	44.28%	0.28	55.72%
TA	kg SO2 eq	1.76	0.783	44.49%	0.977	55.51%
FE	kg P eq	0.0319	0.0155	48.44%	0.0165	51.56%
ME	kg N eq	0.279	0.125	44.82%	0.154	55.18%
TET	kg 1.4-DCB	201.15	112.41	**55.88%**	88.74	44.12%
FET	kg 1.4-DCB	3.79	1.96	**51.77%**	1.83	48.23%
MET	kg 1.4-DCB	3.63	1.76	48.51%	1.87	51.49%
HTc	kg 1.4-DCB	3.11	1.41	45.37%	1.7	54.63%
HTnc	kg 1.4-DCB	1449.71	629.4	43.42%	820.31	56.58%
LO	m2a crop eq	153.19	70.01	45.7%	83.18	54.3%
MR	kg Cu eq	0.416	0.22	**52.87%**	0.196	47.13%
FF	kg oil eq	14.53	7.01	48.28%	7.51	51.72%
WC	m3	14.56	5.86	40.2%	8.71	59.8%

Tabel E. 2- Absolute vales and percentage of Beetroot vs Chickpea sensitivity analysis.

Impact category	Unit	Total	beets		chickpea	
GW	kg CO2 eq	0.52	0.122	23.43%	0.398	**76.57%**
OD	kg CFC11 eq	0.00000699	0.000000413	5.91%	0.00000657	**94.09%**
EOFH	kg NOx eq	0.00307	0.000284	9.24%	0.00279	**90.76%**
PMF	kg PM2.5 eq	0.00166	0.000179	10.78%	0.00148	**89.22%**
EOF	kg NOx eq	0.0031	0.000293	9.47%	0.0028	**90.53%**
TA	kg SO2 eq	0.00913	0.000538	5.89%	0.00859	**94.11%**
FE	kg P eq	0.0000946	0.0000267	28.16%	0.000068	71.84%
ME	kg N eq	0.00145	0.000133	9.21%	0.00131	**90.79%**
TET	kg 1.4-DCB	2.07	1.44	**69.86%**	0.623	30.14%
FET	kg 1.4-DCB	0.0467	0.0257	**55.05%**	0.021	44.95%
MET	kg 1.4-DCB	0.0328	0.0136	41.64%	0.0191	58.36%
HTc	kg 1.4-DCB	0.0213	0.00367	17.23%	0.0176	**82.77%**

HTnc	kg 1.4-DCB	8.34	0.27	3.23%	8.07	**96.77%**
LO	m2a crop eq	0.678	0.0714	10.53%	0.607	**89.47%**
MR	kg Cu eq	0.00451	0.00272	**60.4%**	0.00178	39.6%
FF	kg oil eq	0.0971	0.0363	37.4%	0.0608	62.6%
WC	m3	0.16	0.0216	13.52%	0.138	**86.48%**

Tabel E. 3- Absolute vales and percentage of Moroccan Falafel original vs Moroccan Falafel Sweet potato sensitivity analysis.

Impact category	Unidade	Total	Original		Sweet potato	
GW	kg CO2 eq	90.85	47.96	52.79%	42.89	47.21%
OD	kg CFC11 eq	0.00263	0.00139	52.71%	0.00124	47.29%
EOFH	kg NOx eq	0.503	0.277	55.15%	0.226	44.85%
PMF	kg PM2.5 eq	0.302	0.166	54.87%	0.136	45.13%
EOF	kg NOx eq	0.509	0.28	55.09%	0.228	44.91%
TA	kg SO2 eq	1.77	0.977	55.33%	0.788	44.67%
FE	kg P eq	0.0321	0.0165	51.29%	0.0156	48.71%
ME	kg N eq	0.279	0.154	55.27%	0.125	44.73%
TET	kg 1.4-DCB	203.96	88.74	43.51%	115.23	56.49%
FET	kg 1.4-DCB	3.51	1.83	52.07%	1.68	47.93%
MET	kg 1.4-DCB	3.72	1.87	50.35%	1.84	49.65%
HTc	kg 1.4-DCB	3.15	1.7	53.97%	1.45	46.03%
HTnc	kg 1.4-DCB	1452.9	820.31	56.46%	632.58	43.54%
LO	m2a crop eq	155.48	83.18	53.5%	72.3	46.5%
MR	kg Cu eq	0.417	0.196	46.97%	0.221	53.03%
FF	kg oil eq	14.73	7.51	51.02%	7.21	48.98%
WC	m3	14.23	8.71	61.19%	5.52	38.81%

Tabel E. 4 - Absolute vales and percentage of Sweet potato vs Chickpea sensitivity analysis.

Categoria de impacte	Unidade	Total	chickpea		sweet potato	
GW	kg CO2 eq	0.575	0.398	69.2%	0.177	30.8%
OD	kg CFC11 eq	0.00000728	0.00000657	90.32%	0.000000705	9.68%
EOFH	kg NOx eq	0.0033	0.00279	84.35%	0.000517	15.65%
PMF	kg PM2.5 eq	0.00171	0.00148	86.51%	0.00023	13.49%
EOF	kg NOx eq	0.00333	0.0028	84.15%	0.000528	15.85%
TA	kg SO2 eq	0.00936	0.00859	91.72%	0.000776	8.28%
FE	kg P eq	0.000101	0.000068	67.02%	0.0000335	32.98%

ME	kg N eq	0.00143	0.00131	91.95%	0.000115	8.05%
TET	kg 1.4-DCB	2.18	0.623	28.55%	1.56	71.45%
FET	kg 1.4-DCB	0.0353	0.021	59.51%	0.0143	40.49%
MET	kg 1.4-DCB	0.0361	0.0191	52.95%	0.017	47.05%
HTc	kg 1.4-DCB	0.0228	0.0176	77.2%	0.00521	22.8%
HTnc	kg 1.4-DCB	8.47	8.07	95.28%	0.4	4.72%
LO	m2a crop eq	0.772	0.607	78.63%	0.165	21.37%
MR	kg Cu eq	0.00456	0.00178	39.1%	0.00278	60.9%
FF	kg oil eq	0.105	0.0608	57.71%	0.0445	42.29%
WC	m3	0.146	0.138	94.5%	0.00804	5.5%

Tabel E. 5- Absolute values and percentage of comparision between the adpotion of 30% renewable energy and the original product.

Impact categories	**Unidade**	**Total**	**MFO 100**		**MFO 70/30**	
GW	kg CO2 eq	1433.96	736.25	51.34%	697.71	48.66%
OD	kg CFC11 eq	0.00627	0.00315	50.17%	0.00313	49.83%
EOFH	kg NOx eq	4.71	2.38	50.58%	2.33	49.42%
PMF	kg PM2.5 eq	1.96	0.986	50.32%	0.973	49.68%
EOF	kg NOx eq	4.79	2.42	50.57%	2.37	49.43%
TA	kg SO2 eq	7.07	3.56	50.42%	3.5	49.58%
FE	kg P eq	0.214	0.109	50.65%	0.106	49.35%
ME	kg N eq	0.637	0.319	50.03%	0.319	49.97%
TET	kg 1.4-DCB	9067.49	4440.88	48.98%	4626.6	51.02%
FET	kg 1.4-DCB	61.25	29.61	48.35%	31.64	51.65%
MET	kg 1.4-DCB	80.73	39.12	48.45%	41.62	51.55%
HTc	kg 1.4-DCB	91.04	44.97	49.4%	46.07	50.6%
HTnc	kg 1.4-DCB	4053.7	2024.52	49.94%	2029.18	50.06%
LO	m2a crop eq	378.08	188.73	49.92%	189.35	50.08%
MR	kg Cu eq	3.56	1.73	48.7%	1.83	51.3%
FF	kg oil eq	436.22	225.34	51.66%	210.88	48.34%
WC	m3	38.42	19.14	49.82%	19.28	50.18%

Tabel E. 6- Absolute values and percentage of comparision between the adpotion of 50% renewable energy and the original product.

Impact categories	**Unidade**	**Total**	**MFO 100**		**MFO 50/50**	
GW	kg CO2 eq	1408.26	736.25	52.28%	672.01	47.72%
OD	kg CFC11 eq	0.00626	0.00315	50.28%	0.00311	49.72%
EOFH	kg NOx eq	4.67	2.38	50.98%	2.29	49.02%

PMF	kg PM2.5 eq	1.95	0.986	50.53%	0.97	49.47%
EOF	kg NOx eq	4.76	2.42	50.95%	2.33	49.05%
TA	kg SO2 eq	7.03	3.56	50.7%	3.46	49.3%
FE	kg P eq	0.213	0.109	51.09%	0.104	48.91%
ME	kg N eq	0.637	0.319	50.05%	0.318	49.95%
TET	kg 1.4-DCB	9191.3	4440.88	48.32%	4750.41	51.68%
FET	kg 1.4-DCB	62.6	29.61	47.31%	32.98	52.69%
MET	kg 1.4-DCB	82.4	39.12	47.48%	43.28	52.52%
HTc	kg 1.4-DCB	91.77	44.97	49,00%	46.8	51,00%
HTnc	kg 1.4-DCB	4056.8	2024.52	49.9%	2032.28	50.1%
LO	m2a crop eq	378.49	188.73	49.86%	189.76	50.14%
MR	kg Cu eq	3.62	1.73	47.87%	1.89	52.13%
FF	kg oil eq	426.58	225.34	52.82%	201.25	47.18%
WC	m3	38.51	19.14	49.71%	19.37	50.29%