ENVIRONMENTAL, ECONOMIC AND SOCIAL SUSTAINABILITY OF FOOD CHAINS BASED ON LIFE CYCLE APPROACH AND MULTI-CRITERIA DECISION ANALYSIS APPLIED TO NOVEL TOMATO PRODUCTS

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ABSTRACT

ENVIRONMENTAL, ECONOMIC AND SOCIAL SUSTAINABILITY OF FOOD CHAINS BASED ON LIFE CYCLE APPROACH AND MULTI-CRITERIA DECISION ANALYSIS APPLIED TO NOVEL TOMATO PRODUCTS

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Designing agricultural systems and food value chains to reduce their impact on the world is a priority. This study evaluates the environmental, economic and social sustainability of six novel dried tomato products, namely, tomato leather product-1 with rubisco protein and tray dryer, tomato leather product-2 with pea protein and tray dryer, tomato bar product-1 with rubisco protein and MW vacuum dryer, tomato bar product-2 with pea protein and MW vacuum dryer, tomato bar product-3 product with rubisco and conventional dryer, and tomato bar product-4 product with pea protein and conventional dryer.

Life cycle assessment (LCA) was used to assess environmental sustainability. With respect to economic sustainability, this research has extended the life cycle costing (LCC) approach by including economic aspects. Social impacts, which have not been studied much on food products, were also analyzed using social LCA by developing a hybrid model consisting of micro or product-specific criteria and global criteria at the macro level. The system under assessment for the environmental, economic, and social pillars was bounded throughout the cradle-to-market life cycle. The analytic hierarchy process (AHP) survey determined the degree of importance of the criteria and key stakeholders in the sustainability assessment model. The multi-criteria decision analysis (MCDA) methods of TOPSIS (Technique for order by preference by similarity to ideal solution) and SAW (Simple additive weighting) were used to solve the trade-offs between risks and benefits in sustainability decisions of tomato products in the food science field.

The results provided hotspots for the revision of the tomato products and the sustainability scores. In fact, the sustainability rankings were changed by the addition of the product-specific criteria (sensory quality, nutrient content and research outputs). Product enrichment and texturization were found to affect the overall sustainability scores as much as the selected drying method. The greatest environmental risks were at the raw material production stages for rubisco and olive powder production. Although the cost of a tray dryer is not economical compared to the MW vacuum dryer and conventional dryer, the economic prosperity generation and labor productivity impact categories were determined to be best for leather products with pea protein. Among the bar products, rubisco protein with a conventional dryer has the greatest economic sustainability score. The results reveal the regional impacts of purchasing stakeholders of raw materials. Purchasing pea protein was determined responsible for major social risks. This three dimensional sustainability framework with sustainability score can be a model for companies planning to measure and improve their food products. In addition, as a key component of the Mediterranean Diet, novel tomato products may contribute to the growing popularity of healthy diets.

Keywords: Environmental sustainability, Economic sustainability, Social sustainability, Novel tomato products, Multi-criteria decision analysis (MCDA), Life cycle assessment (LCA)

ÖZ

ÇOK KRİTERLİ KARAR VERME VE YAŞAM DÖNGÜSÜ YAKLAŞIMINA GÖRE GIDA ZİNCİRLERİNİN ÇEVRESEL, EKONOMİK VE SOSYAL SÜRDÜRÜLEBİLİRLİĞİNİN YENİLİKÇİ DOMATES ÜRÜNLERİNDE DEĞERLENDİRİLMESİ

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Tarımsal sistemlerin ve gıda değer zincirlerinin dünya üzerindeki etkilerini azaltacak şekilde tasarlanması öncelikli bir konudur. Bu çalışmada, yenilikçi ve kurutulmuş altı domates ürününün (rubisco proteinli ve tepsili kurutucuda kurutulmuş domates pestili-1; bezelye proteinli ve tepsili kurutucuda kurutulmuş domates pestili-2, rubisco proteinli ve vakumlu mikrodalga kurutucuda kurutulmuş domates bar-1; bezelye proteinli ve vakumlu mikrodalga kurutucuda kurutulmuş domates bar-2, rubisco proteinli ve konveksiyonel kurutucuda kurutulmuş domates bar-3 ve bezelye proteinli ve konveksiyonel kurutucuda kurutulmuş domates bar-4) çevresel, ekonomik ve sosyal boyutlarda sürdürülebilirliği değerlendirilmiştir.

Bu çalışmada çevresel sürdürülebilirliği belirlemek için Yaşam Döngüsü Değerlendirmesi (YDA) metodu kullanılmıştır. Ekonomik sürdürülebilirliğin değerlendirmesinde kullanılan yaşam döngüsü maliyetlendirme yöntemi global ekonomik konular da dahil edilerek YDA bazlı olacak şekilde geliştirilmiştir. Sosyal boyutta sürdürülebilirlik değerlendirmesi daha önce yapılan çalışmalarda gıda ürünlerine önemli sayıda konu olmamıştır. Bu araştırmada, sosyal etkileri değerlendirmek için sosyal YDA kullanılarak mikro-ürüne özgü kriterler ve makro düzeydeki kriterlerden oluşan hibrit bir model geliştirilmiş ve yenilikçi domates ürünlerinin sürdürülebilirlik analizi yapılmıştır.

Çevresel, ekonomik ve sosyal boyutlarda sürdürülebilirlik değerlendirmesi tarladan markete yaşam döngüsü ile sınırlandırılmıştır. Etki kriterlerinin ve kilit paydaşların önem derecesini belirlemek için Analitik Hiyerarşi Süreci (AHP) ile anket yapılmıştır. İdeal Çözüme Benzerliğe Göre Tercih Sıralama (TOPSIS) ve Basit Toplamlı Ağırlıklandırma (SAW) çok kriterli karar verme (ÇKKV) teknikleri, riskler ve faydalar nedeniyle karar alınması zorlaşan gıda bilimi alanındaki sürdürülebilirlik değerlendirmesi modelinin çözümünde kullanılmıştır.

Sonuçlar, ürünlerin sürdürülebilirlik puanlarını ve iyileştirmeleri için önemli noktaları göstermiştir. Yeni domates ürünlerinin sürdürülebilirlik sıralamasını ürüne özgü kriterler (duyusal kalite, besin içeriği ve sürdürülebilirliğe fayda sağlayan teknolojik kriterler) etkilemiştir. Ürün zenginleştirme ve tekstüre etmenin seçilen kurutma yöntemi kadar sürdürülebilirlik puanını etkilediği sonucuna varılmıştır. En yüksek çevresel risk rubisco ve zeytin tozu üretimine yönelik hammadde üretim aşamalarında tespit edilmiştir. Tepsili kurutucunun maliyeti, vakumlu mikrodalga veya geleneksel kurutucularla karşılaştırıldığında ekonomik olmasa da, ekonomik refah üretimi ve işgücü verimliliği etki kategorilerinin bezelye proteinli pestil ürünlerinde en iyi olduğu belirlenmiştir. Bar ürünlerinde, rubisco protein ve geleneksel kurutucuyla kurutulmuş ürün en yüksek ekonomik sürdürülebilirlik puanına sahiptir. Sonuçlar, satın alma ortaklarının bölgesel etkilerini ortaya çıkarmıştır. Bezelye proteinin üretildiği bölgesel kaynaklı sosyal riskler oluşturduğu belirlenmiştir. Önerilen model, gıda ürünlerini ölçmeyi ve iyileştirmeyi planlayan şirketler için bir model olabilir. Ayrıca, Akdeniz diyetinin anahtar bir bileşeni olan domates ürünleri sağlıklı ürün çeşitliliğine katkıda bulunabilir.

Anahtar Kelimeler: Çevresel sürdürülebilirlik, Ekonomik sürdürülebilirlik, Sosyal sürdürülebilirlik, Yenilikçi domates ürünleri, Çok kriterli karar verme (ÇKKV), Yaşam döngüsü analizi (YDA)

To My Mom & Dad, Sultan & Ziya

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ABBREVIATIONS

A	Alternative (product)
AHP	Analytic Hierarchy Process
C	Criteria
DPPH	1,1-diphenyl-2-picrylhydrazyl (DPPH)-2,2-diphenyl-1-picrylhydrazyl
ELCA	Environmental Life Cycle Assessment
ESS	Earth System Science
EUROSTAT	European Statistical Office
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
IC	Impact Category
ISO	International Organization for Standardization
JRC	European Commission Joint Research Centre.
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCDA	Multi-Criteria Decision Analysis
METU	Middle East Technical University
SAW	Simple Additive Weighting
SC	Subcategory
SETAC	Society of Environmental Toxicology and Chemistry
SHDB	Social Hotspots Database
TOPSIS	Technique for Order by Preference by Similarity to Ideal Solution
UNEP	United Nations Environment Programme
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje
W	Weight

CHAPTER 1

INTRODUCTION

1.1. Background

Food product systems need to be integrated into sustainability concepts to avoid negative impacts on the environment (environmental sustainability), to achieve profitable outcomes (economic sustainability) and to benefit society (social sustainability) (FAO, 2018). The food value chain is a system composed of subsystems such as production, waste management, the supply chain, human resources or energy (FAO, 2018). It includes all stakeholders and steps in the food production life cycle, from primary production or raw materials to consumption, and adds value to every activity in between (FAO, 2018).

The United Nations plays a crucial role with its conferences and reports on the sustainability and protection of the world. The Brundtland Report "Our Common Future" was the first outcome of efforts that had specific recommendations and first stated sustainability in 1987. In 1992, Agenda 21 was published as an implementation plan. Then, the Johannesburg Plan of Implementation was announced in 2002. The World Summit declared environment, economic and social aspects as key elements to be balanced for sustainable development (United Nations, 2005). The 2030 Agenda for Sustainable Development has announced protection issues with integrated policies (United Nations, 2023).

The idea of sustainable development is different from that of sustainability. While sustainability is addicted to enhancing the "property" of the system at any time, sustainable development refers to the improvement of the process, which involves dynamic changes that are also about the trend of long-term sustainability (EUROSTAT, 2007).

Sustainable product considerations present a connection between marketing and environmentally friendly production. The impact of investment inputs on environmental sustainability in venture decision-making has been examined (Yang et al., 2024). A sustainable product is not a labeled organic product but rather an approach that evaluates and monitors the environmental, economic and social impacts on the community and the planet (Hadland, 2020). The author stated that sustainable food involves less use of land, water and energy, local production with low emissions, animal well-being (which is not an issue of organic certification), ecofriendly packaging, and ethical and fair working conditions. A sustainability assessment of food systems is conducted to determine which of the options for products, processes or decisions have less pressure or more benefits for humankind. Sustainability analysis has environmental, economic and social pillars. The environmental pillar is concerned with the impact on the environment resulting from a product or process system. The economic pillar relates to long-term investment decisions that should guide sustainable economic activities (European Commission, 2019). In addition to achieving better sustainable development, social sustainability gives companies the responsibility to develop their business in terms of improving the social conditions of stakeholders (Giannarakis et al., 2023).

Life cycle assessment (LCA) is a methodical investigation of the environmental burdens of a product/ process activity (Goedkoop et al., 2013). It was established for the defense industry in the 1960s and standardized as a procedure with ISO 14044:2006 (ISO, 2006). It is then used in different sectors, for labeling procedures, for energy comparisons, for product design, for the selection of alternatives in food production and transportation, and even for quality assurance. Environmental LCA has various benefits, such as the selection of similar products, the selection of stakeholders, the emphasis of environmental burdens in process activities, product or process redesign, the calculation of changes in environmental burdens after revisions, and policy formulation (Heijungs and Guinée, 1992). After the first LCA guidelines were proposed (Heijungs & Guinée, 1992), useful LCA guidelines were established (Guinée, 2002; Jolliet et al., 2004). Subsequently, the LCA is divided into four stages (ISO, 1998). The computational structure of LCA is systematically described by Heijungs & Suh (2002), as shown in Table 1.1.

Table 1.1. *First Published LCA Procedure with the Steps, Results and Disciplines* (Heijungs & Guinée, 1992)

Step	• **Activities**	**Indicator**	**Expertise**
Inventory analysis	• drawing up the process tree • entering the process data • application of the allocation rules • creating the inventory table	Inventory table with environmental interventions; energy, waste, etc.	system theory, process engineering
Impact Assessment	Classification: • selection of the problem types • definition of classification factors • creating the environmental profile • normalization of the effect scores	environmental profile with effect scores	environmental science
	Evaluation: • evaluation of the environmental profile evaluation of the reliability and validity	environmental index or judgment	decision-making
Improvement Analysis (Interpretation)	• dominance analysis • marginal analysis	starting points for redesign	process engineering

The LCA method faces challenges in managing a large number of data and indicators, deciding on the type of data and their aggregation, and linking data correctly (Heijungs et al., 2013). The major challenge of the LCA procedure is the availability of not only data but also their processing and calculation. The burdens of impact can be assessed through a cause-and-effect chain (Du et al., 2019). During LCA, different activities can be recognized (Heijungs & Suh, 2002):

- Each LCA is inherently distinctive in purpose and scope. During the assessment, data needs to be transformed into meaningful results, such as the calculation of emissions from the aggregation of unit processes.

- The LCA procedure can involve different stakeholders and their judgments, including not only activities in supply chains but also weights and redesigns of products after the results.

- The scale of the LCA can be different. For example, it can be small scale to see only production loads (gate to gate), it can aim to see hotspots in the whole life cycle. The scale can be a production scale for a company or a laboratory scale for a designer.

- LCA and the reporting of its results can also differ in terms of visualization, meaningful representations, and figures.

The assessment of each dimension has different theoretical maturations (Traverso et al., 2012). Although there are standardized ISO 14044:2006 (ISO, 2006) directives for environmental impact from product or process systems, the economic and social dimensions are not measured by a standardized methodology.

Economic sustainability is measured by life cycle costing (LCC). The organization of Society of Environmental Toxicology and Chemistry (SETAC) published an environmental cost analysis framework by integrating environmental concerns into industrial and commercial activities (Hunkeler et al., 2008). Although older than LCA (Kloepffer, 2008), there is no standardized method for assessing LCC (Degieter et al., 2022). Its division into three categories, namely, conventional, environmental, and societal LCC, increases its comprehensiveness.

Using LCC, activities that affect economic sustainability are divided into: (i) system planning, (ii) preliminary design, (iii) detailed design and revisions, (iv) production/construction, and (v) disposal (Blanchard & Fabrycky, 1998). In fact, as an iterative process, product life cycle cost analysis starts in the research phase with the identification of objectives, is applied in the preliminary system design phase, is evaluated in the detailed product/system design phase, and can be monitored in the production and construction phase. While the system planning and theoretical design phase estimates more than half of the cost, 95% of the cost is captured by accumulation just before production (Blanchard & Fabrycky, 1998). Blanchard and Fabrycky, (1998; 2014) also associate LCC as a "design for affordability" as profitability under system design assessment. The authors recommended life cycle cost analysis under affordability analysis.

On the other hand, whether LCC should be assessed according to cost level is controversial (Neugebauer et al., 2016). Accordingly, the authors also encouraged that economic impact categories (also called endpoint categories) should have some link to the macroeconomic level and economic outcomes from the product system. In Neugebauer et al. (2016), it is also noted that cost alone cannot provide an impact pathway. At the impact assessment stage, appropriate indicators characterize the underlying flow. However, the cost factor is not necessary because it uses the unit of measurement. Therefore, Swarr et al. (2011) state that there is no need to include different characterization factors to aggregate a category measure. However, Neugebauer et al. (2016) and Gluch & Baumann (2004) recommend broadening the scope of economic analysis. They noted that presenting indicators only in the case of monetization might underestimate the economic pillar that borders the natural environment.

Social sustainability is complementary to environmental and economic assessments, filling the gap in social impact (Jørgensen et al., 2010). Knowledge about social sustainability in a society is important in terms of preferences for a food product. For instance, in the wine sector, consumers prefer to pay more for sustainable products than for conventional products (Baiano, 2021). Organizations are attempting to measure the societal impact of financial investments, whereas firms are seeking to pursue investments that are socially sustainable (Alda, 2021; Martí-Ballester, 2015). For instance, consumer preferences shift when consumers learn of information, suggesting that the production of a food product violates human dignity (Toussaint et al., 2021).

Guidelines framing social sustainability are published on social issues (ISO, 2006; UNEP et al., 2009; United Nations, 2011; European Commission, 2019; UNEP, 2020; United Nations, 2023). The guidelines for social life cycle assessment (Benoit & Mazijn, 2009) present the principles for social LCA, recommending the use of a system boundary as in environmental LCA. Social impact assessment can be carried out through different methods, as well as through the categorization of impact, the occurrence of hotspots, their consequences for people and communities, the involvement of stakeholders in the assessment of social impact, and multicriteria decision analysis (Gulisano et al., 2018). In addition to environmental sustainability, social assessment is also combined with LCA (Neugebauer et al., 2016). However, despite life cycle-based approaches, social LCA is not as robust as environmental sustainability (Benoit-Norris et al., 2012; Mazac et al., 2023). In social LCA, there is no accepted and widely applied command framework such as environmental LCA (Sureau, 2016; Sureau et al., 2018). Given the problems of assessing different dimensions together and some mitigating developments (Jørgensen et al., 2012), there is still no robust tool for social assessment.

According to (UNEP, 2020), social LCA is used to evaluate the social impact of products and processes in their life cycle. It is therefore recommended to adopt the ISO 14044:2006 environmental life cycle procedure. The procedure of the LCA is to define the purpose and scope of the assessment, decide on objectives to follow the other steps, perform an inventory analysis for impact and determine ways to measure the data, perform the impact assessment by identifying impact categories, obtain the results and make some comments to improve the product/process. Unlike other dimensions, the social environment affects social sustainability in both positive and negative ways. Social dimensions are defined as social impacts (Norris, 2006). The determination of criteria for measuring social sustainability is based on political consensus, stakeholder choices, voluntary standards, consultancy, literature reviews and theory (Sureau, 2016).

Sustainable development can be achieved by involving stakeholders in the consumption and production stages. Therefore, the life cycle approach is the best tool to encourage this involvement (Traverso et al., 2012). In terms of implementation, the environmental and economic sustainability of beer packaging alternatives have been analyzed (Niero and Kalbar, 2019). However, only packaging production is included in the system boundary, excluding transportation and the consumer and producer stages. LCC has not been combined with LCA, although there are studies on LCC (Swarr et al., 2011). Consumer preferences change when information about the inhumane situation in which the food product is produced (Toussaint et al., 2021).

1.2. Motivation and Objectives of the Research

Food is a very important life source for our planet. A food system should consider people's health and environmental impacts to be sustainable (Lancet Commission, 2019). Food systems burden between 19% and 29% of global greenhouse gas emissions, of which agriculture alone (including land use change) is responsible for approximately 14%-24% of global anthropogenic emissions (Lancet Commission, 2019). 800 million individuals are undernourished (FAO, 2018) globally, which contributes to premature death and morbidity (Lancet Commission, 2019), more than 2 billion individuals are at risk of hunger (FAO, 2014). The dietary trends of even small increases in red meat or dairy product consumption will make the estimated 10 billion people worldwide in 2050 very difficult. Thus, changing dietary patterns to healthy diets of nuts, fruits, vegetables and legumes, which are UN sustainable development goals, is highly recommended. In the European Union, the proportion of the environmental impact of the production of food has reached 30% of consumable goods. This ratio is even high for some ecosystem services, such as eutrophication, which accounts for 58% of the total impacts (Sengstschmid et al., 2011).

Tomato is a key component of the Mediterranean diet. However, not everyone can access this diet with a novel food product. Tomatoes are highly nutritious and inexpensive to produce in the Mediterranean region and have various product options. It has very healthy components such as dietary fibers, lycopene, beta-carotene, protein, vitamin C, total phenolics, and flavonoids (Hoffman, 2022). The tomato-processing sector is a very large part of production, with 40 million tons of tomatoes processed globally (Garofalo et al., 2017). Thus, the hypothesis for the production of novel tomato products is that it is possible to produce and functionalize the tomato snack bar by minimizing the amount of ingredients and processes and to determine its physicochemical, functional, textural and sensorial properties. The bioavailability of phenolics in tomatoes increases when cooking in olive oil (Hoffman, 2022). Thus, as another key Mediterranean component, olive powder was used as an ingredient in the products. This research aimed to assess these products.

Earth system science (ESS) addresses global issues and problems, most of which are related to environmental services and human impacts. Thus, although this research is not limited to food science, it has sustainable food systems and ESS linkages with appropriate indicators.

Research Question 1: How can we analyze the sustainability of tomato products, in which dimensions?

In this thesis, the environmental, economic, and social sustainability of dried tomato products were analyzed. An impact category in the environmental dimension that measures more than one dimension may be economically viable but carries a high risk of environmental issues. Food sustainability studies have focused mainly on the environmental dimension. In fact, there are only 59 economic sustainability assessments out of 1882 sustainability studies (Degieter et al., 2022). The different methodological approaches (Gharsallah et al., 2021) show that indicators and their use are key aspects that vary across studies.

In addition, social sustainability may be low in economic contribution but high in benefits. Trade-offs should be resolved by considering a systems approach integrated into the hybrid approach of multicriteria decision analysis. Although overall sustainability is proposed as a sum of three pillars, there are some linkages and trade-offs between the sustainability dimensions. In the literature, this problem has been solved using data analysis. Abu et al. (2021) selected appropriate waste treatment methods using the AHP multicriteria decision approach in the environmental, economic and social dimensions. They also used the technical dimension as a fourth dimension to measure the level and capacity of the process. Thus, not only the products used in this study but also the life cycle sustainability of the systems can be compared.

There is also a need to avoid double counting when combining environmental, economic, and social dimensions (Hunkeler et al., 2008). The challenge is to obtain an appropriate set of indicators that are compatible with other dimensions but without double counting any measure (UNEP, 2020). This also contributes to the literature about the food system by providing a cradle-to-market assessment of three pillars by avoiding double counting.

Research Question II: What are the limitations in sustainability knowledge, how can we contribute to it, and on which side?

Environmental sustainability assessment is standardized by the method LCA, and the assessment of economic and social dimensions is not standardized. The economic assessment is performed by the LCC approach. Although there is a link between LCC and environmental LCA according to the environmental type of LCC, there is no linkage between environmental LCC and social LCA. Since LCC is controversial because of its limited cost, the set of appropriate economic impact categories consisted not only of costs but also of global and physical measures that contribute to gross domestic product (GDP). The additional criteria constructed the linkage between economic LCC and social LCA. In this research, the LCC method was enhanced by eight LCA-based criteria to assess the economic footprint more comprehensively. The socioeconomic aspects of risks and benefits at the macro- or global level are presented in the Social Hotspots Database (SHDB) (Benoit & Mazijn, 2009). However, SHDB has not been applied in the economic dimension in the literature. Unlike previous studies, this model utilized and clustered the SHDB (Benoit-Norris et al., 2019) for the economic assessment model. This study aims to combine economic analysis with the LCA approach to provide a model for economic sustainability analysis. Thus, the rules and definitions of the LCA standard (ISO, 2006) are used to propose an LCA-based LCC framework.

One of the main objectives is to assess the social sustainability of novel food products. Thus, it aims to identify criteria and measure them with appropriate indicators, focusing on process-based criteria as well as macro level data, which is usually done in sustainability studies. This requires not only sustainability or social science knowledge but also process engineering knowledge. In addition, another aim of this study is to assess social sustainability. In fact, the standardized life cycle-based methodology of (Norris, 2006) uses a standard set of criteria. It is possible to use type II impact categories, which use the causes and effects of impact linking the two phenomena of inputs and impacts with type I impact categories (Benoit & Mazijn, 2009). The SHDB (Benoit-Norris et al., 2019) uses the type I social LCA method, which accesses the performances and uses the exact measures of criteria (Sureau, 2020). In this research, it is not directly applied, but type II social LCA impact categories were also combined with the most appropriate product-specific impact subcategories. Therefore, this study proposes a hybrid impact pathway. It proposes a comprehensive analysis for ranking sustainability to capture social footprints at both the product and global levels. The challenges related to social sustainability are solving both benefits and risks. These are normalized by multicriteria decision analysis. The results are used for iterative solutions of revised product design scenarios to achieve more sustainable products. The results are also expected to guide producers to achieve deeper supply chains with more beneficial outcomes.

To the best of our knowledge, TOPSIS and SAW methods are first used by this research to calculate the sustainability scores of tomato products in the field of Food Technologies. MCDA methods with benefits and disadvantages are explained to utilize them in the field of sustainability of Construction Building Technologies by Sánchez-Garrido et al. (2022). The waste management systems are compared by just explaining the specifications of MCDA techniques including AHP, ELECTRE, TOPSIS, VIKOR, and PROMETHEE, and recommending the AHP as the most widely used in sustainable waste management (Abu et al., 2021). Monte-Carlo simulation is utilized as a multi-criteria approach to determine the carbon and water footprints of Italian red wine (D'Ammaro et al., 2021). However, it does not give the sustainability scores of alternatives under environmental, economic and social criteria or overall.

Research Question III: What are the burdens associated with the design of tomato products?

To increase social sustainability in production and consumption, the impact of each dimension has been emphasized not only for benefits but also for risks. The model was used to capture all the risks during the life cycle by the comprehensive set of proper criteria.

Research Question IV: How can we achieve more sustainable food designs, practically in novel-dried tomato products?

This research not only focuses on methodology but also includes a case study on new product development. The results will be valuable for consumers or interested parties looking for ways to make sustainable food choices. As products were created for the Mediterranean Diet, the aim is also to increase the consumption of these products. The sustainability study of each product or process is inherently distinctive. Mancini et al. (2023) note that micro level studies need primary data, while macro level country-based studies use databases. Therefore, there is no readily accepted set of criteria that directly applies to all life cycles (UNEP, 2020). Among 109 sustainability studies, only three are related to the global impact of products (Onat et al., 2017). In this study, it was suggested that sources of micro level data specific to products be used with global-level impacts. Thus, a hybrid methodology was created by integrating global-level LCA criteria with product-specific criteria via the normalization scheme of multicriteria decision analysis.

In this study, appropriate impact categories and subcategories with related indicators are modeled to measure the social sustainability of dried tomato products along the food value chain. The SHDB (Benoit-Norris et al., 2019) method was not directly applied, but impact subcategories were linked and combined with the most appropriate product-specific impact categories. The macro level social themes of the categories were clustered using the SHDB (Benoit-Norris et al., 2019) on a life cycle basis. Those from the food system (micro levels) are combined to rank a sustainability index. Thus, the impact categories from the SHDB are not used directly but are linked and combined with the most relevant impact categories from the product system. Hence, a hybrid framework has been proposed in this study. The evaluation method includes expert judgments by assigning weights and the mathematical method of the multicriteria decision method. Thus, the approach not only gives experts the flexibility to combine specific criteria related to the product or process system but also to rank preferences in a sustainability model.

A stakeholder approach has been used that considers multiple actors in the food value chain, such as employees, workers, consumers and society. As a further contribution, a survey was performed to determine the importance of the impact categories. Through the AHP pairwise comparison questionnaire, links between the criteria importance were identified. An impact category with an environmental dimension, although economically viable, may carry a high risk of environmental issues. The prioritization of criteria is also meaningful for future work in the selection of impact categories. It also allows for ranking scores in the selection of products. In this context, comparisons between different tomato products provide a comprehensive framework for food practices that combine multiple dimensions of sustainability.

Research Question V: How should we perform the assessment and to what extent, only at the production stage or at a broader stage?

When the system boundary is deliberately chosen, the wider it is, the greater the impact captured. The difficulties related to sustainability are resolving the system dynamics of both benefits and risks. When MCDA methods such as VIKOR and TOPSIS are used in combination with LCA, the issues of uncertainty, inclusion of expert preferences and aggregation of criteria are significantly resolved (Onat et al., 2017). Since SHDB does not address uncertainty in the data, the TOPSIS method can overcome those uncertainties during multicriteria decision analysis. The evaluation method of this study also includes a questionnaire for expert evaluations by calculating the AHP weights of each criterion. Thus, the approach provides flexibility for experts not only to combine specific criteria related to the product or process system but also to rank preferences in the sustainability model.

This study focuses on applied agri-food science in the context of Earth System Science. This dissertation comprises the literature on sustainability science to achieve the right tools and contribute to the universe of knowledge. It conducts environmental assessments and proposes assessment models for economic and social sustainability as well as for overall sustainability. In contrast to the literature, this study provides a sustainability score in addition to hotspots of life cycle activities during the impact assessment stage of LCA.

This research not only focuses on methodology but also includes practical case studies for sustainable product development. To enhance overall sustainability, environmental, economic, and social impacts have been highlighted not only for benefits but also for risks. The results contribute to the Functional Tomato Products (FunTomP) Project funded by the European Union as an interdisciplinary project with several objectives, including process and product development, waste utilization, health and sustainability.

1.3. The Architecture of the Dissertation

The plan of the PhD dissertation is shown in Figure 1.1. First, a studied literature review was given to determine the strength of the methodology (Chapter 2). For each pillar of the sustainability dimension (environmental, economic and social), this section includes the conceptual state of the art, aspects and practices in different sectors under a specific dimension of sustainability. In addition, gaps in the literature are identified, and methodological solutions are provided with contributions (section 2.5). This thesis has an implementational dimension in addition to methodological contributions. The case study is given (Chapter 3) by applying the proposed methodological framework in environmental, economic and social dimensions. The objectives of implementation have positive and negative aspects in terms of sustainability criteria. The solution space is multidimensional (a set of 32 criteria). In the application section, six novel products: Tomato Leather-1 (Rubisco protein and tray dryer), Tomato Leather-2 (Pea protein and tray dryer), Tomato Bar-1 (Rubisco protein and MW vacuum dryer), Tomato Bar-2 (Pea protein and MW vacuum dryer), Tomato Bar-3 (Rubisco protein and conventional dryer), and Tomato Bar-4 (Pea protein and conventional dryer) were benchmarked in terms of sustainability. A questionnaire was administered with a mathematical evaluation method. The results are given in terms of the three dimensions of environmental, economic, social, and overall integration (Chapter 4). Finally, discussions and conclusions are made by returning to the objectives of the study and by referring to future works (Chapter 5).

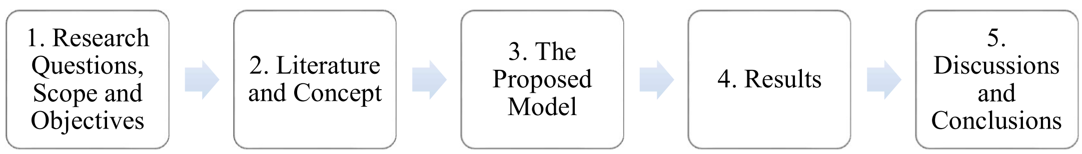

Figure 1.1. Flow of the PhD Manuscript

CHAPTER 2

LITERATURE REVIEW

2.1. Conceptual Framework

In this section, the state of the art for environmental, economic and social analysis is given. In addition, the three-pillar sustainability approach, the concept of food value chain and sustainability goals are also mentioned in this section.

2.1.1. Environmental Sustainability

Sustainability assessment is conducted to determine which of the options for products, processes or decisions are less pressing or more beneficial for humankind. The environmental pillar is concerned with the impact on the environment resulting from a product or process system. Environmental sustainability can be assessed by LCA (ISO, 2006), the planetary boundaries approach and the product environmental footprint (PEF). Planetary boundaries are used to define safe operating processes for a more sustainable Earth. However, the planetary boundary framework is limited in providing linkages between systems. Karlsson Potter & Röös, (2021) provided sustainable options for plant-based foods with a low environmental footprint with a sustainability level classification. With LCA, they used the cradle-to-retailer boundary and planetary boundaries that limit the impact categories to safe limits for humans. Willett et al. (2019) also used the planetary boundaries method for Earth systems, namely, climate change, the nitrogen cycle, the phosphorus cycle and freshwater resources, land use and biodiversity.

The LCA method of sustainability helps to determine the key flows and impacts in deeper supply chains. Unlike environmental footprints, which are related to emissions and resources, LCA concerns impacts (Vanham et al., 2019). During the impact assessment of an LCA, the key flow is characterized by appropriate indicators. After the first LCA guidelines (Heijungs & Guinée, 1992), the ISO 14044:2006 (ISO, 2006) guidelines were proposed for cradle-to-grave environmental aspects, and useful guidelines for LCA were proposed (Guinée, 2002; Jolliet et al., 2004). It is characterized by four stages (ISO, 1998). The first stage is the goal and scope definition, which defines the research question and the reason for using LCA. The system boundary should be drawn to show which scope of the life cycle it will or will not fall under. Figure 2.1 shows cradle-to-grave, cradle to gate and gate-to-gate types of boundaries of the life cycle in the LCA handbook (JRC, 2010). To achieve more sustainable production and consumption patterns, the handbook also advises that one must consider the environmental implications with an entire life cycle from "cradle-to-grave".

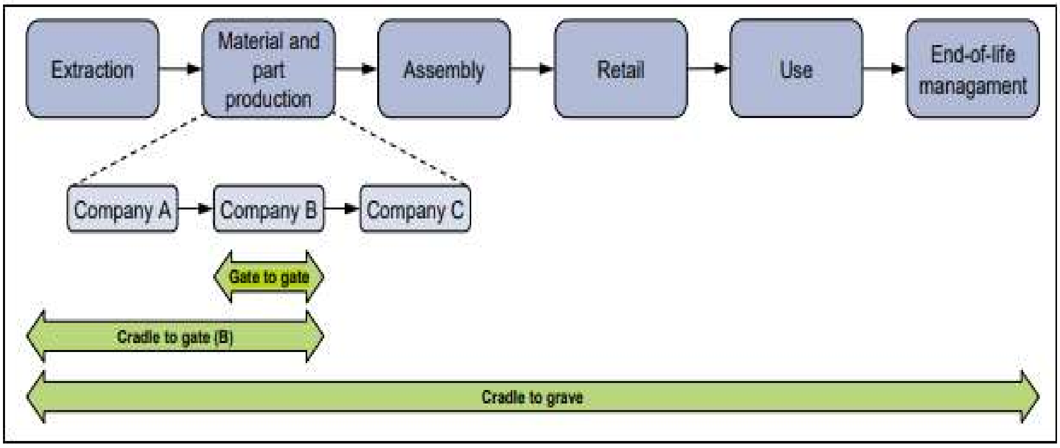

Figure 2.1. Types of System Boundaries (JRC, 2010)

The functional unit should be determined for the same calculation per unit according to the process specification. Second, the inventory analysis is created by refining the process flows, product system and system boundary. In this phase, quantitative and qualitative data are collected with allocation steps for multifunctional processes. It is the systematic examination of the environmental burdens of a product or a process activity (Goedkoop et al., 2013). In addition to open-loop recycling, coproduction or waste processing with multiple processes should be considered in LCA allocation. Inventory analysis generates an inventory table of key streams consisting of aggregated values. The third step of the LCA, impact assessment, aims to transform these aggregated values into meaningful results. At this stage, a characterization procedure is applied to classify the inventory results into impacts. Normalization is also applied to facilitate aggregation. In addition, weights are assigned to the characterizations to obtain a final score on the sustainability burdens of the product. The last step of the LCA involves analyzing the accuracy of the previous steps and results. These results can be compared with previous results, sensitivity analyses or interpretations and data checks.

An LCA provides a way to measure and quantify burdens with indicators set on the environmental profile (Sureau, 2016). It assesses and improves the system in terms of environmental burdens and informs potential stakeholders about their needs, such as strategic decisions and design revisions (ISO, 2006). It is also used to compare products that are functionally similar. In addition, stakeholders for the same products are compared during purchasing decisions. In addition, it shows the impact of key flows in process activities and hotspots, which are the most emphasized burdens. Environmental life cycle assessment (ELCA) is applied by design engineers for environmentally friendly design during product improvement phases and then labeled. The iterative procedure of ELCA is applied after the revision of the product design to observe changes in environmental burdens from one impact category to another. It can be used by governmental organizations for policy-making purposes (Guinée, 2002).

The ELCA method is a robust method that was introduced in 2009 (Goedkoop et al., 2009). The ReCiPe method is an LCA method that uses midpoints and endpoints of environmental impact (Netherlands National Institute for Public Health and the Environment, 2017). Midpoints are the causes of impact, and endpoints are the consequences. It is a robust method consisting of 3 endpoints and 18 midpoints (Wernet et al., 2016). Endpoint logic was developed from the protected area approach developed earlier (Heijungs & Suh, 2002). This method is a consensus of

50 experts attending SETAC's conference to have a robust framework of midpoints and endpoints. Some LCA methods may use endpoint impact categories such as climate change, while others may consider midpoint categories (causes) and endpoint categories (consequences) such as harm to human health or harm to the natural environment. During the regular conferences, they redesign the midpoint and endpoint and their levels by making the environmental LCA method more flexible and standardized (Goedkoop et al., 2009).

2.1.2. Economic Sustainability

Economic sustainability assessment can be performed via different accounting methods (Timonen et al., 2017). The LCC method assesses the economic conditions of a product system. It is used to design a product to minimize the total cost to make it more economical or profitable. Three types of cost analysis approaches using the whole life cycle (cradle-to-grave approach) have been published. The first is conventional LCC, which refers to the cost of a system to the producer or consumer throughout its life cycle (Blanchard & Fabrycky, 1998). It was first used in the 1960s in the defense industry to decide between projects based on their costs. Costing is widely used in sustainability assessments, such as comparing the operating costs of technologies (Acar et al., 2022). Environmental LCC was later proposed under the code of principles of life cycle sustainability assessment of environmental, economic, and social pillars by the SETAC (Swarr et al., 2011). The second approach to LCC is environmental cost analysis, which considers the cost and cost of externalities arising from the life cycle. Hunkeler & Rebitzer (2003) first referred to it as an environmental approach to assessing LCC. However, the authors state that environmental LCC cannot monetize environmental impact, which may lead to double counting with non monetized environmental LCA (Kloepffer, 2008). Environmental LCC uses the costs incurred during the use and end-of-life (EOL) phases of a product. For example, changing from labor taxes to environmental taxes is a suggestion for the environmental cost of sustainability (EUROSTAT, 2007). End-of-life costs can be the cost of environmental systems such as packaging recycling. The last type of life cycle costing analysis is societal LCC, which relates to the number of labor hours spent in assessments. The assessment provides the number of hours of work required for a unit of life. Hence, a higher number means that the workers are in poor condition for societal quality. However, working hours are also included in the social LCA (Benoit-Norris et al., 2012). Therefore, double counting, quantification and regionalization of indicators are still problematic in societal analysis (Hunkeler & Rebitzer, 2003; Jørgensen et al., 2010). In addition, the value-added LCC is calculated by subtracting costs from revenue for each step from production to transportation via the systems approach of environmental LCC (Wohner et al., 2020). Assessing economic sustainability from a societal perspective is a challenge. Factors such as the role of labor, type of inputs, import dependency and innovation potential determine the value added in an economy (Wood & Hertwich, 2013). The value added to GDP is measured positively or negatively by taxation, labor, capital and surplus components in the supply chain. Thus, the contribution to GDP is measured by a total cost indicator, such as the GDP/capita economic performance indicator mentioned earlier by Wood & Hertwich (2013) and used by the World Bank (2011).

In addition to LCC, input–output analysis is also conducted with financing data collected from public institutions. Timonen et al. (2017) noted that readily available input–output data from organizations can be used in conjunction with LCA and can reduce the workload of LCA. The third method of economic evaluation is cost–benefit analysis or benefit metrics. Financial cost–benefit analysis is related to profitability analysis with cash flows. Therefore, this method is not suitable for the design of new products. Environmental cost-benefit analysis is also available. However, it uses a valuation approach that is not parallel to cradle-to-grave or the whole life cycle.

Economic and social linkages are hot topics for the research community in the field of sustainability. Social cost–benefit analysis refers to a benefit analysis of society, which is limited to considering stakeholders in the life cycle. In addition, the criterion of contribution to economic development is included as a reason for social impact under the community category of the Guidelines for Social Life Cycle Assessment (Benoit & Mazijn, 2009). Sureau (2016) also examines the economic dimension and governance in the social LCA framework. The EU has declared economic prosperity as a key objective with the strategy of an eco-efficient economy that ensures high living standards and full and high-quality employment throughout the European Union (EUROSTAT, 2007). The indicators of economic prosperity are GDP, investment in research and innovation, education and training that enhance the EU's competitiveness in the knowledge economy. According to (EUROSTAT, 2007), the main indicator of socioeconomic development is the GDP per capita growth rate. Therefore, GDP is widely used for economic performance, the state of the economy and the quality of development. Thus, they defined the main indicators for balanced economic growth in three categories, as shown in Table 2.1.

Investments such as capital, labor and surplus value are considered under the economic development dimension. Labor productivity is also specified as the contribution to GDP under the competitiveness criterion. Under this criterion, R&D expenditures and energy intensity that contribute to GDP are mentioned. Under the employment heading, it combines different types of employment.

Table 2.1. *The Indicators for Socioeconomic Development of the EU*

(EUROSTAT, 2007)

Contribution to GDP		
Economic Development	Innovation, Competitiveness and Eco-efficiency	Employment
▪ Dispersion of regional GDP ▪ Investment ▪ Household saving	▪ Labor productivity ▪ International cost competitiveness ▪ R&D expenditure ▪ Energy intensity	▪ Total employment ▪ Female employment ▪ Dispersion of regional employment rates ▪ Unemployment

Energy intensity is considered a socioeconomic factor under the Innovation, Competitiveness and Eco-efficiency category (EUROSTAT, 2007) and is correlated with GDP, as shown in Figure 2.2. The eco-efficiency indicator is defined as the amount of energy used for a unit of economic output. However, eco-efficiency has also been studied as an outcome of ecological efficiency and is measured as the ratio of product value (LCC) to environmental impact (LCA) (Lyrstedt, 2005).

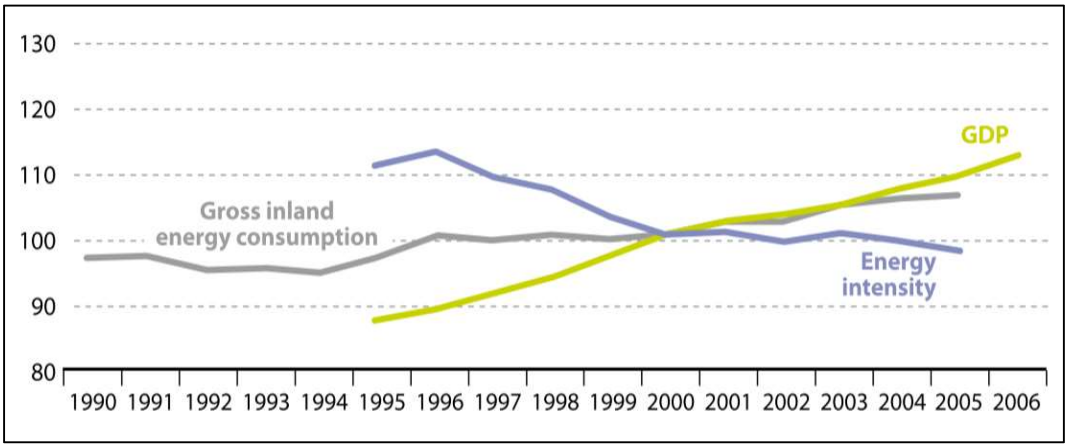

Figure 2.2. Energy Intensity of the European Union-27 (EUROSTAT, 2007)

There are interlinked cross-cutting areas between sustainability pillars (Jolliet et al., 2004; Jørgensen et al., 2010). The boundary of economic assessment can define the environmental or social dimension (Neugebauer et al., 2016). Social or socioeconomic LCA is also a technique that evaluates socioeconomic dimensions (Benoit & Mazijn, 2009). The Oxfam Poverty Index was developed to assess socioeconomic pressure on businesses (Oxfam International, 2008). Since then, the framework has been applied to large corporations to provide a new business model of the impact on society and the economy. However, it is not a comparable methodology because it is assessed only on a case-by-case basis (ad hoc approach). Poverty is also a factor of GDP as a category impact factor for the social pillar in improving the well-being of society (EUROSTAT, 2007). As this study aims to provide a comparable and adaptable framework, the poverty footprint was also included in the categorization of economic related indicators.

2.1.3. Social Sustainability

Environmental LCA measures the environmental outputs of the product system on human health not related to social issues. On the other hand, social sustainability is assumed as serious as environmental LCA (Sureau, 2020). Social sustainability is concerned with the welfare of stakeholders related to the social outputs of the product system. This approach provides a multidisciplinary approach for solving engineering problems.
Social sustainability, within the scope of corporate social responsibility, gives companies the responsibility to develop their business not only in terms of sustainable development but also in terms of improving the social conditions of stakeholders (Giannarakis et al., 2023). Business performance assessed in social responsibility developed in the 19th and 20th centuries (Macombe et al., 2013). Social corporate social responsibility was subsequently transformed into the Social Life Cycle Assessment Guidelines by SETAC and working groups of the United Nations (Benoit and Mazijn, 2009). However, it does not have an impact or results, as in social LCA (Macombe et al., 2013).

The nutrient content and health benefits of food products are topics studied under the social pillar of sustainability. For example, MW drying is determined to sustain nutrient content by up to 90% by reducing the duration of drying (Qu et al., 2022). Wiktor et al. (2021) studied the retention of bioactive compounds by changing the dryer. Moro et al. (2021) studied green methods of extraction to increase the retention of phenolic compounds. Another study focused on plant protein sources while using new drying technologies (Singh et al., 2020). Martínez-Castaño et al. (2020) and (Abu et al., 2021) attempted to increase public health by designing sustainable food processes and decreasing waste.

The social dimension in a product life cycle is defined as social impacts by Norris (2006) and was first introduced as the sustainability line by the Joint Research Center (JRC) in Ispra, Italy. However, it has been criticized that the subcategories of impact are not outcomes but rather static conditions such as child labor (Macombe et al., 2013). However, LCA is the best tool for promoting this engagement (Traverso et al., 2012), as it does not yield impacts or results as social LCA does (Macombe et al., 2013). There are two main types of impact assessments (Benoit & Mazijn, 2009). The first is the reference point scale, which allows the estimation of social risks at different levels of social performance. Registrations, standards, international instruments, or best practices set the thresholds. The second is a type of cause and effect chain that uses three main ways to achieve pathways: (Sureau et al., 2020) the first group of studies searches for new proper indicators that determine impacts; the second group validates the existing variables through experimental studies; and the last group of type II social LCAs uses known models for implementation.

Figure 2.3 shows another approach (Sureau, 2020) that considers the governance of product chains. She shows the environmental LCA with E-LCA, social with S-LCA and interconnections. In fact, health issues and monetary flows are interdependent themes.

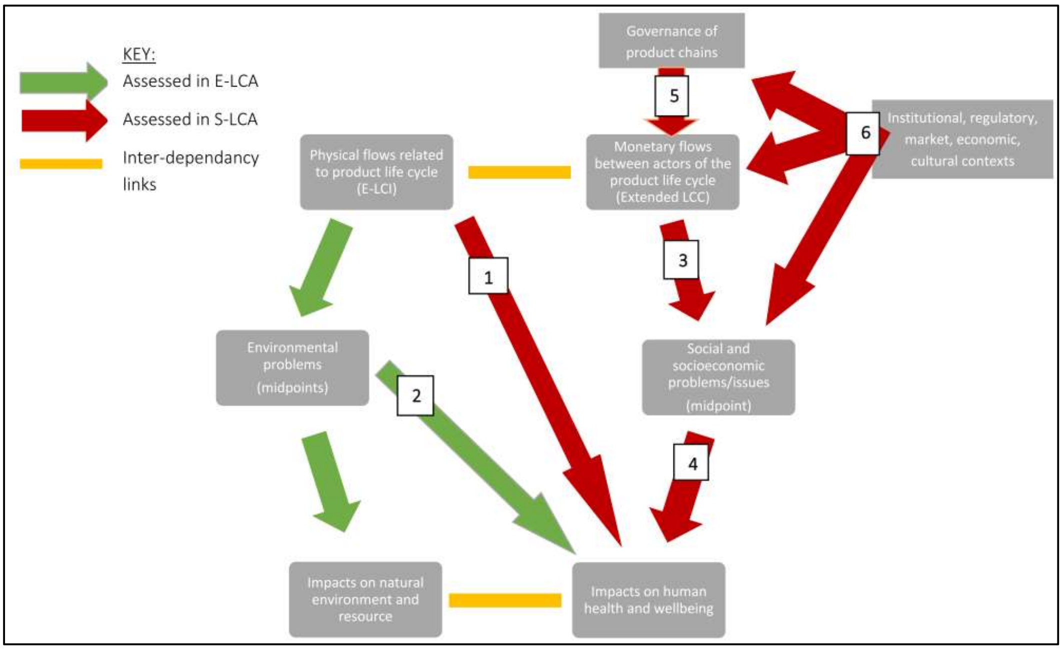

Figure 2.3. The Social LCA Approach of Sureau, (2020)

The stakeholder approach consists of the value chain actors in the UNEP Guidelines, as shown in Table 2.2. It has also been expanded to include more indicators and “children” stakeholder (UNEP, 2021).

Table 2.2. *Stakeholder Categories and Subcategories in the UNEP/SETAC Guidelines* (Benoit and Mazijn, (2009); UNEP, (2021))

Stakeholder categories	**Subcategories**
Stakeholder “worker”	Freedom of Association and Collective Bargaining Child Labor Fair Salary Working Hours Forced Labor Equal opportunities/Discrimination Health and Safety Social Benefits/Social Security
Stakeholder “consumer”	Health and Safety Feedback Mechanism Consumer Privacy Transparency End of life responsibility
Stakeholder “local community”	Access to material resources Access to immaterial resources Delocalization and Migration Cultural Heritage Safe & healthy living conditions Respect of indigenous rights Community engagement Local employment Secure living conditions
Stakeholder “society”	Public commitments to sustainability issues Contribution to economic development Prevention & mitigation of armed conflicts Technology development Corruption
Value chain actors (not including consumers)	Fair competition Promoting social responsibility Supplier relationships Respect of intellectual property rights

Social LCA is a method adapted from environmental LCA. However, it is not standardized or applied in food life cycles as it is for other products or processes. Therefore, how to assess and measure sustainability performance is still a question. In fact, each issue requires a thorough investigation throughout the steps of LCA. The Social Hotspots Database (SHDB) is a social assessment tool licensed in 2013 based on the type I of Reference Scale social LCA and is available to researchers as an inventory tool through OpenLCA, Sima Pro or separately via a website (Benoit-Norris et al., 2012).

The product social impact life cycle assessment (PSILCA) is also an alternative to SHDB. The SHDB consists of 57 sectors from different geographical regions of the world and, for each sector, an inventory that combines reports from institutions in 244 countries. The processes in the database are associated with economic factors for 13,908 unit processes. Using the SHDB, the geographical information of the product system and the sector needs to be identified with known activities (Benoit-Norris and Norris, 2015). SHDB has been adopted in the content analysis of the study Du et al. (2019), adding additional social dimensions to the existing ones by referring to the recommendations in Table 2.2 (Benoit and Mazijn, 2009). The database uses more than 200 references, including freedom of associations such as the World Bank, OECD, Labor Organization, FAO, and World Health Organization.

Social LCA is the only method for social assessment that is most consistently specific to sectors such as the food sector (Benoit-Norris et al., 2019). Inventory data are examined according to the basic flow of the product system once the country, purchased cost, and sector have been identified. In fact, risk changes can be shown by changing the sector and country of origin (*SHDB*, 2023). This model is based on imports and exports of goods and services between countries. In this way, the impact of a product system can reach deep into the supply chains of materials. Therefore, the impact assessment includes the effects of supply chain activities. During the social LCA, the characterization of social issues in Table 2.3 is performed by considering the risks in each subcategory, as given in Table A.1 in the Appendix A.

Table 2.3. *Impact Categories of the Social LCA Model in the SHDB*

(Benoit-Norris and Norris, 2015)

Labor rights and decent work	Health and safety	Human rights	Governance	Community infrastructure
· Child labor · Forced labor · Excessive · working time · Wage assessment · Poverty · Migrant labor · Freedom of association · Unemployment · Labor laws · Discrimination · Social Benefits	· Injuries and fatalities · Toxics and hazards	· Indigenous rights · High conflicts · Gender equity · Human health issues	· Legal systems · Corruptions	· Hospital beds · Drinking water · Sanitation · Children out of school · Smallholder vs. commercial farms

To quantify the social impact in Table 2.3 associated with product systems, the "medium risk hourly equivalents" (MRHE) metric is used. It provides a quantitative measure of the social risks associated with the different stages of a product's life cycle, from raw material to disposal (Benoit and Mazijn, 2009). MRHE is a measure of the indicative risk observed in worker hours in relation to the average (medium) risk of producing one USD of output of the assessed sector. By using MRHE in combination with the SHDB, organizations can identify and assess social risks and opportunities in their supply chains. This enables them to identify hotspots and prioritize areas for action in their policies.

There are various applications in social life cycle sustainability assessments. This approach is becoming more popular in the literature because of the benchmarking of firms in terms of the footprints of their products on the market. However, its applications in the food sector are very limited. The literature has been searched for social sustainability in peer-reviewed journals with the words social and issue (or impact, topic, indicator) and agriculture (or food, production, consumption). Publications were excluded if the standardized steps of the life cycle methodology were not applied, as in the inclusion criteria of Degieter et al. (2022). Studies that did not specify cradle-to-grave, system boundaries, or functional units were excluded. In these circumstances, few studies have assessed the social impact of food production systems (Sundin et al., 2023). In addition, only six papers on social LCA with an application on agri-food crops were selected as the best in a systematic literature review conducted between 2013 and 2019 (Arcese et al., 2023). Among these, none have a cradle-to-grave system boundary for a food system.

Social sustainability assessments in the food sector have mostly focused on harvesting and growing stages (Manik et al., 2013; Mulyasari et al., 2023; Thuayjan et al., 2022) and very few food sectors (Toussaint et al., 2022) due to the difficulty of analyzing whole food systems and the lack of a perspective that combines different stages and disciplines to create a solution. In the agri-food sector, one of the comprehensive studies examined sustainability in three dimensions of cattle systems (Zira et al., 2023). The authors exclude social issues when there is a lack of data or refer some of them to previous benchmarks of pig systems (Zira et al., 2020). Another social sustainability study provided results on welfare, health insurance, security, fair wages and job security and employment through social LCA on small-scale palm oil plantations and related stakeholders (Mulyasari et al., 2023). Luzzani et al. (2021) present a qualitative analysis and propose a framework for wine companies to sustain their production and management skills. By collecting data through surveys and interviews among wine companies, the authors selected cultural aspects, product quality aspects and health aspects in their purchasing practices and traceability. Unlike previous social dimensions, R&D expenditures and improvements are considered social criteria (Desiderio et al., 2022) or socioeconomic criteria contributing to GDP (EUROSTAT, 2007). Thus, practices in the food sector point to a gap in social sustainability. Mancini et al. (2023) state that social LCA is at a low maturity level compared to environmental LCA. There is no LCA-based application for the social dimension in the food sector. Social LCA can provide metrics at the product/process level, sector level and country level. In fact, social footprinting is also promoted in a corporate social LCA for the manufacturing sector (Benoit-Norris et al., 2019).

The agri-food sector is trying to implement and seek ways to achieve more sustainable transformation. For this purpose, sustainable production is one way, but the assessment of impact and the identification and resolution of problems increase sustainability in the value chain (Arcese et al., 2023). In this respect, the prominent social problems are the use of child labor in agricultural production, working hours, and the health and safety of workers.

2.2. The Three-Pillar Approach of Sustainability

As a conceptual approach, the three-pillar method consisting of environmental, economic and social performance dimensions is calculated by a summation (Kloepffer, 2008) . In fact, it is another perception of the people, planet and prosperity context (Benoit and Mazijn, 2009). In this approach, environmental sustainability is evaluated via LCA. Economic sustainability is assessed by the LCC. Finally, social LCA is applied.

Life Cycle Sustainability Analysis=ELCA+LCC+Social LCA

Sureau, (2020) mentions the limitations of the theoretical background under this formula. Combined applications of LCC-LCA to food products can be performed by conducting separate analyses by accounting for monetary aspects in inventory activities or by combining a database with the same system boundary (Gulisano et al., 2018). However, due to the consistency issues of integration, the authors state that there is a greater need for economic performance related to environmental issues. This study attempts to overcome the challenge of integrating economic and environmental conjoint assessments.

In this study, the environmental, economic, and social pillars of sustainability are integrated by the methods of MCDA to obtain a unique sustainability score. This score gives the sustainability measure not the risks as in the ELCA, LCC and Social LCA. The relations between the pillars are constructed by the weights of the criteria and the normalization scheme of the methods.

2.3. Sustainability of a Food Value Chain

The European Green Deal focuses on the sustainability of European food through an integrated approach that addresses all activities of food chains (Riccaboni et al., 2021). Food value chains are a complicated set of integrated and discrete actors (de Vriesi et al., 2023). Understanding the value chain allows a precise diagram of actors and flows to be drawn. The following are suggested considerations (Macombe et al., 2013):

i. Each stage in the value chain should respond to a singular task.
ii. Different activities carried out by the same actor are separated into stages.
iii. The defined stages should describe the activities actually observed.
iv. All companies at each stage of the value chain should be accounted for and characterized according to identical objectives and benchmarks.

A review of 139 articles on food and agricultural value chains revealed that digitalization is most prevalent in the meat and vegetable chains in Africa and Europe (de Vriesi et al., 2023). They also argue for the significance of digitalization in bringing trust between actors to focus on tangible value chains. Researchers and food sector actors are working on adding value to the agri-food value chain. In this context, Cucagna and Goldsmith (2018) examine the marketing margin concept as value addition considering modern customer demands and estimate the economic value for 454 firms. Thus, food value chains are examined in terms of where value should be added. Sustainability is a way of doing this value addition. The food value chain shown as an example in Figure 2.4 is a fundamental component of agricultural productivity. Although it is recommended to increase (Zainol and Aik, 2021) production, there are risks to the natural environment and resources due to sustainability issues. Thus, in the case of increasing agricultural productivity, the nutritional content should be enhanced under the global problems of climate change (Dagys et al., 2023). In another study, they found that increasing vitamin, phenolic, and carotenoid levels increased antioxidant activity through the valorization of byproducts after processing and storage (Araújo-Rodrigues et al., 2021).

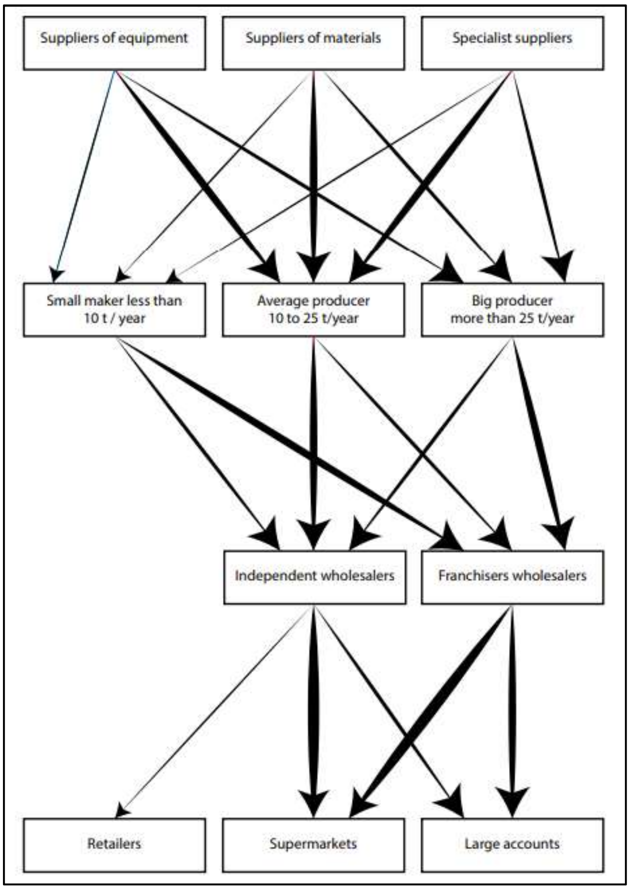

Figure 2.4. An Example of a Value Chain (Macombe et al., 2013)

The actors in food value chains in Figure 2.4 are defined as innovation providers and change makers: farmers, food processors (including packaging and transportation), retailers, and wholesalers, food advisors, consumers, policy makers and researchers (Riccaboni et al., 2021). In this study, the activities of farmers included sustainable practices on farms, digitalization, and applications that lessened soil usage. For food production, the food value chain can be sustained by the production of food waste, a circular economy, and the development of new products that protect good raw materials.

2.4. Sustainable Development Goals (SDGs) Approach

The United Nations in the 2030 Agenda presented the SDG targets for Sustainable Development. Since then, 17 goals have been monitored, with targets within each one. The most relevant goal in terms of sustainability is SDG 12, sustainable consumption and production. Thus, the SDGs also provide a perspective on the sustainability of food systems on both the demand and supply sides.

The first SDG is related to poverty reduction. In fact, poverty is considered within the socioeconomic dimension of sustainability. SDG 2 is about zero hunger. It promotes the localization of production while reducing agricultural food waste and losses. SDG 3, which concerns children's education, is also important in terms of sustainability indicators. Sustainability as infrastructure needs to be built with infrastructure dimensions.

Gender equality is strengthened in SDG 5. Therefore, all processes and activities should promote gender equality to ensure that girls and women have the same rights. Any activity that violates gender equality along the life cycle chain should be avoided. In this case, the design of activities should be modified. SDG 6 on clean water and sanitation is also related to infrastructure readiness for sustainability. SDG 7 asks about the energy intensity of activities. All processes should therefore be measured in terms of energy burden.

Furthermore, under socioeconomic themes, the employment subcategory is related to SDG 8, defined as "Decent Work and Economic Growth” as it has targets such as productive employment and the proportion of unemployed youth. In addition, target 8.8 is also targeted, which is related to socioeconomic criteria. This target relates to labor rights and the safety of working conditions.

Sustainability contributes to the development of many SDGs, both directly and indirectly. In detail, sustainability includes not only monetary but also healthy human well-being conditions. It thus contributes to supporting SDG 3 "Health and Well-being", SDG 8 "Decent Work and Economic Growth", SDG 9 "Industry, Innovation and Infrastructure" and SDG 11 "Sustainable Cities and Communities".

SDG 9 Industry, Innovation, and Infrastructure expect funding processes to be carried out in a way that includes and strengthens infrastructure investments, especially in developing countries. In this sense, strengthening infrastructure investments will increase sustainability.

SDG 13 climate change is directly related to the question of cause and effect on sustainability. However, in the life cycle, burdens are placed on the production of emissions from raw material production to waste disposal. This triggers climate change. On the other hand, there are negative consequences of the natural phenomena associated with climate change, which are reflected in processes from raw material scarcity in production to transportational difficulties. Global warming, which is particularly related to the environmental dimension, also causes economic collapses.

SDG 14 aims to achieve environmental sustainability by reducing plastic waste in the ocean and seas. In this way, it aims to protect the natural environment and preserve biodiversity. At the same time, it aims to reduce the dangers that can be transferred to humans by considering marine resources as natural resources and considering the life chain of living things in the sea in terms of toxicity.

SDG 15 Life on Land aims to prevent the loss of green spaces to agriculture or settlements. It is a goal to monitor and mitigate the increasing risks associated with deforestation, referred to as land to change. This goal is mostly considered under the environmental dimension of sustainability.

SDG 16 is a goal that recalls human rights and is pursued because wars and coups restrict people's fundamental rights, putting human wellbeing at risk of social sustainability.

As a result, sustainability assessment can be performed either qualitatively by considering the targets under the SDG targets or quantitatively by measuring the targets. When food life cycle processes are considered, the SDGs are primarily sustainable consumption and production and, environmentally, climate change, life below water, life on land, sustainable cities and communities, industrial infrastructure, and clean energy. Economic and social assessments can be grouped as no poverty, quality in education, sanitation, gender equality, human rights, decent work, and reduced inequalities.

2.5. The Contribution of the Study

The sustainability assessment of each product is unique in its definition of objectives and scope, with differences in the system boundary, functional unit, defined criteria, and inventory for impact criteria (Goedkoop et al., 2013). This study is novel in terms of novel tomato products, system boundaries, and inventory data for the assessment of environmental, economic, and social pillars.

1. The studies in the literature give the classical method of determining the footprints of products. This research provides a more comprehensive assessment with a broader set of criteria in the environmental, economic and social dimensions. In this research, not only sustainability performances were evaluated, but also their scores were calculated. The TOPSIS and SAW

methods of MCDA were first used to calculate the sustainability scores for benchmarking in the Food Technologies field.

2. No study has addressed the sustainability of three environmental, economic and social dimensions with the cradle-to-market life cycle boundary of novel tomato products. The system boundary has been kept as wide as possible and is limited not only by the production phase (gate-to-gate boundary) but also by the production of raw materials, packaging, transportation, and distribution phases (cradle-to-market). The model also allows for ranking overall sustainability scores in the selection of products.

3. In fact, only 3% of sustainability studies have been found to address the economic dimension (Onat et al., 2017). This economic assessment model of this dissertation has defined economic analysis by comprehensive impact categories measured by life cycle themes of socioeconomic issues. Although the SHDB is a standard way of calculating social assessment, there are some gaps in the integration links between social criteria and the economic dimension that need further study (Sureau et al., 2018, 2020). In this thesis, the social categories identified from the SHDB (Benoit-Norris et al., 2019) and the categories derived from the food system of dried tomato products were combined to rank an economic sustainability score.

4. Although there is a link between environmental LCA and environmental LCC, there is not much linking authority between social LCA and LCC. Although this link has been studied previously with the criteria of investment inputs, the performance outputs of socioeconomic factors are not considered (Yang et al., 2024). Thus, in addition to enhancing economic assessment, this study presents a business investment decision-making model with economic and environmental outputs. To define sustainability and assess it by smart tools considering stakeholders and activities at the micro and macro scale, research has also been conducted (Davis et al., 2022). Unlike previous studies, this model uses and clusters the SHDB (Benoit-Norris et al., 2019)

for economic analysis. The set of appropriate economic impact categories also consists not only of costs but also of global and physical measures that contribute to GDP.

5. Swarr et al. (2011) proposed an environmental LCC approach based on LCA, specifying the purpose and definition, cost inventory, cost assessment and interpretation of the LCA steps. In addition, the author proposed costs directly in the product life cycle (Ciroth et al., 2011). However, the allocation procedure is not suitable for the method of Swarr et al. (2011), unlike standardized environmental LCA. In this method of economic assessment, allocation also becomes possible and appropriate if loads in the base stream have to be assigned as reuse for byproducts.

6. As a further contribution, an AHP survey was conducted to determine the importance of weights among impact categories in the environmental, economic and social dimensions. It also considers the relevance of the criteria using a mathematical weighting method. Thus, the model brings us closer to a definitive conclusion. The social LCA model also includes stakeholder effects. Thus, the linkages between the criteria were also considered in the assessment. The prioritization of the criteria is also meaningful for future work in the selection of impact categories.

CHAPTER 3

SUSTAINABILITY ASSESSMENT OF NOVEL TOMATO PRODUCTS

In this study, a complete LCA procedure was performed for the environmental, economic, and social pillars. The methodological steps are illustrated in Figure 3.1. The LCA stages of ISO 14040:2006 (ISO, 2006) are as follows: (i) objective and scope definition, (ii) obtaining the social inventory, (iii) social impact assessment and (iv) interpretation of results. The interpretation step is explained in the results section. AHP and MCDA methods are used for fostering the model and integration of the impact categories.

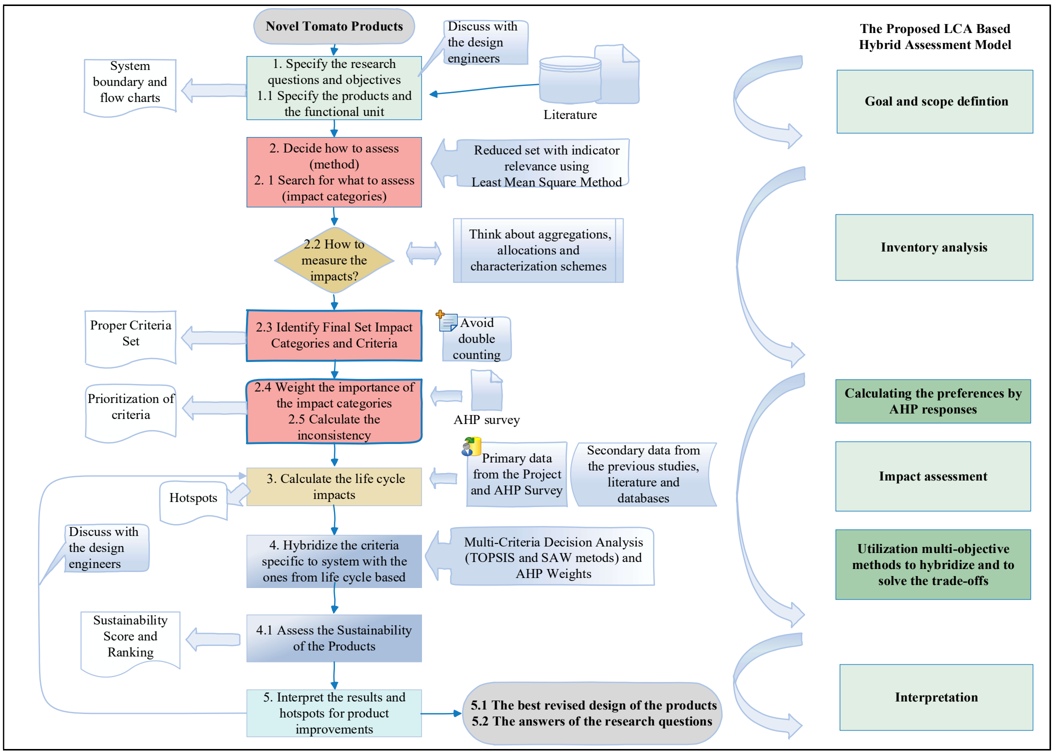

Figure 3.1. Methodological Steps of the Proposed Sustainability Framework

3.1. MATERIALS

The product specifications compared in terms of sustainability were obtained from the work packages of the FunTomP Project as shown in Table 3.1. The tomato products are the dried tomato leathers and the dried tomato bars. The tomato bars were produced according to Gul et al. (2023), and the tomato leaves were produced according to Basdemir et al. (2024). Tomato bars were dried by conventional dryer. While a conventional dryer does not provide good nutrition, it can sustain nutritional preservation. A microwave vacuum dryer was also utilized in addition to a conventional dryer for production due to its greater nutrient preservation, faster operation and lower energy cost. As a novel technology, a microwave vacuum oven (commonly referred to as a microwave) is an electric oven that heats and cooks food by exposing it to electromagnetic radiation in the microwave frequency range. Its operation procedure is not complex. The procedure involves (i) inserting the sample into a vacuum chamber, (ii) lowering the pressure inside the chamber with a vacuum pump, (iii) applying microwaves via a motor drive, (iv) monitoring the process parameters with a control box, and finally (v) cooling the system with a chiller and refrigeration system. When the freeze dryer fasts for up to fifteen hours, MW vacuum decreases this time to minutes.

The products were enriched in pea protein (PP) and rubisco protein (R), which were extracted by Akyüz et al. (2023). Fresh tomato (*Solanum lycopersicum*), tomato pulp and tomato pomace were supplied from Kraft Heinz Gıda (Balıkesir, Türkiye). Pea protein isolates were supplied from Vegrano® (Istanbul, Türkiye). Olive powder was produced according to the procedure of Argun (2022). Mint and salt were purchased from a local market. All chemical components were obtained from Merck (Germany).

Table 3.1. *Description of the Compared Tomato Products*

Products		Product Features
Tomato Leather 1 (R_Tray_Leather)	A1	Tray dryer is used Enriched with rubisco protein
Tomato Leather 2 (PP_Tray_Leather)	A2	Tray dryer is used Enriched with pea protein
Tomato Bar 1 (R_MW_Bar)	A3	MW vacuum dryer is used Enriched with rubisco protein
Tomato Bar 2 (PP_MW_Bar)	A4	MW vacuum dryer is used Enriched with pea protein
Tomato Bar 3 (R_Conv_Bar)	A5	Conventional air dryer is used Enriched with rubisco protein
Tomato Bar 4 (PP_Conv_Bar)	A6	Conventional air dryer is used Enriched with pea protein

To measure the social sustainability of dried tomato products along the cradle-to-market (farm to fork) food value chain, appropriate criteria and indicators related to subcriteria are modeled. The measurements in economic and social dimensions have been modeled as criteria using LCA (macro level) and product-specific criteria (micro level). The hybrid approach was then integrated into the overall score using AHP weightings and two different multicriteria decision analysis methods.

During data processing for the environmental dimension, the Ecoinvent Database (Wernet et al., 2016) was used to obtain an inventory assessment for the environmental impact categories. All assessments were calculated according to the functional unit of the product system. Allocation issues and aggregations among indicators have been identified. The environmental assessment was performed by the "ReCiPe 2016 Endpoint (H) V1.06 Method". For the economic sustainability assessment, the cost of products was calculated by using the Preliminary Estimate Method (Peters et al., 2003) in chemical engineering economics. The other impact criteria of the economic dimension and the macro level social criteria were assessed by the "Social Hotspot 2019 Subcat & Cat Method w Damages/Equalsubcatweights" method from the SHDB (Benoit-Norris and Norris, 2015). The inventory for primary data was created during the work packages of the ongoing FunTomP as mentioned before. All inventory tables were generated, and MCDA calculations were performed in Excel. Since the SHDB requires the input data USD in 2011, prices were converted from 2024 to 2011 with a deflator factor of 1.39 (U.S. Bureau of Labor Statistics, 2024) as shown in Figure C.1 in Appendix C. For industrial use, the electricity price is assumed to be 3.46 Turkish liras/kWh (Enerji Atlası, 2024) as shown in Figure D.1 in Appendix D. The dollar exchange rate is assumed to be fixed at 30 TRYs per dollar in calculations.

3.2. METHODS

The LCA procedure was applied for the environmental, economic and social dimensions of sustainability in addition to determining overall sustainability. Thus, the target and scope definitions, inventory analysis, impact assessment and interpretation of the results are described in environmental, economic and social terms, respectively. One of the main points of LCA is that the system boundary is mostly similar so that economic, social or environmental LCA can be solved consistently (Kloepffer, 2008). This may not be the same because there are some costs in the economic pillar, such as research and development, which are not included in environmental impact (UNEP, 2020).

The life cycle assessment for each pillar should be carried out in the same functional unit to compare the impact of different process activities and raw materials over the entire life cycle. In terms of the environmental inventory, the data for damage to human health are in DALYs (disability-adjusted life years); for the natural environment, the data for the species, year and resources are in USD in 2013. In addition, for the economic assessment, the SHDB provides an inventory on the number of medium risk hours equivalent (MRHE).

3.2.1. Environmental Sustainability Assessment

Sustainability assessment in food systems searches for ways to determine the responsible means of production and consumption. In this section, the method for environmental assessment is explained.

3.2.1.1. Goal and Scope Definition

The purpose of conducting an environmental sustainability assessment is to provide product information by comparing product alternatives, to identify burdens in product life cycles that need to be addressed through product innovation, and to provide a framework for manufacturers or researchers to use LCA. The aim of this study is to identify the main environmental outcomes or hotspots in the supply chain of dried tomato products, thus overcoming the risks highlighted during the design phase. In this way, environmentally friendly methods of production, transportation and packaging, which are in line with the farm-to-fork strategy and the European Commission's Green Deal, should be investigated.

The purpose of this study is defined for target groups or interested parties (as specified in the ISO standard). Conscious consumers are the target group for achieving more sustainable food products in their diet. As a Mediterranean diet, tomatoes are an important part of a sustainable diet for providing information during product choices. Therefore, increasing the consumption of dried tomato products will be possible by addressing the challenges in consumption and production in terms of the environmental, economic, and social parameters of sustainability.

For designers, the results were used for iterative solutions of revised product design scenarios to achieve more sustainable products. During product development, the impact of materials and processes on the environment is considered to improve the environmental profile of the food system.

For producers, the results are also expected to guide producers to achieve deeper supply chains with more beneficial impacts for stakeholders. In addition, more information is provided to support innovation in relation to sustainability aspects.

For public authorities, the results of environmental burdens can be used for marketing authorization or environmental taxation.

The system boundary for the LCA, which determines the depth of the study, defines the economic and environmental inputs and outputs with the system boundary, as shown in Figure 3.2.

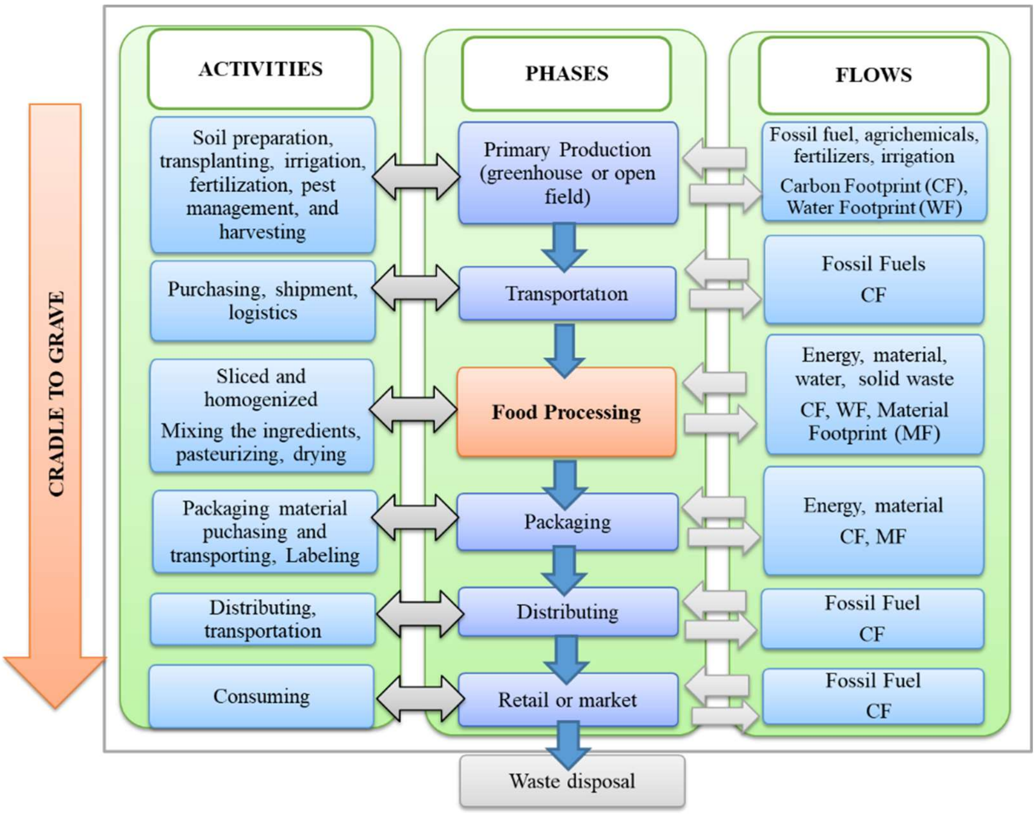

Figure 3.2. The System Boundary of the Environmental Assessment

According to the system boundary, the following steps are involved during the environmental assessment:

- Primary production: Raw materials are estimated together with deeper supply chains in the calculation of material flows.

- Packaging: transportation of packaging materials, manufacturing of materials

- Dried tomato production: production of ingredients, water and energy used in production;

- Distribution: transportation of fresh tomatoes to the factory; transportation of finished products from the factory to the markets

- Food loss and waste: Tomato residue and sugar beet leaf, as byproducts, are allocated to the base streams. During the experimental setup, twenty percent of the tomatoes were seen as residue. Twenty-five percent of sugar beet is allocated to sugar beet leaves (Spagnuolo et al., 1997).

- Waste disposal: The disposal of household waste is not included.

3.2.1.2. Environmental Inventory Analysis

Inventory analysis is the study of product life cycle interactions with the environment. Using the cradle-to-market product system, inventory analysis is performed for the functional unit of products. The functional evaluation unit is taken as one unit of product production for six products. This means 45 grams of tomato bar and 17 grams of tomato leather. This information is gathered from the output of the ongoing project of Functionalized Tomato Products (FunTomP). An inventory from the Ecoinvent database (Wernet et al., 2016) and the appropriate set of environmental impact categories for the dried tomato food system were established by using the ReCiPe method. The inventory tables were constructed according to the process flows in Figure 3.3 and Figure 3.4.

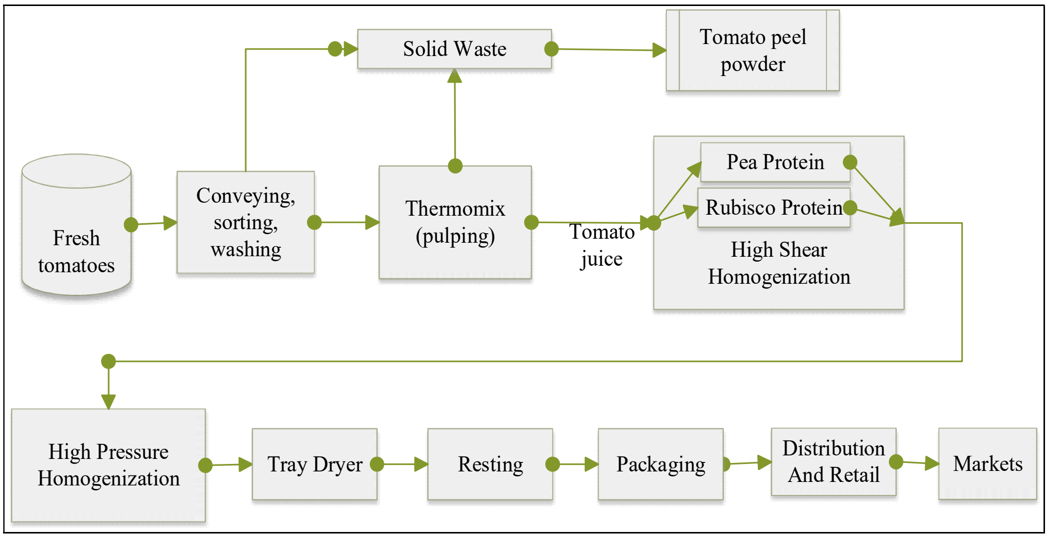

Figure 3.3. Process Flow of the Dried Tomato Leather

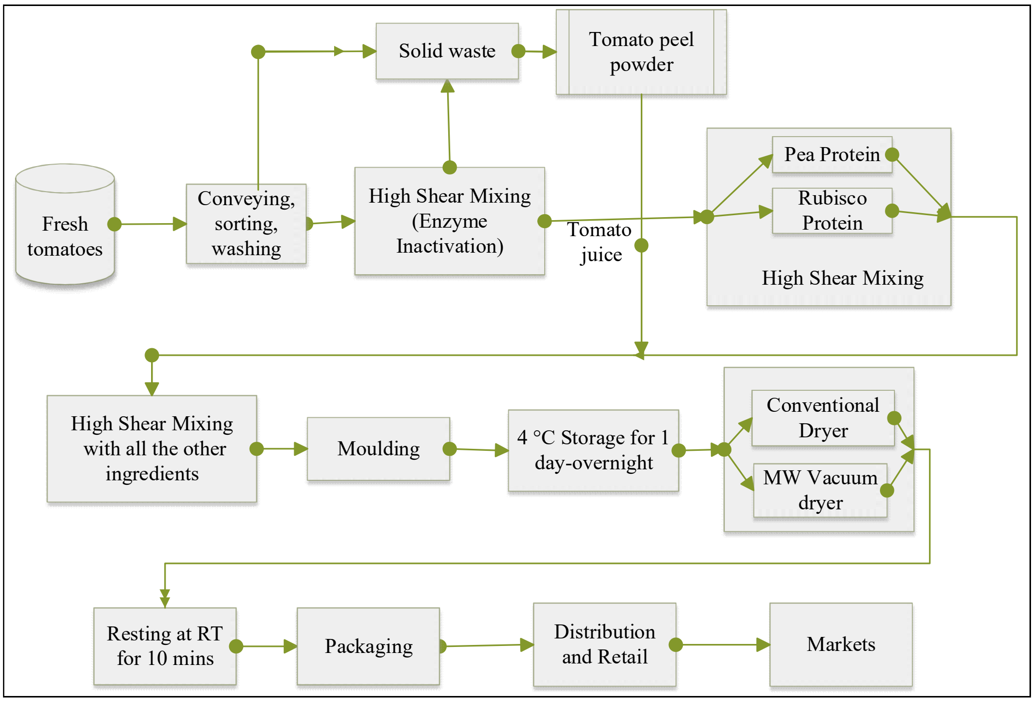

Figure 3.4. Process Flow of the Dried Tomato Bar

After considering allocations and characterizations by functional unit (inventory procedure), an inventory table for each product was created for environmental data interventions entering and leaving the environmental system. All the raw materials, total energy used, process activities and parameters are included in the inventory table. Environmental loads resulting from process activities such as the extraction of raw materials and emissions associated with related products. Radiation, noise, sources, toxicity, heat, etc., are considered.

Since all waste is used during production, none is taken to the waste management unit. When the output of one process is a material input to another process, the allocation should be calculated. The life cycles of Rubisco protein production and olive powder production were also calculated. For the transport inventory, freight is given by truck 7.5-16 metric tons in the Ecoinvent database (Wernet et al., 2016). For 10 tons of trucks traveling at 90 km/h, 0.287 liters of fuel per kilometer are reported (Roy et al., 2007). For fresh tomatoes, the transport distance is assumed to be 75 kilometers from farm to factory, which is double the distance of a truck traveling from the factory and back; for processed products, a distance of approximately 500 kilometers from the factory to the retailer is assumed (Wohner et al., 2020; Karakaya & Özilgen, 2011). All the packaging materials are considered biodegradable polylactic acid, which is extracted from sugar beet for use in packaging (Karakaya & Özilgen, 2011). Then, the next step for impact assessment is applied according to the classification of the environmental impact of the ReCiPe method in the Ecoinvent database.

3.2.1.3. Environmental Impact Assessment

The ReCiPe method (Huijbregts et al., 2017) uses three criteria, damage to human health, damage to the natural environment and damage to natural resources, to determine the environmental footprint (i.e., impact category), as shown in Figure 3.5.

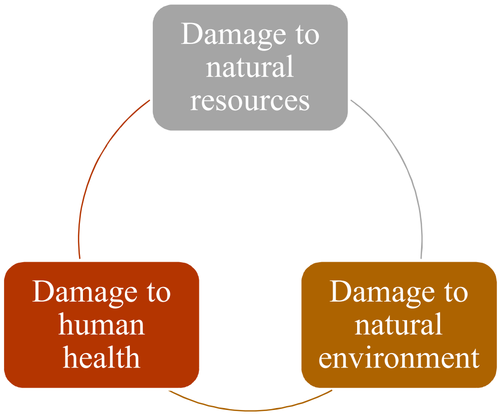

Figure 3.5. Impact categories of the ReCiPe method (Huijbregts et al., 2017)

This method assesses the potential environmental footprint (impact category) by considering three protected areas (criteria) of damage to human health, damage to the natural environment, and damage to natural resources. The classification factors were taken from the Ecoinvent database shown in Table 3.2.

Table 3.2. *ReCiPe Method's Impact Criteria* (Huijbregts et al., 2017)

Midpoint Impact Criteria of the ReCiPe Method	
1. Global warming	10. Terrestrial ecotoxicity
2. Stratospheric ozone depletion	11. Freshwater ecotoxicity
3. Ionizing radiation	12. Marine ecotoxicity
4. Ozone formation, human health	13. Human carcinogenic toxicity
5. Fine particulate matter formation	14. Human non carcinogenic toxicity
6. Ozone formation, terrestrial ecosystems	15. Land use
7. Terrestrial acidification	16. Mineral resource scarcity
8. Freshwater eutrophication	17. Fossil resource scarcity
9. Marine eutrophication	18. Water consumption

The impact of the 18 environmental criteria was determined by multiplying the classification factors by the contribution of the functional unit of the process to the environmental problems for each activity. Thus, for the environmental footprint, the environmental profiles and impact categories in Table 3.3 were created.

Table 3.3. *Impact Categories and Subcategories of the Environmental Model*

Impact Category	**Impact Subcategories (SC)**	**Key References**
Environmental Footprint	Damage to Human Health (SC1)	The ReCiPe LCA Method in the Ecoinvent Database (Huijbregts et al., 2017; Netherlands National Institute for Public Health and the Environment, 2017)
	Damage to Natural Environment (SC2)	
	Damage to Natural Resources (SC3)	

3.2.2. Economic Sustainability Assessment

To construct the economic sustainability model, the LCA procedure is followed by enhancing the LCC with the life cycle themes.

3.2.2.1. Goal and Scope Definition

The system boundary for economic assessment is given in Figure 3.6. The product alternatives and the functional units are the same as those used for the environmental assessment.

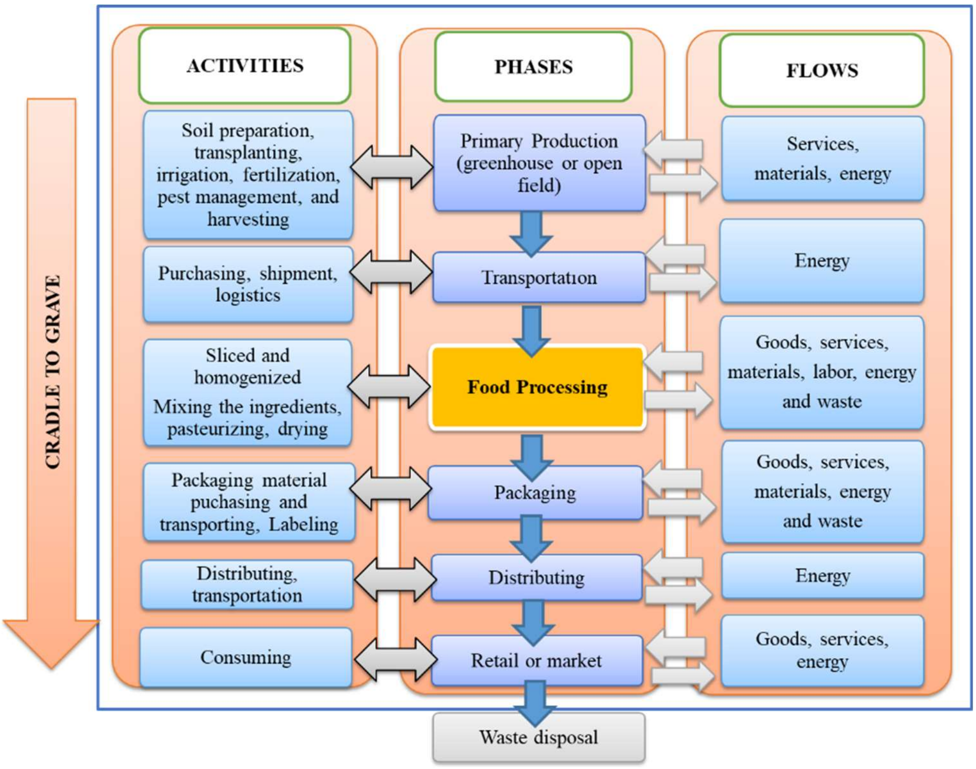

Figure 3.6. The System Boundary of the Economic Sustainability Assessment

3.2.2.2. Economic Inventory Analysis

During the inventory analysis, preliminary data on processes, materials, and flows were obtained from design engineers as primary data. Thus, information on deeper supply chains has been obtained from product designers, tomato production facilities (Kraft Heinz, Balıkesir) and packaging companies (İSPAK, Ankara).

To gather the inventory for each step in the food supply chain, the region of inputs in the economic inventories in the SHDB (Macombe et al., 2013) should be indicated by sector, region and cost.This means that the economic impact for the macro level impact categories depends on the specifications shown in Table 3.4.

Table 3.4. *Sector and Region Analysis of Inventory Data*

Inventory	Sector in the SHDB	Region
Fresh tomato	Vegetables, fruit, nuts	Türkiye
Low methoxyl pectin	Chemical, rubber, plastic products	France
Green olive to produce olive powder	Vegetable oils and fats	Türkiye
Sugar beet leaves to produce rubisco protein	Sugarcane, sugar beet	Türkiye
Tomato pomace	Vegetables, fruit, nuts	Türkiye
Salt	Mineral products nec	Türkiye
Pea protein	Food products nec	China
Chemical ingredients	Chemical, rubber, plastic products	Germany
Pectinase enzyme	Chemical, rubber, plastic products	Denmark
Salt	Mineral products nec	Türkiye
Mint, thyme, red pepper	Food products nec	Türkiye
Compostable packaging material	Chemical, rubber, plastic products	Italy
Energy for processes	Energy	Türkiye
Transportation	Transport	Türkiye

3.2.2.3. Economic Impact Assessment

The economic impact assessment was performed not only calculating the cost of the life cycle but also global criteria for economic indicators. The cost criteria were calculated from the sum of the total capital investment and total production cost (Peters et al., 2003) according to the cost per functional unit in the inventory table.

As mentioned in Ciroth et al. (2011), time was ignored in the previous LCA-based LCC method (Swarr et al., 2011). This approach provides the advantage of less complexity in cost calculations. Since the proposed economic assessment is an LCA-based approach, the economic assessment does not need to consider the time value of costs through discounting, as in the environmental LCC procedure.

The economic assessment is summarized from the first step to the impact assessment under the circumstances in Table 3.5.

Table 3.5. *Proposed Economic Model in the Characteristics of LCC based on the* Degieter et al. (2022)

Goal	To calculate the economic impact of designed tomato food system
Scope	To compare different production scenarios for identified stakeholder categories
Functional Unit	45 grams for tomato snack bar, 17 grams for tomato leather
System Boundary	Cradle to market
Stakeholders (Interested parties)	farmer, employers (local community), consumers and society
Phases	Entire food value chain approach is selected with multiple phases according to the goal and focus of the study
Externalities	Double counting is prevented when selecting indicators in two pillars of sustainability
Revenues	In the proposed method, cash flows were not anticipated since the price is unknown.
Type of Costs	The cost calculation was done by Preliminary Estimate Method (Peters et al., 2003) by considering all the investment and production costs from raw material to consumer in retail shown in Table E.1 in Appendix E.

Table 3.5. *Proposed Economic Model in the Characteristics of LCC based on the* Degieter et al. (2022) *(cont'd)*

Data	The impact category "Economic feasibility" is achieved by cost calculation. SHDB is used for impact categories of economic dimension. The Ecoinvent database is utilized for environmental impact.
Weighting	AHP weighting is done for categories after doing a survey with a set of credible experts as shown in Table B.1 in Appendix B (Saaty, 1990; Saaty and Vargas, 2013)
Integration-Normalization	Integration of the impact categories from economic and environmental dimensions are done with the TOPSIS and SAW multi-criteria methods
Sensitivity Analysis	Performed in the iterative nature of LCA after achieving the first results of the impact
Interest	As the proposed economic assessment is an LCA-based approach, the economic assessment does not need to consider the time value of costs through discounting as in the environmental LCC procedure. As mentioned previously (Swarr et al., 2011) in the LCA-based LCC method (Ciroth et al., 2011), time value is ignored. This will provide the advantage of less complexity in cost calculations.

3.2.2.4. Relating Life Cycle Criteria with Economic Sustainability

The methodology aims to incorporate macro level categories into the model to extend the concept of economic analysis. The product-level cost criterion exists in the LCC model. However, macro or global-level categories are sought to integrate the proposed economic model. With the key references in Table 3.6, three impact subcategories were measured by the eight criteria.

Table 3.6. *Impact Subcategories and Criteria Identified in the Proposed Economic Sustainability Model*

Impact Category	**Impact Subcategory (SC)**	**Criteria (C)**	**Key References**
Economic Footprint	Economic feasibility and affordability (SC1)	Cost of the Product (C1) Total capital investment (C1.1) Total production cost (C1.2)	(Timonen et al., 2017) (Hunkeler et al., 2008) (Blanchard and Fabrycky, 1998a) (Gharsallah et al., 2021)
	Prosperity generation (SC2)	Smallholder vs. Commercial farms (C2) Poverty (C3) Legal system (C4)	(Benoit-Norris and Norris, 2015) (Oxfam International, 2008)
	Labor productivity (SC3)	Wage assessment (C5) Injuries and fatalities (C6) Occ. toxicity and hazards (C7) Social benefits (C8)	(Benoit-Norris and Norris, 2015) (Gharsallah et al., 2021) (EUROSTAT, 2007)

1. Economic Feasibility and Affordability: In this model, the “Economic Feasibility and Affordability” category was calculated by Preliminary Cost Estimation (Peters et al., 2003) as in Table E.1 in Appendix E. The economic impact is related to the cost of investment and production, as seen in the first manifestation of the system (Timonen et al., 2017). Blanchard and Fabrycky (1998a, 2014) also refer to LCC as design for affordability. In addition, they express affordability as profitability. This indicator contributes to GDP as a long-term investment in the LCC literature (Degieter et al., 2022; De Menna et al., 2018;Ciroth et al., 2011; Hunkeler et al., 2008; Gluch and Baumann, 2004; Li et al., 2018; Neugebauer et al., 2016). To analyze the resilience of the food system, price and income are also considered socioeconomic factors (Seekell et al., 2017).

2. Prosperity Generation: The local economy is used as an economic indicator in Sustainability Assessment of Food and Agriculture (SAFA) systems and Response-inducing Sustainability Evaluation (RISE) methods (Gharsallah et al., 2021) supplementary data). In addition, the Indicateurs de Durabilité des Exploitations Agricoles (IDEA) approach assesses economic sustainability using national minimum legal wages (Gharsallah et al., 2021).

3. Labor productivity: Labor productivity is seen as a factor for economic prosperity by increasing competitiveness in economic activities and GDP (EUROSTAT, 2007). Labor productivity criteria are also used in the economic dimension of the Sustainable Rice Platform (SRP) methodology and performance indicators and the Monitoring Tool for Integrated Farm Sustainability (MOTIFS) (Gharsallah et al., 2021). Since the upward trend in employment contributes to GDP growth, an increase in labor productivity is likely to affect employment both qualitatively and quantitatively. For stable employment, an increase in GDP indicates an increase in labor productivity. Since GDP growth is the main factor for a country's economic development, labor productivity is defined as one of the impact categories. To measure economic sustainability, annual income per worker, as an agricultural factor, is an indicator of labor productivity by the European Commission (2019). As labor productivity increases with good economic performance, environmental impacts such as global warming potential also increase (Thomassen et al., 2009). This trade-off or positive correlation can be solved by a multicriteria objective method. Higher labor productivity also implies less use of machinery, which is another correlation to be solved. Thus, labor activity is added to the economic indicators to determine its contribution to GDP and its correlation with environmental impact.

The category criteria of “property generation” and “labor productivity” are quantified by socioeconomic elements from the SHDB (Benoit-Norris and Norris, 2012; 2015), as shown in Figure 3.8. The health-related criterion of the SHDB is not included to avoid double counting with the human health factor, which already has a criterion for environmental impact. These characterizations of social issues are the risks in the SHDB in Table A.1 in Appendix A., which are categorized differently than the proposed social model.

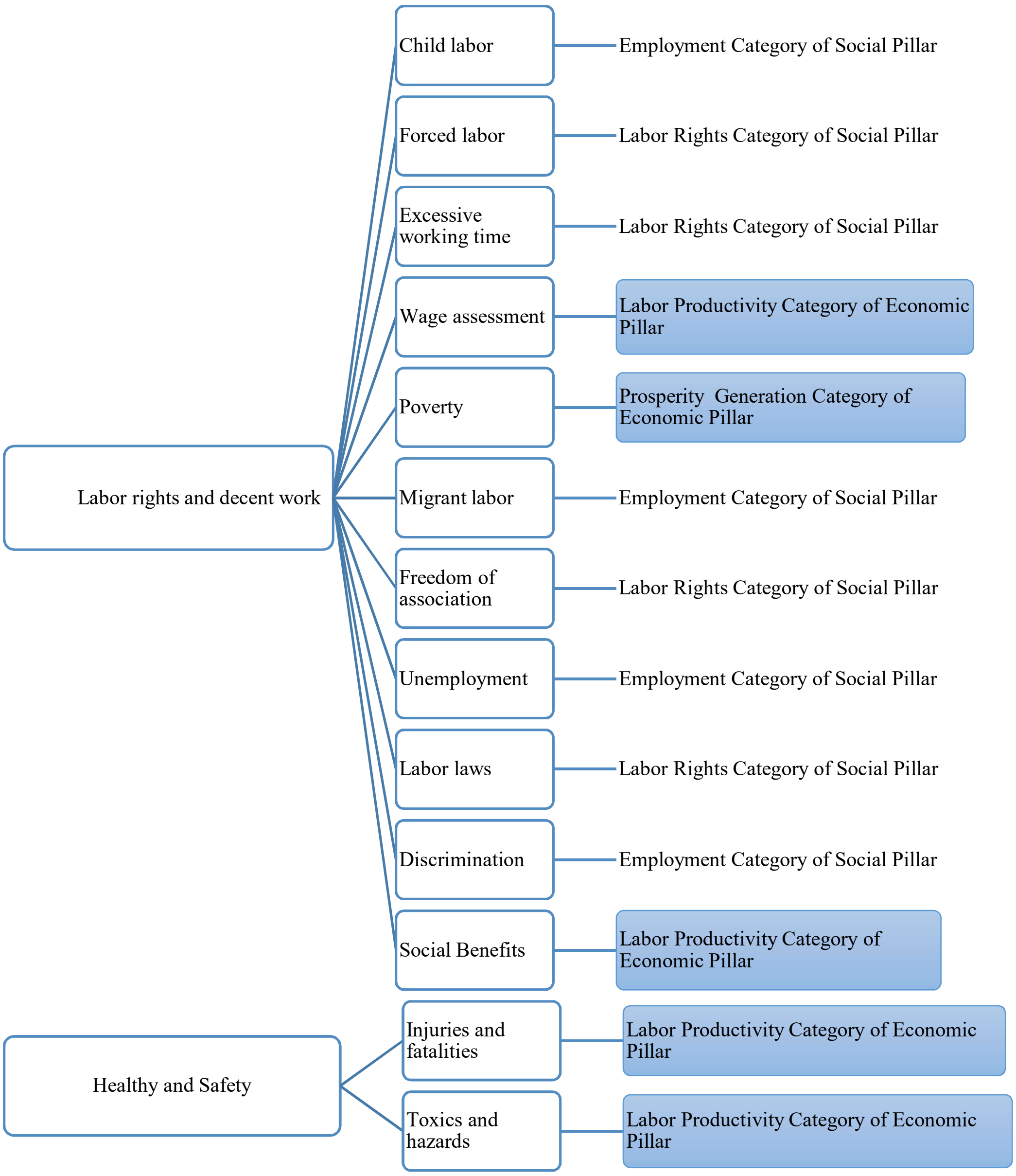

Figure 3.7. Criteria Set in the Economic Model Retrieved from the Social LCA Model of Benoit-Norris and Norris, (2015).

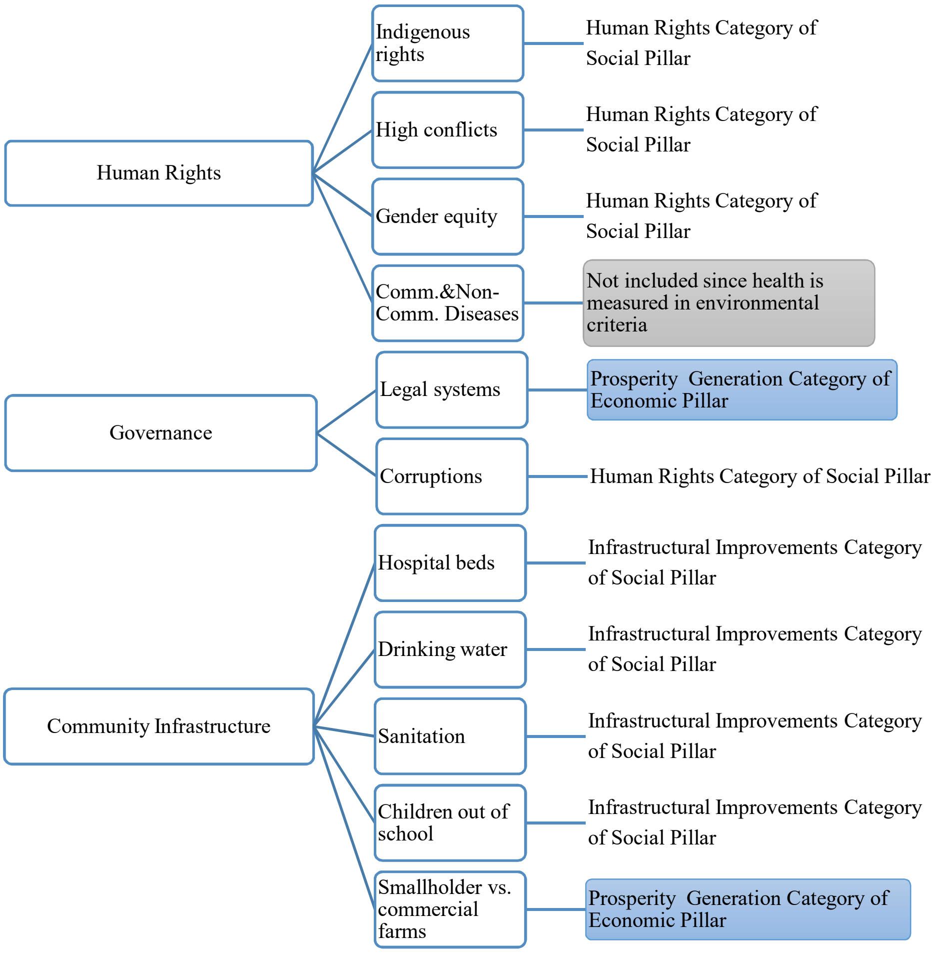

Figure 3.7. Criteria Set in the Economic Model Retrieved from the Social LCA Model of Benoit-Norris and Norris, (2015) (cont'd)

Some of them are used in economic measures, as shown in blue. The others are left as they are in social aspects. The impact categories defined as economic feasibility are characterized by the cost of the product, three criteria for poverty production, and four criteria for labor productivity, as shown in Figure 3.8.

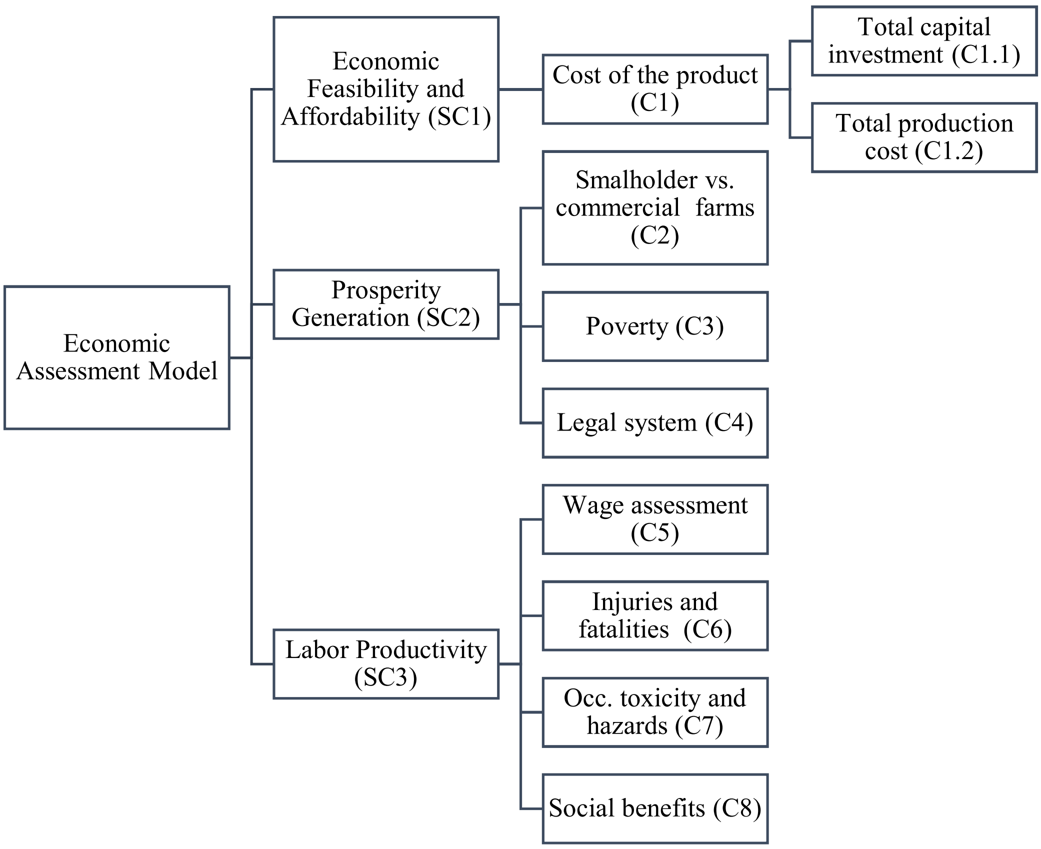

Figure 3.8. The Subcategories and Criteria of the Economic Assessment Model

3.2.3. Social Sustainability Assessment

3.2.3.1. Goal and Scope Definition

Food product design is expected not only to put less pressure on the Earth but also to minimize social consequences if there is a risk and maximize if there is a benefit. Thus, the social performance of the designed food products should also be prioritized. This study aims to rank the social performance of designed food products. As the design of food products is expected to put less pressure on the environment, the social aspects of the design are intended to minimize the risk and maximize the benefit. The results are publicly available for the use of comparative arguments. The target audience for sharing the results is also the project members who design the products and adjust the system requirements to achieve the most sustainable solutions. This process can serve as an example for food companies trying to create a social policy engagement strategy, as they try to select the final product from different product designs. Moreover, this assessment facilitates this by highlighting social hotspots that enable the management of social risks in addition to achieving results that contribute to the process.

The system boundary of the case study is highlighted in Figure 3.9, showing stakeholders along the food value chain from primary production to consumption.

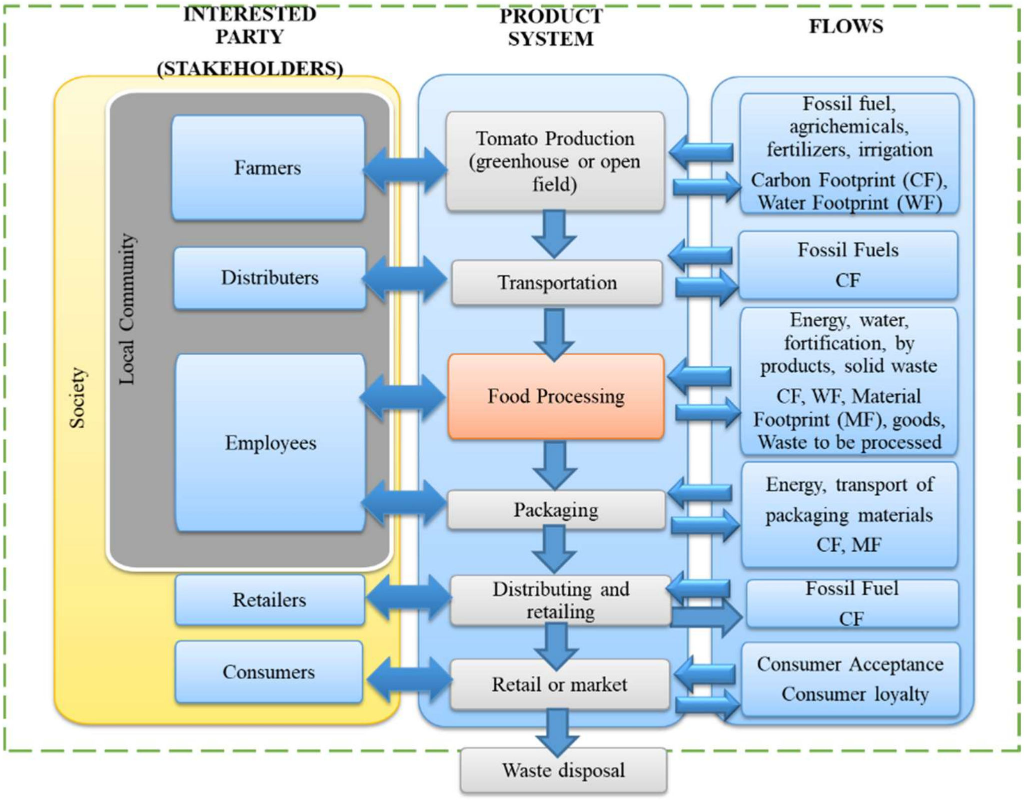

Figure 3.9. The System Boundary for Social Sustainability Assessment

The system boundary has become a combination of multiple stages in the food value chain. Since the aim of the study is the evaluation of products and the food system, the system boundary extends from primary production to the end user, the consumer. If the aim was to compare only the sustainability of drying technology, a gate-to-gate approach could be applied, where the system boundary only includes food production. However, this study aimed to determine the total life cycle and its impact on economic, social and environmental impact categories. Since the aim is not only to compare the sustainability of drying technology but also to compare all activities from primary production to those of the end user, the consumer, a cradle-to-market boundary, has been applied. Thus, the boundary is drawn only by ignoring waste disposal in households.

3.2.3.2. Social Inventory Analysis

The social inventory of criteria from the SHDB is measured by the functional unit. The results per functioning of the life cycle show that the impact is increased and decreased by the functional unit. During the calculations, the functional unit was considered, and 17 grams of tomato leather product and 45 grams of tomato bar product were obtained. In environmental LCA, the correlation is linear with the amount of material and energy used for life cycle activities. However, the social assessment of SHDB does not provide specific product data (Ekener-Petersen et al., 2014). Therefore, the response in terms of social dimensions can be proportional or static. For example, the benefits to research and innovation capacity and sensory analysis criteria are product-specific but cannot be operationalized. As the additional criteria are not life cycle-based (such as static data), the proposed model provides a hybrid-based assessment with the integration of multicriteria decision-making methods.

The foreground information on materials and process activities is collected from design engineers. The energy used and the costs of inputs in addition to recycling allocations are calculated. The relationships between elements in the product system and flows such as materials, energy, and waste are modeled to describe the life cycles of the activities. This analysis was performed using the reference scale (SHDB) (Benoit-Norris et al., 2012). In addition to the inventory of materials, the inventory of processes has also been considered. The distribution of raw materials (from farms or warehouses to the facility) and finished products from the facility to retail is estimated in kilometers (Wohner et al., 2020; Karakaya and Özilgen, 2011). Not only processes and packaging but also food allocations are considered. For example, tomato waste has been separated into tomato powder in inventory analysis.

During inventory analysis, for each step in the food supply chain, the locations of inputs and outputs should be specified sectorally, regionally and internationally for each product (Macombe et al., 2013). For each step in the food supply chain, the region of the entries for each product under comparison should be specified by sector and nation, as shown in Table 3.7.

Table 3.7. *Sector and Region of the Inventory in Social Analysis*

Inventory	**Selected Sector in the SHDB/Region**
Pea protein isolate	Food products nec/China
Chemical ingredients for Rubisco protein	Food products nec/Germany
Mint, thyme, red pepper	Food products nec/Türkiye
Salt	Mineral products nec/Türkiye
Sugar beet for Rubisco Protein production	Sugarcane, sugar beet/Türkiye
Green olives for olive powder production	Vegetable oils and fats/Türkiye
Tomato and tomato pomace	Vegetables, fruit, nuts/Türkiye
Water	Water/Türkiye
Chemicals in Rubisco protein Production	Chemical, rubber, plastic products/Germany
Low Methoxyl Pectin	Food products nec/France
Pectinase enzyme	Chemical, rubber, plastic products/Denmark
Biodegradable packaging material	Chemical, rubber, plastic products/Italy
Processes	Electricity/Türkiye
Transportation	Transport nec/Türkiye

All the raw materials and processes with total energy used, process activities and parameters are included in the inventory table for use in calculations at the impact assessment step. Since all waste is used during production, none is taken to the waste management unit. For the transport inventory, freight is given by trucks (7.5-16 metric tons). For 10 tons of trucks traveling at 90 km/h, 0.287 liters of fuel per kilometer are reported (Roy et al., 2007). The transport distance is assumed to be 75 kilometers from farm to factory, which is double the distance of a truck traveling from the factory and back. For processed products, a distance of approximately 500 kilometers from the factory to the retailer is assumed. Biodegradable polylactic acid, which is extracted from sugar beet for use in packaging, was selected as the packaging material (Karakaya and Özilgen, 2011). Once the data are collected, an inventory table is used to process it during calculations to create appropriate graphical visualizations.

3.2.3.3. Social Impact Assessment

In this step, the objectives and scope are presented, the process design is determined, and inventory data are explored. This stage is used for the assessment criteria. While constructing a proper criteria set and framework to assess a comprehensive social LCA, it is advised to select the criteria that are significant for stakeholders, integrate them into the product/process system and provide perspectives on causes and impacts. (Sureau et al., 2018) In this stage, a suitable set of social criteria is identified from the literature recommendations and the preferences of expert groups according to the AHP survey. The predetermined set of criteria, combined with the Sustainable Development Goals (Desiderio et al., 2022; Sundin et al., 2023), indicators of sustainability goals (Backes and Traverso, 2022; United Nations, 2023) and the results of Toussaint et al. (2022), are very informative for determining inclusion in the model. In addition, the main literature on the social life cycle (Norris, 2006 ; Benoit-Norris et al., 2019) and sustainability reporting guidelines (Giannarakis et al., 2023; UNEP, 2020) is utilized.

Three endpoint impacts, seven impact subcategories and 21 criteria (attributes) have been recognized along the food chain according to ISO 14044:2006, with key references in Table 3.8.

Table 3.8. *Deployment of Social Impact Categories, Subcategories and Criteria with Key References*

Impact Category (IC)	**Impact Subcategory (SC)**	**Criteria (C)**	**Key References**
Workers/ Employers (IC1)	Employment (SC1)	Unemployment (C1) Discrimination (C2) Migrant labor (C3) Child labor (C4)	(Benoit-Norris et al., 2014) (Benoit and Mazijn, 2009) (S. Wang et al., 2022) (Navarro et al., 2018) (Sierra et al., 2017)
	Labor Rights (SC2)	Forced labor (C5) Excessive working time (C6) Freedom of association (C7) Labor laws (C8)	(Benoit-Norris et al., 2014) (Abu et al., 2021) (Maxim, 2014) (J. Wang et al., 2009)
Consumers (IC2)	Sensory Satisfaction (SC3)	Sensory analysis (C9)	(Abu et al., 2021)
	Nutritional Quality (SC4)	Total phenolic compound and flavonoid content (C10) DPPH antioxidant Activity (C11) Protein content (C12)	(Lacirignola et al., 2012) (Moro et al., 2021) (Martínez-Castaño et al., 2020) (Sundin et al., 2023) (Araújo-Rodrigues et al., 2021) (Singh et al., 2020)

Table 3.8. *Deployment of Social Impact Categories, Subcategories and Criteria with Key References (cont'd)*

Impact Category (IC)	Impact Subcategory (SC)	Criteria (C)	Key References
Society (IC3)	Benefits to research innovation capacity (SC5)	Research and innovation outputs (C13)	(Desiderio et al., 2022) (UNEP, 2020)
	Infrastructural Improvements (SC6)	Access to drinking water (C14) Access to sanitation (C15) Children out of school (C16) Access to hospital beds (C17)	(Benoit-Norris et al., 2014)
	Human Rights (SC7)	Gender equity (C18), Indigenous rights (C19), High conflicts (C20), Corruption (C21)	(Benoit-Norris et al., 2014)

Social criteria for which no data were available in the case study were excluded. The appropriateness of the criteria was tested with the least mean square (LMS) method. When the performance of the alternatives is almost identical, the criterion is removed from the list of criteria, even though it is important. For example, in dried food products, the water activity of the products is almost identical and has been excluded from the criteria set. Stakeholders affected by the impact of the dried tomato product food value chain were identified as the endpoint impact category.

In the proposed social performance model, the consumer category has been constructed solely about the product. Its characterization is related to product utility, both in terms of sensory and nutritional analysis. Moreover, in the context of community stakeholders, the data related to the criterion "benefit to research and innovation capacity" are also product specific. It is characterized by the number of outputs, such as articles published in FunTomP, patents, papers, posters, and dissemination activities related to the supply chain of the individual product. The macro level impact criteria are taken from the characterization topics in the SHDB and are differentially categorized in this study. These characterizations of social issues are the risks in the SHDB, as defined in Table A.1 in Appendix A, which are categorized differently in this model.

Employment: This category of impact is highly relevant to the Guide to Social Life Cycle Assessment (Benoit and Mazijn, 2009). The Indicateurs de Durabilité des Exploitations Agricoles (IDEA) approach also assesses social sustainability through contributions to employment (Gharsallah et al., 2021). Van Ittersum et al. (2008) also use agricultural employment criteria in their assessment. Discriminatory employment is used by Alipour et al. (2018) as an indicator of social assessment. Unemployment, migrant labor, and child labor are themes in the "Workers' Rights and Decent Work" (Benoit-Norris et al., 2014). The Sustainable Rice Platform (SRP) methodology proposes child labor as an indicator of social sustainability. As a result, unemployment, discrimination, gender equality, child labor and migrant labor, which are all considered to be related to employment, are included in this factor.

Labor rights: The social LCA (Benoit-Norris et al., 2014) model incorporates a separate "Labor Rights and Decent Work" in its category. Its approach also includes labor rights in its social assessment model (supplementary material of Gharsallah et al., 2021). Antunes et al. (2017) refer to the hours of work as labor rights in their holistic social assessment model. In this study, forced labor, excessive working hours, participation in freedom of association, and labor laws are all considered to capture labor rights.

Product utility: Product utility is defined as the perception of the consumer in addition to the functionality of the product (UNEP, 2020). The Indicateurs de Durabilité des Exploitations Agricoles (IDEA) uses product quality criteria within a social sustainability approach (supplementary material of Gharsallah et al., 2021). Product utility is set as the criterion for the consumer impact category. First, sensory analysis performed by a professional company was included as an indicator of consumer acceptance. Second, nutritional content was assessed as part of the product benefit. Among the product-based criteria, DPPH antioxidant activity, which was determined in the FunTomP work packages, was compared. The antioxidant capacity of the human body is protected from cancer due to ascorbic acid and phenols (Gómez-Romero et al., 2007). The total phenolic content and flavonoid content can vary according to the drying process, as temperature and time are important for degradation after adding olive powder as the raw material. Due to the added vegetable protein, the protein content also increased in the ideal product design. Since the products are dry, food safety risks do not seem to be important in this model, as they are previously added at the farm level (Rasul and Thapa, 2004).

Benefit to research and innovation capacity: Research, innovation and knowledge outcomes have been quantified by considering the life cycle of the Functionalized Tomato Products Project (FunTomP). Named "research criterion" in the review article of social LCA (Desiderio et al., 2022) and "technology development" in the Guidelines for Social LCA (UNEP, 2020), this criterion has been additionally included in the model.

The data used in the model for product utility are given in Table 3.9. The sensory score was obtained from the analysis of Seluz Fragrance and Flavor (Istanbul, Türkiye), which is a partner of FunTomP. The nutrient content of the products was analyzed by project work packages. Research and innovation achievements for each product have been considered the deliverables and outputs in the ongoing FunTomP related to each product.

Table 3.9. *Product-Specific Parameters of the Social Dimension*

Products	Sensory Score	Sum of TPC and Flavonoids after Normalization	DPPH (EC_{50} mg/ml)	Protein content (%)	Research Innovation Performance Score
A1	2.75	0.144	1.431	0.493	20
A2	3.50	0.169	1.803	0.493	14
A3	2.20	0.489	0.460	0.781	19
A4	2.80	0.326	0.670	7.813	16
A5	2.75	0.487	0.600	0.781	19
A6	3.50	0.385	0.630	7.813	14

Infrastructural improvements: This impact subcategory aims to embed infrastructure arising from product supply chains into the social model. Access to drinking water, access to sanitation, children out of school, and access to hospital beds are infrastructure related criteria already covered in the SHDB model. Van Ittersum et al. (2008) also employ "social infrastructures and services" criteria to quantify infrastructure improvements in their suggested evaluation of agricultural systems.

Human Rights: It is assumed that the risk of corruption negatively affects all social groups and prevents the risk to human rights from increasing (UN Human Rights, n.d.). Equity is also considered within the social concept of sustainability (Rasul and Thapa, 2004). Antunes et al. (2017) used gender equity in the social viability of irrigated agriculture systems. This category is organized according to the themes of gender equality, indigenous rights, high conflict, and corruption already presented by the SHDB.

Thus, 3 endpoint impacts (stakeholders are at the end of the chain of cause and effect resulting from impact), 7 impact subcategories and 21 criteria (states of attributes) are combined to assess the social sustainability model in Figure 3.10.

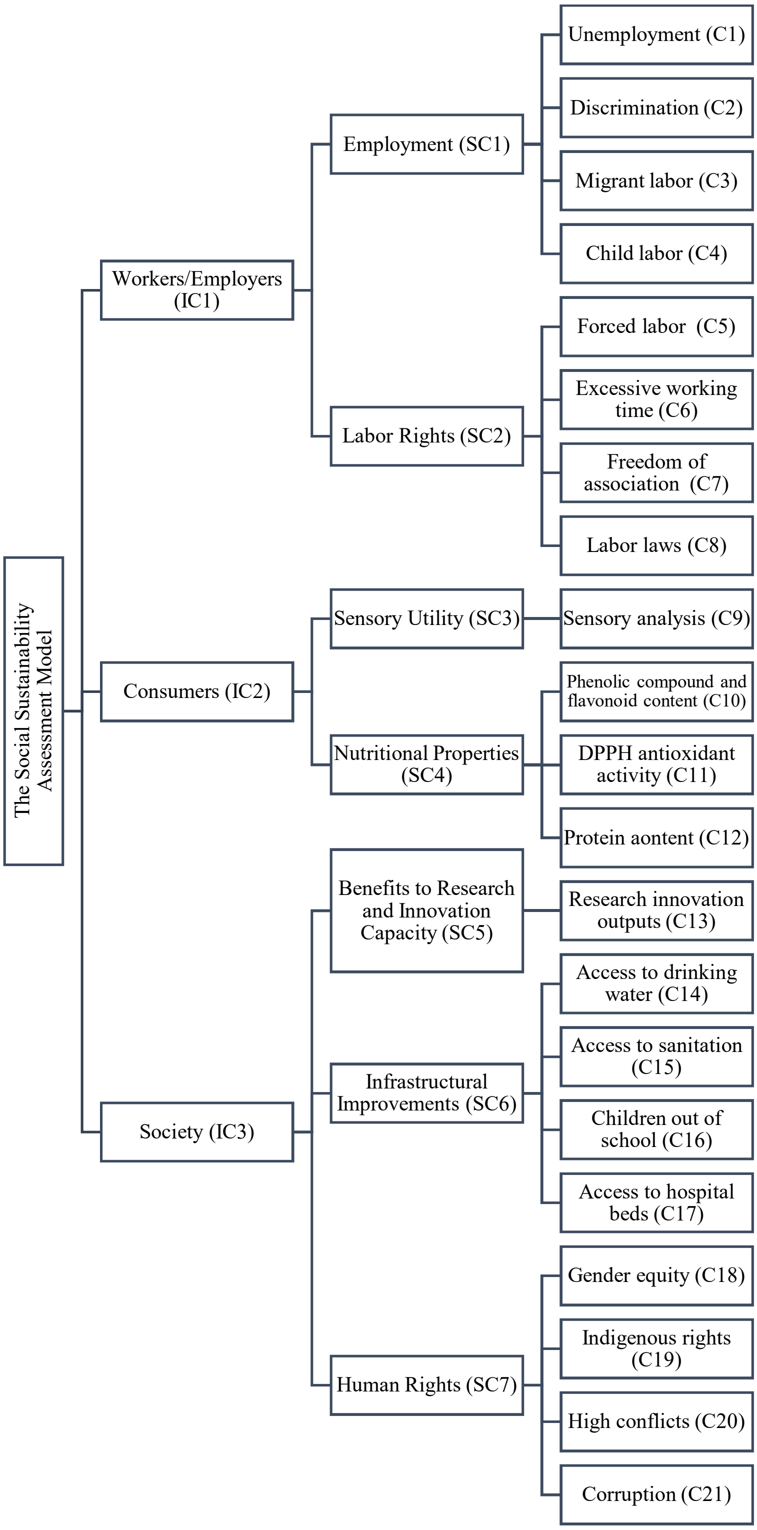

Figure 3.10. The Impact Categories and Criteria of the Proposed Social Sustainability Model

3.2.4. The Analytic Hierarchy Process (AHP) and Multi-Criteria Decision Analysis (MCDA)

In this study, the assessment model is evaluated across three pillars, under which each of the impact categories and subcategories are considered. The AHP questionnaire and experts' priorities are useful for ranking sustainability. The weights can also form a hierarchy of priorities in terms of criteria (Saaty, 1990; Saaty and Vargas, 2013).

The problem is that there is an invariant number of criteria, and when comparing the choice, the alternative products or the choice is not uniform in all criteria. However, there are a number of objectives with different attributes and trade-offs. For example, while employment increases social sustainability, it does not guarantee very good labor rights. Since there are micro level criteria in addition to macro level criteria taken from the SHDB, they are hybridized with TOPSIS and SAW multicriteria decision analysis methods. Multicriteria decision analysis can be used in various applications, such as project selection, classification, and ranking problems.

3.2.4.1. AHP Survey

The AHP is a well-established tool for prioritizing criteria (Winston, 2003). This allows us to compare alternatives in pairs and select the most superior alternative (Saaty, 1990). At least eight experts should be selected for the AHP method (Sierra et al., 2017). The AHP questionnaire was administered by interviews with eleven experts in this study. Credible experts, according to the information on expertise, experience and effort in Table 3.10, answered the survey. The information about the experts is given in Table B.1 in Appendix B.

In this method, the criteria are compared in pairs on a scale of “1=Equally Important”, “3=Moderately Important”, “5=Strongly Important”, “7=Very Strongly Important”, and “9=Extremely Important” (Saaty, 1990; Saaty and Vargas, 2013).

Table 3.10. *Defining and Selecting the Experts for the AHP Survey*

Specifications	**Options**
1. Gender	F/M
2. Education	BS, MS, PhD
3. Working	U: University, I: Private-Industry, R: Research Center, F: Food Plant P: Public Institution
4. Professional	1: Social science, 2: Biology/Chemistry, 3: Environmental or Civil Eng., 4: Economy, 5: Health, 6: Food or Chemical Eng., 7: Sustainability
5. Professional experience (must be at least 5 years)	Years; 5-10; 10-15; 15-20; 20-25; 25-
6. Author of peer-reviewed journal articles	Yes/No (Y/N)
7. Invited to speak at a conference	Yes/No (Y/N)
8. A proceeding or poster in a sustainability conference	Yes/No (Y/N)

Prioritization is performed by weighting the three impact categories and their subcategories. Weights for the impact categories and subcategories are determined by the questionnaire. To obtain experts' opinions, the criteria (dimensions) were compared pairwise through face-to-face surveys, as shown in Table 3.11 and Table 3.12.

Table 3.11. *AHP Questionnaire for Environmental and Economic Performance Scores*

Environmental Pillar			Economic Pillar		
"Damage to Human Health"	versus	"Damage to Natural Environment"	"Economic Feasibility and Affordability"	versus	"Prosperity Generation"
"Damage to Human Health"	versus	"Damage to Natural Resources"	"Economic Feasibility and Affordability"	versus	"Labor Productivity"
"Damage to Natural Environment"	versus	"Damage to Natural Resources"	"Prosperity Generation"	versus	"Labor Productivity"

Table 3.12. *AHP Questionnaire for Social Performance Score*

Pairwise Comparisons for Social Pillar		
"Employer/Worker"	versus	"Consumer"
"Employer/Worker"	versus	"Society"
"Consumer"	versus	"Society"
"Employment"	versus	"Labor Rights"
"Sensory Satisfaction"	versus	"Nutrient Content"
"Benefits to Research and Innovation Capacity"	versus	"Infrastructural Improvements"
"Benefits to Research and Innovation Capacity"	versus	"Human Rights"
"Infrastructural Improvements"	versus	"Human Rights"

The relative importance of the sustainability dimensions was also calculated, as shown in Table 3.13, so that the final weights could be calculated by the specific weight under each pillar.

Table 3.13. *AHP Questionnaire for Overall Performance Score*

Pairwise Comparisons		
"Environmental Pillar"	versus	"Economic Pillar"
"Environmental Pillar"	versus	"Social Pillar"
"Economic Pillar"	versus	"Social Pillar"

The relative importance of the experts is also assumed equal. The criteria under each impact subcategory are assumed to have equal importance. The criteria are assumed independent in terms of organizational type, which is found to affect sustainable development goals such as no poverty (Heriyati et al., 2024). Thus, when there is more than one criterion, the weights of the related impact subcategories are equally shared. The results of the questionnaire were verified by calculating the consistency index; if the expert's consistency index was not appropriate, the expert reviewed the decision first, and if the inconsistency was high, the data were discarded. An index less than or equal to 0.10 indicates that the expert is consistent in their pairwise comparisons. Otherwise, the expert chose the criteria randomly or without reflecting on his/her judgment. If the inconsistencies in an expert's judgments are too high, the expert could revise his/her judgment. Depending on the inconsistency rate, it can be subtracted from the geometric mean (Forman and Peniwati, 1998).

3.2.4.2. Multi-Criteria Decision Analysis (MCDA)

Given that the problem has a fixed number of criteria, the criteria are not uniform when comparing alternative products or choices. For example, when working overtime increases, it does not guarantee that employment will increase. The comparisons of sustainability in the model involve trade-offs among the criteria, as shown in Figure 3.11.

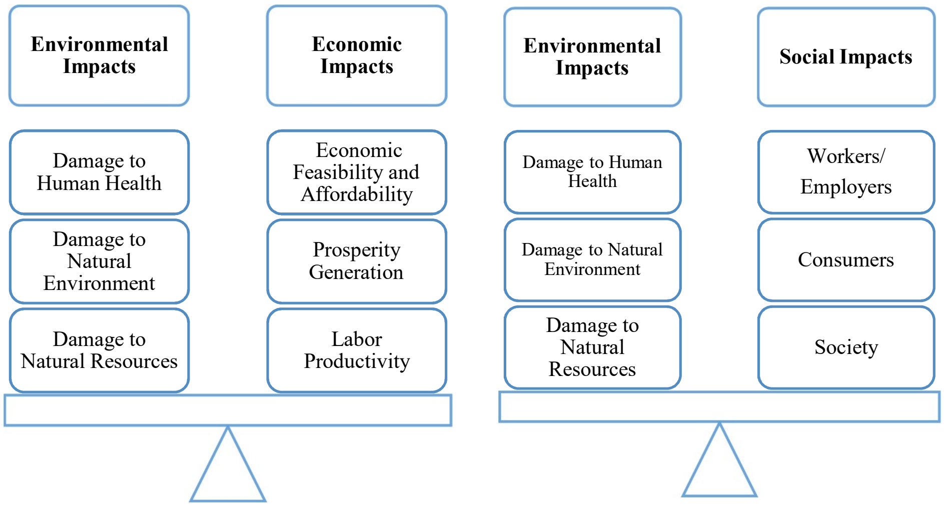

Figure 3.11. Trade-off between Sustainability Pillars

The environmental impact categories are the risks that should be minimized. In addition to the cost criterion, all criteria of the economic dimension are minimized to increase sustainability. Since economic inventory is given as medium risk hours in SHDB, these need to be minimized in addition to the cost criterion to increase sustainability. Among the social impact criteria, there are both risky and beneficial (maximized) criteria. In this study, a model for the social sustainability assessment of a food value chain was created considering stakeholders and a number of different criteria.

The MCDA algorithm is used when comparing electricity generation technologies (Maxim, 2014), packaging materials (Niero and Kalbar, 2019; Wohner et al., 2020), and modern construction methods (Sánchez-Garrido et al., 2022). Zarghami and Szidarovszky (2011) provide the solution of a goal (a level of achievement) in alternatives using criteria.

In this study, there was no best (or dominant) dried tomato product for the 32 criteria of the overall sustainability model. Selection and ranking problems have been solved by structuring the problem as a multicriteria decision matrix. The decision is to find non dominated alternatives (Pareto optimal) in the multidimensional space. There are no dried tomato products that are the best (or dominant) among all the criteria. In fact, many criteria imply a multidimensional space. The optimal solution is a very difficult procedure based on the priorities or weights given to the different criteria. Therefore, it is necessary to determine the weights. In this study, weights were determined by pairwise comparisons using the AHP questionnaire as calculated in the previous section.

TOPSIS Method

In this study, the ranking of alternatives to achieve the sustainability objective is calculated with both TOPSIS and SAW. TOPSIS and SAW are two selected methods in terms of performance among 56 different multicriteria methods (Wątróbski et al., 2019). TOPSIS uses the distance to the ideal solutions, similar to other multicriteria decision methods of VIKOR, while the SAW and COPRAS methods use the scoring approach (Sánchez-Garrido et al., 2022). The authors considered the relative importance assigned to each MCDA method with benefits and disadvantages to utilize them in the field of construction building technology. They achieved performances of 52% for the TOPSIS method, 26% for the COPRAS method, 9% for the VIKOR method, and 4% for the SAW method, which are similar to the performances of (Zavadskas et al., 2016).

Normalization during the scoring scheme is different for each method. In TOPSIS, the performance score is obtained by calculating the proximity to the best (benefit) and worst (risk) solutions, while in SAW, the score for each product is calculated by summing each row. Uncertainty not directly given by the SHDB is handled by the TOPSIS procedure by providing ranges to specify model attributes (Durbach and Stewart, 2012; Wieckowski and Salabun, 2020).

TOPSIS evaluates alternatives (products) after calculating the Euclidean distances of an alternative to the ideal (for maximized criteria) and anti-ideal (for minimized criteria) solutions, as depicted in Figure 3.12. It is preferred when comparing alternative multicriteria methods in sustainability applications such as electricity generation technologies (Maxim, 2014), packaging materials (Niero and Kalbar, 2019; Wohner et al., 2020), and modern construction methods (Sánchez-Garrido et al., 2022).

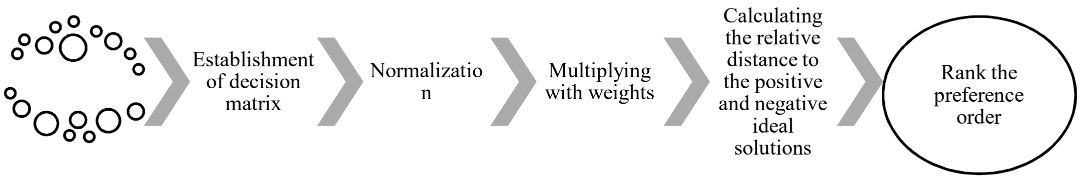

Figure 3.12. Procedure of the TOPSIS Algorithm (Sánchez-Lozano et al., 2013)

It is a listing of the product alternatives (A) to the criteria (C) with the evaluation parameter (X) of each product on each criterion. The steps for each technique is given as following:

Step 1:

Construct the decision matrix for the number of N criteria.

X_{ij}=

	C1	**C2**	**C3**	**…**	**Cn**	**Score**
A1	X_{11}	X_{12}	X_{13}		X_{1n}	S_1
A2	X_{21}	X_{22}	X_{23}		X_{2n}	S_2
A3	X_{31}	X_{32}	X_{33}		X_{3n}	S_3
A4	X_{41}	X_{42}	X_{43}		X_{4n}	S_4
A5	X_{51}	X_{52}	X_{53}		X_{5n}	S_5
A6	X_{61}	X_{62}	X_{63}		X_{6n}	S_6

The decision matrices of TOPSIS and SAW after normalization are given from Table F.1 to Table F.6 in Appendix F.The consolidated score for the product on all criteria is shown as S. The positive criteria (benefits) should be maximized, and negatives (risks) should be minimized. There is no dominant (meaning best in every criterion) solution among the products. There are some problems with the difference in the units of criteria in the problem. Therefore, the aggregated solution of S cannot be reached by summing the evaluations in the row. Normalization solves this problem. Thus, the matrix is normalized to obtain dimensionless numbers in the fraction between zero and one.

Step 2:

The normalization scheme in TOPSIS involves obtaining a normalized matrix *R*:

$R_{ij} = \frac{x_{ij}}{\sqrt{\sum x_{ij}^2}}$ where i is for each product (alternative) and j is for criteria

$R_{ij}=$

	C1	C2	C3	…	Cn
A1	R_{11}	R_{12}	R_{13}		R_{1n}
A2	R_{21}	R_{22}	R_{23}		R_{2n}
A3	R_{31}	R_{32}	R_{33}		R_{3n}
A4	R_{41}	R_{42}	R_{43}		R_{4n}
A5	R_{51}	R_{52}	R_{53}		R_{5n}
A6	R_{61}	R_{62}	R_{63}		R_{6n}

Step 3:

Each column of the normalized matrix *R* is multiplied by the criteria weights found by the AHP method to obtain a weighted normalized matrix V:

V_{ij}=

	W1	W2	W3	…	Wn
	C1	**C2**	**C3**		**C_n**
A1	V_{11}	V_{12}	V_{13}		V_{1n}
A2	V_{21}	V_{22}	V_{23}		V_{2n}
A3	V_{31}	V_{32}	V_{33}		V_{3n}
A4	V_{41}	V_{42}	V_{43}		V_{4n}
A5	V_{51}	V_{52}	V_{53}		V_{5n}
A6	V_{61}	V_{62}	V_{63}		V_{6n}

Thus, the V matrix captures the experts' preferences regarding the criteria. The benefits and risks are determined by underlining the best and worst evaluations of each criterion for the six different products. For example, the lowest value of risk should be the most desirable variable. TOPSIS finds what is the best and worst in the circumstances of the problem. In finding the best and worst solution (product), it looks at how far it is from the utopia (the best possible).

Step 4:

The ideal A* is identified as a positive ideal solution (the best option) for the maximizing criteria, and the negative ideal solution A^- is identified as a negative ideal solution (the worst option) for the minimizing criteria such as risks and costs.

Step 5:

Compute the distances as a matrix from the best and worst options as S^* and S^-

Step 6:

For each product, intuitively determine the closeness between zero and one as C* to the ideal best (S*) and the worst (S^-) solution by a mathematical solution. Thus, final social performance is achieved for each product.

Step 7:

Rank the preference order according to the descending order of C_i*.

SAW Method

SAW aggregates weighted evaluations with different normalization method with the following rules:

Step 1:

The decision matrix is again constructed for each product and alternative. However, the normalization procedure is different from that of TOPSIS.

Step 2:

The normalization rule involves constructing a matrix with the following rule:

$r_{ij} = \frac{x_{ij}}{x_j^*}$ if the criterion is a benefit criterion

$r_{ij} = \frac{x_j^-}{x_{ij}}$ if the criterion is a risk or cost criterion

Since in the social criterion there are some minimized indicators there has to be attention to the normalization at this stage.

Step 3:

A weighted and normalized matrix is obtained by multiplying the AHP weights.

Step 4:

The calculation of the performance scoring scheme is also different from that of TOPSIS. In TOPSIS, the performance score is achieved by calculating the closeness to the best and worst solutions, and the score for each product is calculated by the sum of each row.

Step 5:

Ranking with SAW is performed in descending order again.

CHAPTER 4

RESULTS

The results are achieved and discussed in terms of three dimensions of sustainability with the impact categories and subcategories summarized in Figure 4.1.

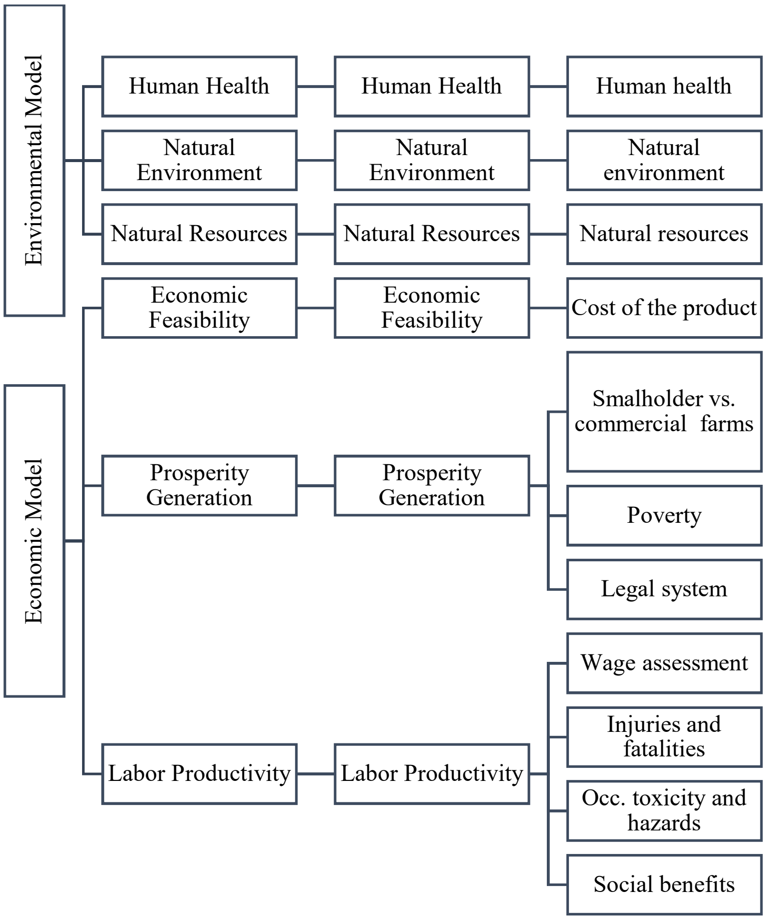

Figure 4.1. AHP Tree of the Proposed Sustainability Performance Model

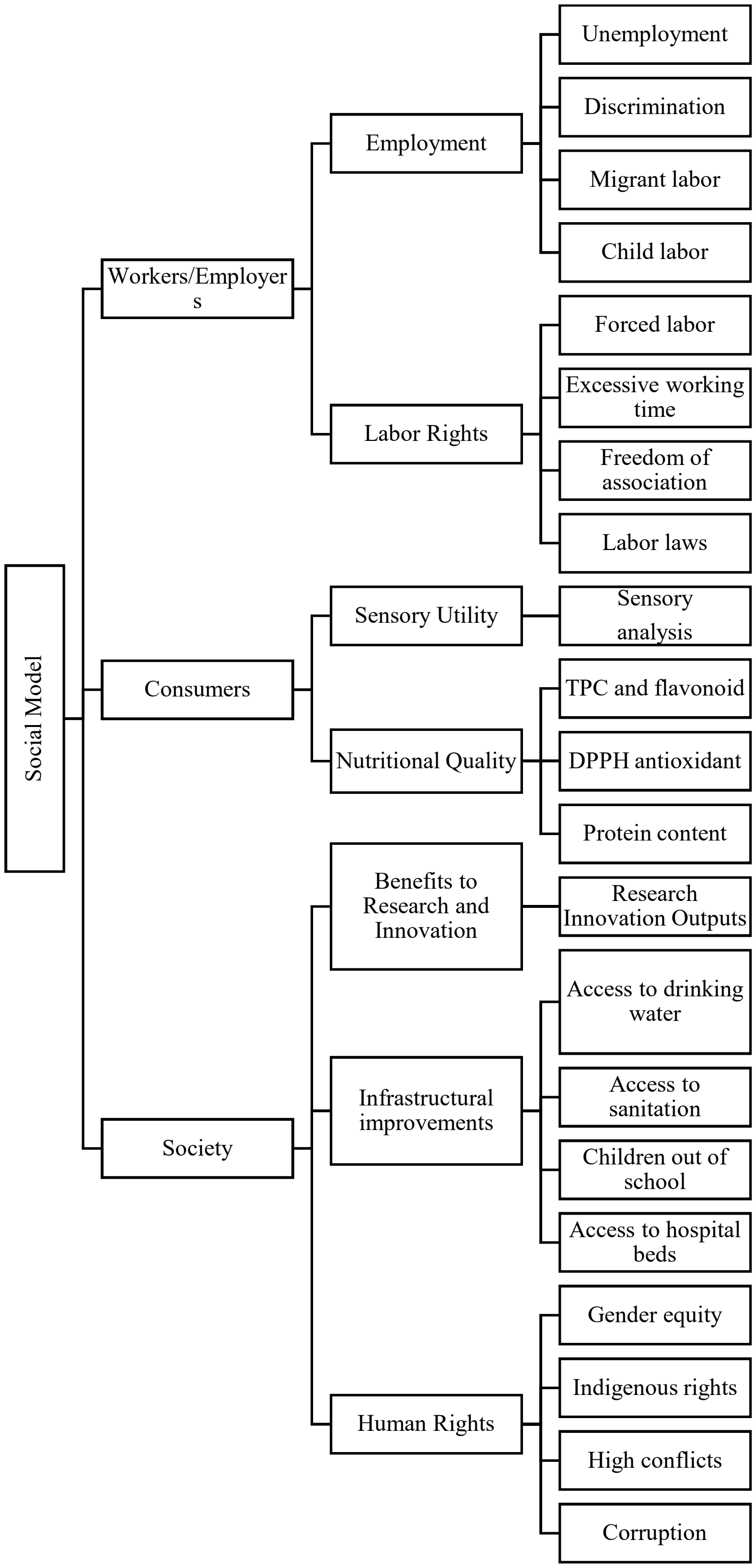

Figure 4.1. AHP Tree of the Proposed Sustainability Performance Model (cont'd)

In environmental studies, the aim of sustainability in food production is to maintain social balance while striving for ecological balance. In this study, the model developed not only respects product-specific criteria but also incorporates macro level data used in databases (such as Ecoinvent and SHDB, which use data from a large network). The application part aims to analyze the impact of different dried products in the product life cycle and provide some recommendations to improve the sustainability of the whole process. It also provides a framework for conducting sustainability assessments in production supply chains and hotspots to iterate the procedure toward the most sustainable production method. Consequently, traditional methods are compared with innovative techniques to identify the most sustainable activities and the most relevant social indicators.

An AHP survey was performed to identify the relationships among the impact categories/subcategories and their levels of importance. It is also used for multicriteria analysis of agricultural products (Mugiyo et al., 2021). The assessment model has been integrated by the TOPSIS and SAW multicriteria methods for objectives with different attributes and trade-offs.

4.1.1. AHP Prioritization of the Impact Categories

The AHP method uses intervals denoted as "multiples" in pairwise importance comparisons (e.g., if criterion B is 3 times more important than criterion B, it chooses an importance of 3). Since there are 11 experts, the individual expert judgments need to be summed. The aggregation of the answers and opinions of the experts about weights can be achieved by geometric or arithmetic means. The geometric mean of experts is more consistent with the AHP for calculating the final weights of criteria since it has ratio scale measures and the logic of how many times more preferable one is over another (Forman and Peniwati, 1998).

The weight of each expert for each performance criterion is given in Table B.2 in Appendix B. The environmental dimension was found to be the most important

(56%), followed by the social (28%) and economic (16%) dimensions (λmax= 3.0, IR (index random consistency)= 0.53 and consistency ratio= 0 (should be <0.01)).

In terms of the environmental dimension, the weight calculations according to the preferences of the eleven experts for each impact category are shown in Table 4.1. The subcategory of "environmental damage" was found to be the most important among all of the criteria (λmax =3.01, IR (index random consistency) =0.53 and consistency ratio =0.01 (should be <0.01)). This is due to the experts' preference that the consequences of environmental damage trigger other impacts, such as natural resources and human health. The objective function (MCDA) should minimize risk when the criterion is risk and maximize risk when the criterion is beneficial.

Table 4.1. *Weights of the Environmental Impact Subcategories, Criteria and Goals*

Impact Category	**Weight**	**Impact Subcategory**	**Weight**	**Impact Criteria**	**Best**	**Weight**
Environmental Footprint	0.56	Damage to Human Health	0.31	Damage to Human Health	Min.	0.31
		Damage to Environment	0.44	Damage to Environment	Min.	0.44
		Damage to National Resources	0.25	Damage to National Resources	Min.	0.25

Among the economic impact categories in Table 4.2, "property generation" is selected as the most important in Table 4.2 (λmax=3, IR (index random consistency)= 0.53 and consistency ratio= 0 (should be <0.01)). Nevertheless, it is observed that the economic impact categories are almost the same.

Table 4.2. *Weights of the Economic Impact Categories, Subcategories, Criteria, and Goals*

Impact Category	Weight	Impact Subcategory	Weight	Impact Criteria	Best	Weight
Economic Footprint	0.16	Economic Feasibility and Affordability	0.34	Cost of the product	Min.	0.341
		Prosperity Generation	0.37	Smallholder v commercial farms	Min.	0.124
				poverty	Min.	0.124
				Legal system	Min.	0.124
		Labor Productivity	0.29	Wage assessment	Min.	0.072
				Injuries & fatalities	Min.	0.072
				Occ. toxicity & hazards	Min.	0.072
				Social benefits	Min.	0.072

According to the social performance score results, the prioritization for stakeholders is as follows: IC1 Employer/Employee (26.8%), IC2 Customer (35.5%) and IC3 Society (37.7%) (λ_{max}=3.08, IR (Index Random Consistency) =0.53 and Consistency ratio =0.08 (should be <0.01)). In terms of the social dimension, which is 29% important among the three pillars, nutritional quality has the greatest importance as shown in Table 4.3. All but two of the 11 experts agreed that nutritional quality is the most important criterion. Under the society heading, the criterion of developing research and innovation capacity, which is not included in the SHDB model and added to the social performance score of this study, is the least important but is still noteworthy at 7% (λmax= 3.0, IR (Index Random Consistency)= 0.53 and Consistency ratio= 0 (should be <0.01)).

Table 4.3. *Weights of the Social Impact Categories, Subcategories, Criteria, and Goals*

Impact Category	Weight	Impact Subcategory	Weight	Impact Criteria	Best	Weight
Employer	0.27	Employment	0.63	Unemployment	Min.	0.042
				Discrimination	Min.	0.042
				Migrant labor	Min.	0.042
				Child labor	Min.	0.042
		Labor Rights	0.37	Forced labor	Min.	0.025
				Excessive working time	Min.	0.025
				Freedom of association	Min.	0.025
				Labor laws	Min.	0.025
Consumer	0.36	Sensory Satisfaction	0.28	Sensory analysis	Max.	0.100
		Nutritional Satisfaction	0.72	TPC+Flavonoid Content	Max.	0.085
				DPPH antioxidant activity	Max.	0.085
				Protein content	Max.	0.085

Table 4.3. *Weights of the Social Impact Categories, Subcategories, Criteria, and Goals (cont'd)*

Impact Category	Weight	Impact Subcategory	Weight	Impact Criteria	Best	Weight
Society	0.38	Benefits to Research and Innovation Capacity	0.19	Research Innovation capacity development	Max.	0.069
		Infrastructural Improvements	0.46	Access to drinking water	Min.	0.044
				Access to sanitation	Min.	0.044
				Children out of school	Min.	0.044
				Access to hospital beds	Min.	0.044
		Human Rights	0.35	Gender equity	Min.	0.033
				Indigenous rights	Min.	0.033
				High conflicts	Min.	0.033
				Corruption	Min.	0.033
TOTAL	1		1			1

As shown in Figure 4.2, nutritional quality, which is not a criterion in the SHDB LCA model, is validated at this highest level of importance for inclusion in social modeling and is hybridized with product-specific criteria in the current study. The criteria with the second highest importance are employment and infrastructural improvements, with a value of 17%.

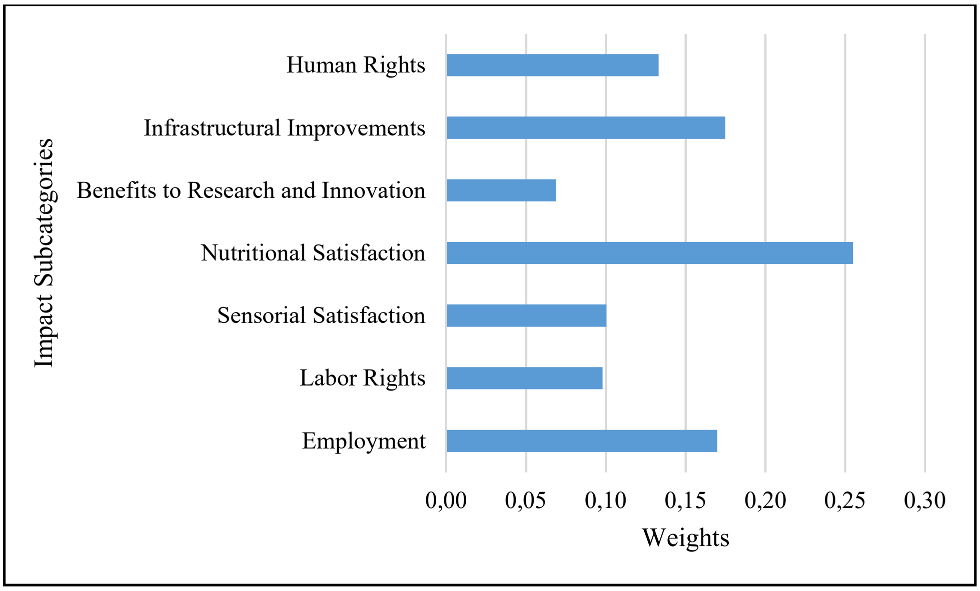

Figure 4.2. Weights of Social Impact Subcategories

According to the results in Table 4.4, the importance of environmental sustainability is greater than that of economic and social concerns. The hypothesis that environmental impacts affect consumer preferences while buying food products is very convenient (Dangelico et al., 2024). This may be because environmental and health concerns are more irreversible than economic and social outcomes. Considering the weights, none of the impact categories or subcategories were found to be irrelevant.

Table 4.4. *AHP Weights of the Sustainability Assessment Model*

Impact Category	Weight (W) (A)	Impact Subcategory	W	Impact Criteria	Best	W (B)	W (A*B)
Environmental Footprint	0.56	Damage to Human Health	0.31	Damage to Human Health	Min.	0.310	0.17
		Damage to Environment	0.44	Damage to Environment	Min.	0.440	0.25
		Damage to National Resources	0.25	Damage to National Resources	Min.	0.250	0.14
Economic Footprint	0.16	Economic Feasibility and Affordability	0.34	Cost of the Product	Min.	0.34	0.05
		Prosperity Generation	0.37	Smallholder v Commercial Farms	Min.	0.124	0.02
				Poverty	Min.	0.124	0.02
				Legal System	Min.	0.124	0.02
		Labor Productivity	0.29	Wage Assessment	Min.	0.072	0.012
				Injuries & Fatalities	Min.	0.072	0.012
				Occ Tox & Haz	Min.	0.072	0.012
				Social Benefits	Min.	0.072	0.012
Social Footprint	0.28 (A)						
Worker/ Employer	0.27	Employment	0.63	Unemployment	Min.	0.043	0.012
				Discrimination	Min.	0.043	0.012
				Migrant labor	Min.	0.043	0.012
				Child Labor	Min.	0.043	0.012
		Labor Rights	0.37	Forced labor	Min.	0.025	0.007
				Excessive Working Time	Min.	0.025	0.007
				Freedom of association	Min.	0.025	0.007
				Labor laws	Min.	0.025	0.007

Table 4.4. *AHP Weights of the Sustainability Assessment Model (cont'd)*

Impact Category		Weight	Impact Subcategory	Weight	Impact Criteria	Best	Weight (B)	Weight (A*B)
Social Footprint 0.28 (A)	Consumer	0.36	Sensory Satisfaction	0.28	Sensory Analysis	Max.	0.10	0.028
			Nutritional Satisfaction	0.72	Nutrient Compound (TPC+Flavonoid Content)	Max.	0.08	0.024
					DPPH Antioxidant Activity	Max.	0.08	0.024
					Protein Content	Max.	0.08	0.024
	Society	0.38	Benefits to Research Innovation Capacity	0.18	Research Innovation Capacity Development	Max.	0.07	0.02
			Infrastruc. Imp.	0.46	Access to Drinking Water	Min.	0.04	0.012
					Access to Sanitation	Min.	0.04	0.012
					Children out of school	Min.	0.04	0.012
					Access to hospital beds	Min.	0.04	0.012
			Human Rights	0.35	Gender Equity	Min.	0.03	0.01
					Indigenous Rights	Min.	0.03	0.01
					Indigenous Rights	Min.	0.03	0.01
					High Conflicts	Min.	0.03	0.01
TOTAL		1		1			3	1

Since the overall sustainability assessment is calculated by means of the weights, it is expected that the environmental aspects are more dominant in the overall score.

4.1.2. Results of the Life Cycle Impact Assessment

The impact is interpreted as hotspots without assigning weights. In the MCDA section, the model is solved in detail by prioritizing the impact categories. The identification of hotspots with the most significant risks or impacts should be iterative to check and analyze stages in the supply chain and deeper supply chains in activities. This step drives the results and outputs of the social LCA designed for opportunities and recommendations to reduce risks/burdens in the decision-making process. Hotspots show the risk levels for each impact category in each activity. Thus, high risks of activities are seen from the hotspots.

4.1.2.1. Results of Environmental Impact

The agri-food sector uses intensive operations based on machinery, irrigation, chemical content, transportation, and processes. These activities result in high-energy use and contribute to greenhouse gas emissions such as carbon dioxide and methane (Garofalo et al., 2017). Global warming, terrestrial ecotoxicity, non carcinogenic toxicity in humans and scarcity of fossil resources are the main hotspots in sustainability, as identified in the supply chains of dried tomato products in Figure 4.3. In fact, this impact is very familiar to the agri-food sector, as activities in this sector affect the environmental status of global warming and energy (Galanakis, 2018). Among the three impact categories, the most affected are natural resources due to energy use. The fact that the other impact categories are not significant shows the benefits of the trend of preference in the choice of green supply chains in the processes of the designed products.

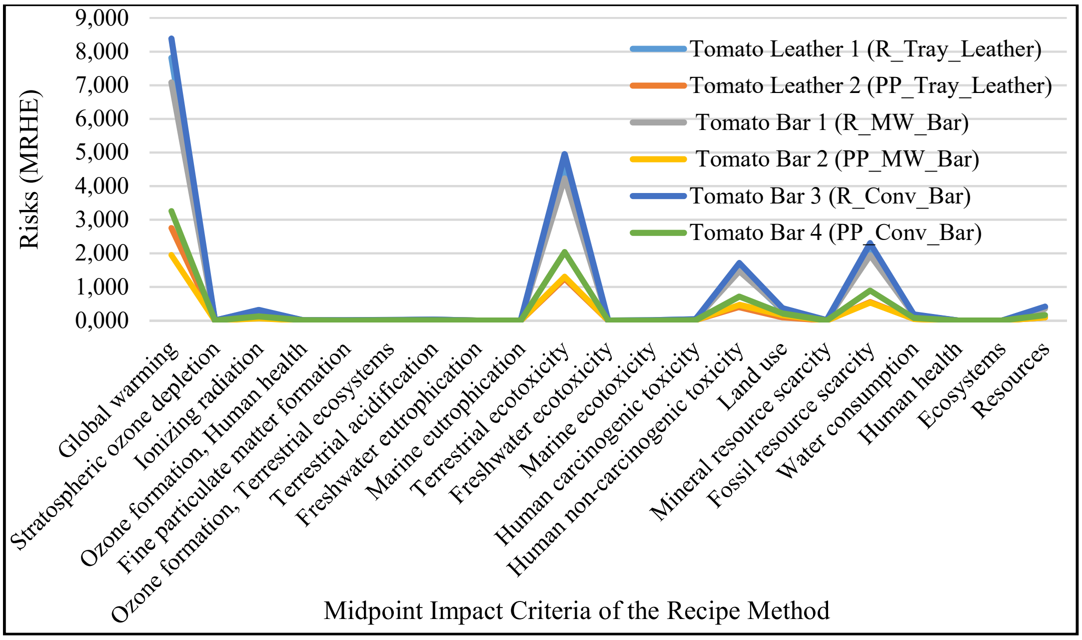

Figure 4.3. The Environmental Burdens According to Impact Criteria

Figure 4.4 represents the environmental risks for each product in three endpoint impact categories, which are damage to human health, ecosystems and resources. Rubisco protein, which is extracted from sugar beet leaves, has a greater impact on protein sources than does pea protein. A comparison of the drying technologies used for tomato bar products revealed that the use of a conventional dryer in tomato bar 4 is also less preferable than the use of a MW vacuum dryer.

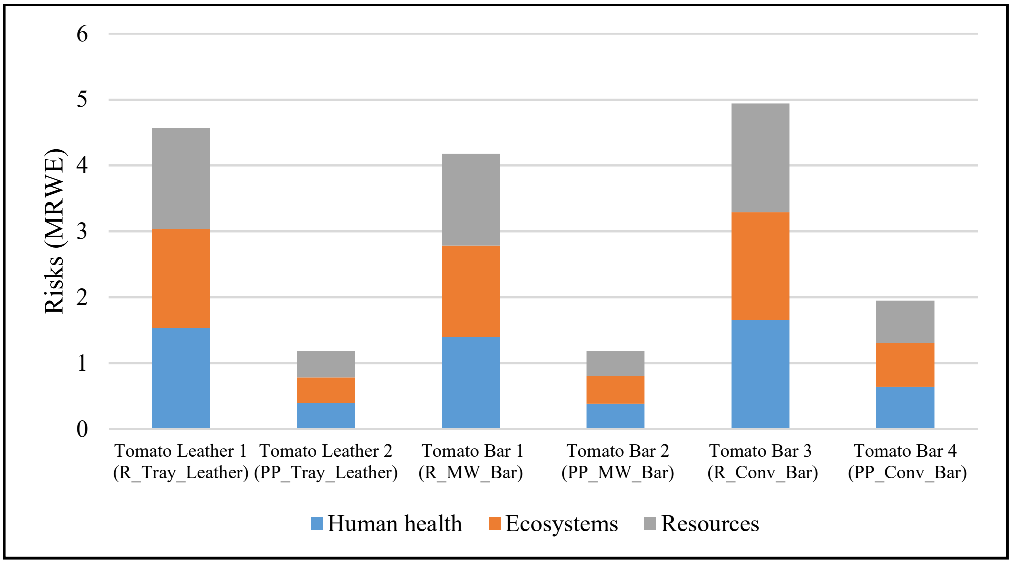

Figure 4.4. The Environmental Risks of Each Product after Normalization with the Average

The most significant activities and materials are shown in Figure 4.5-4.10 for each product separately to understand the source of the environmental burden of each activity. In the illustrations, "other ingredients" refer to tomato juice, olive powder and salt. Rubisco protein had a greater impact than tray drying in Figure 4.5.

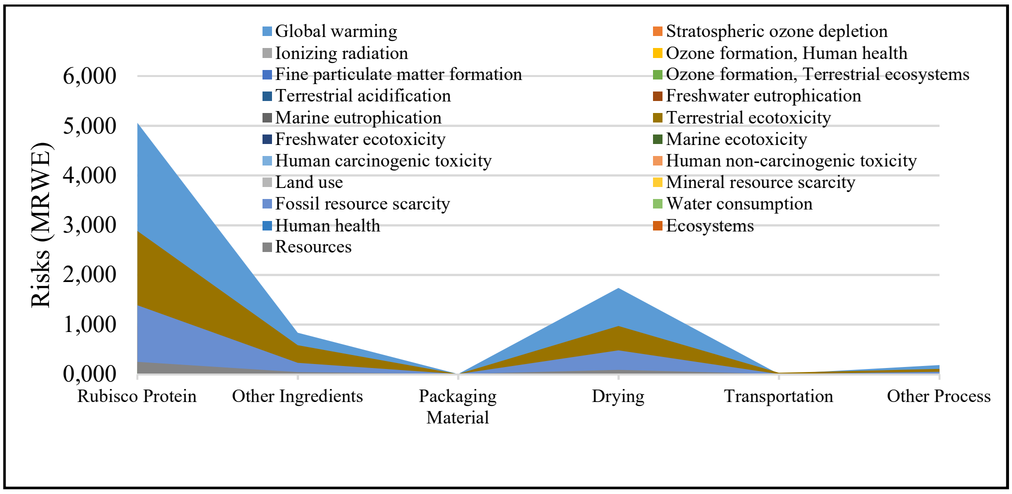

Figure 4.5. The Environmental Hotspots of Tomato Leather Product-1(Rubisco protein_Tray dryer_Leather)

Tomato leather products with pea protein were burdened by tray dryer as shown in Figure 4.6.

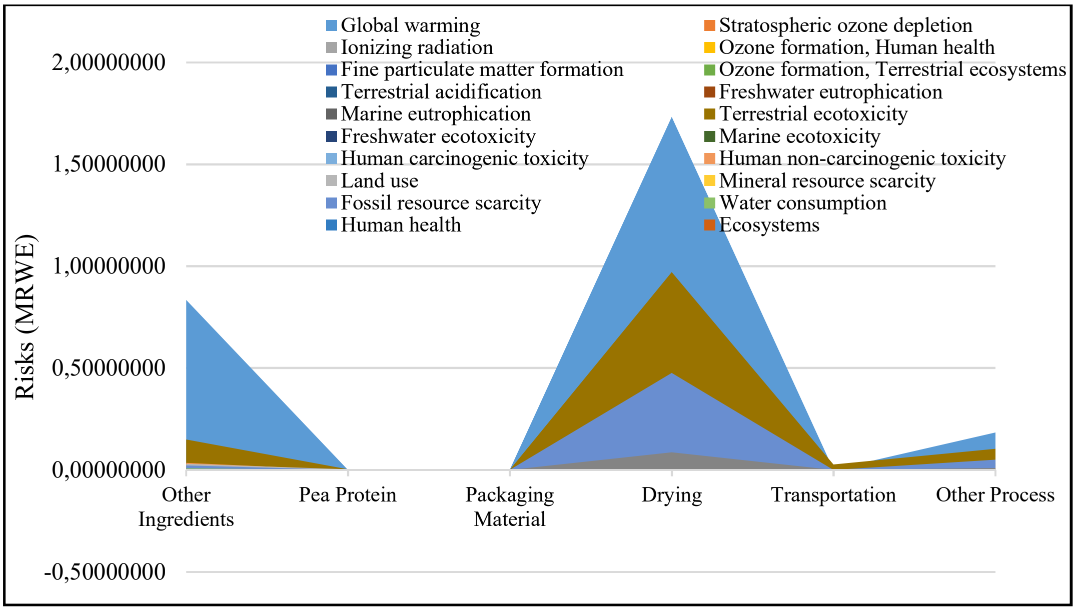

Figure 4.6. The Environmental Hotspots of Tomato Leather Product-2 (Pea protein_Tray dryer_Leather)

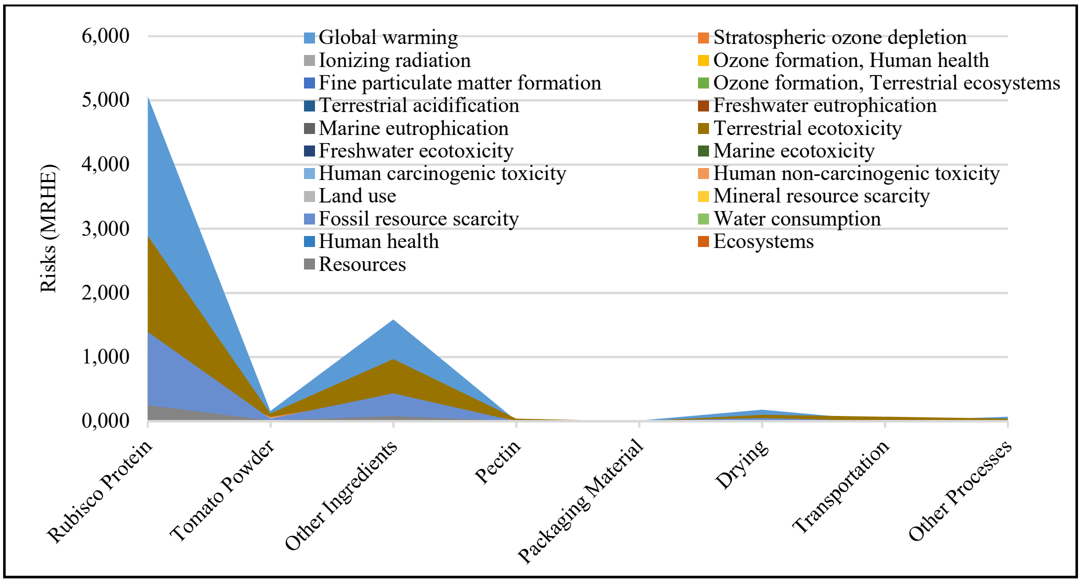

Figure 4.7. The Environmental Hotspots of Tomato Bar Product-1 (Rubisco protein_MW vacuum dryer_Bar)

When using MW vacuum drying, as shown in Figure 4.8, other ingredients, which represent the raw materials of tomato juice, olive powder and salt, had a greater impact than did the drying process, while Rubisco protein had the greatest impact, as shown in Figure 4.7.

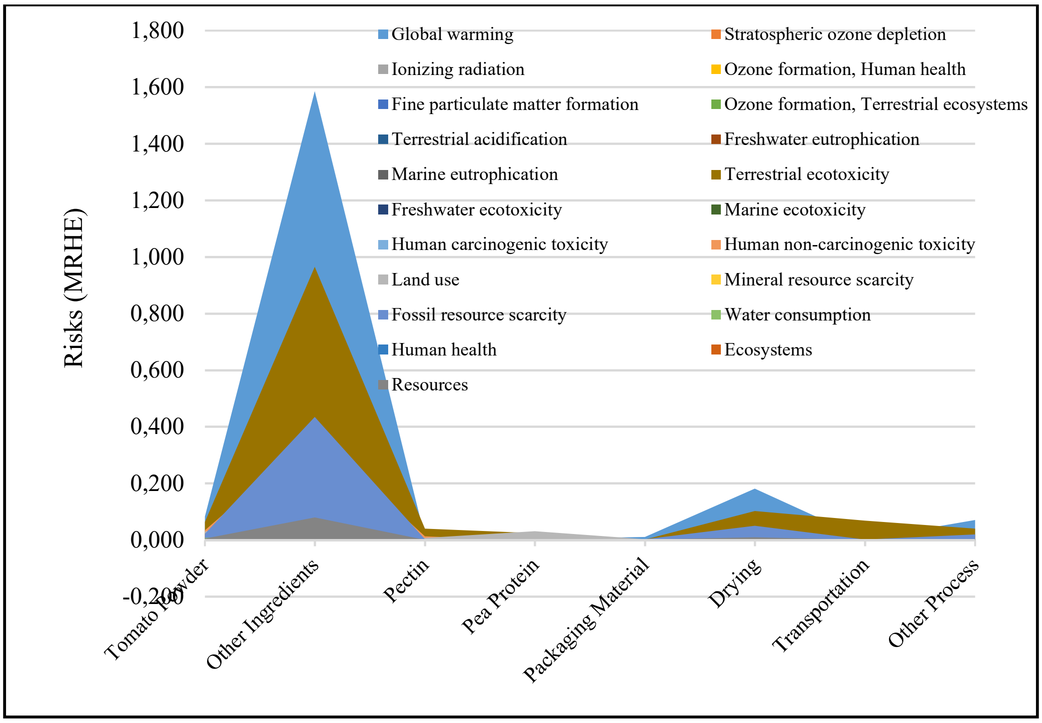

Figure 4.8. The Environmental Hotspots of Tomato Bar Product-2 (Pea protein_MW vacuum dryer_Bar)

The tomato bar products shown in Figure 4.9 and Figure 4.10 have almost the same environmental load from the “other ingredients” due to olive powder production and from conventional drying, while Rubisco protein again has the greatest impact, as shown in Figure 4.9. This shows that texturization is as important as process technology.

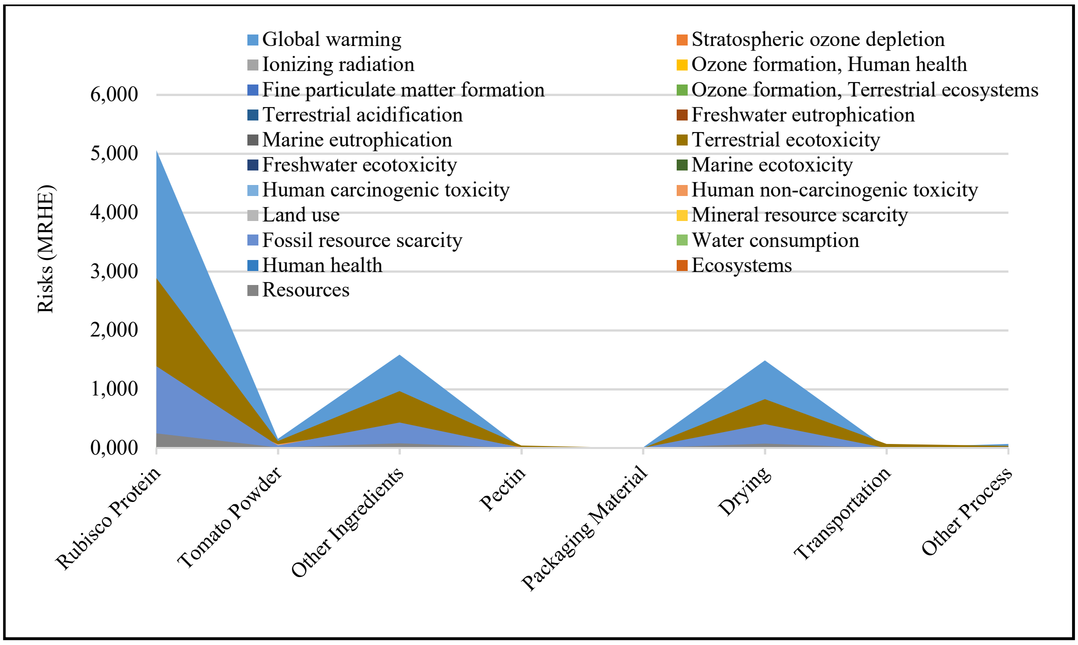

Figure 4.9. The Environmental Hotspots of Tomato Bar Product-3 (Rubisco protein_Conventional dryer_Bar)

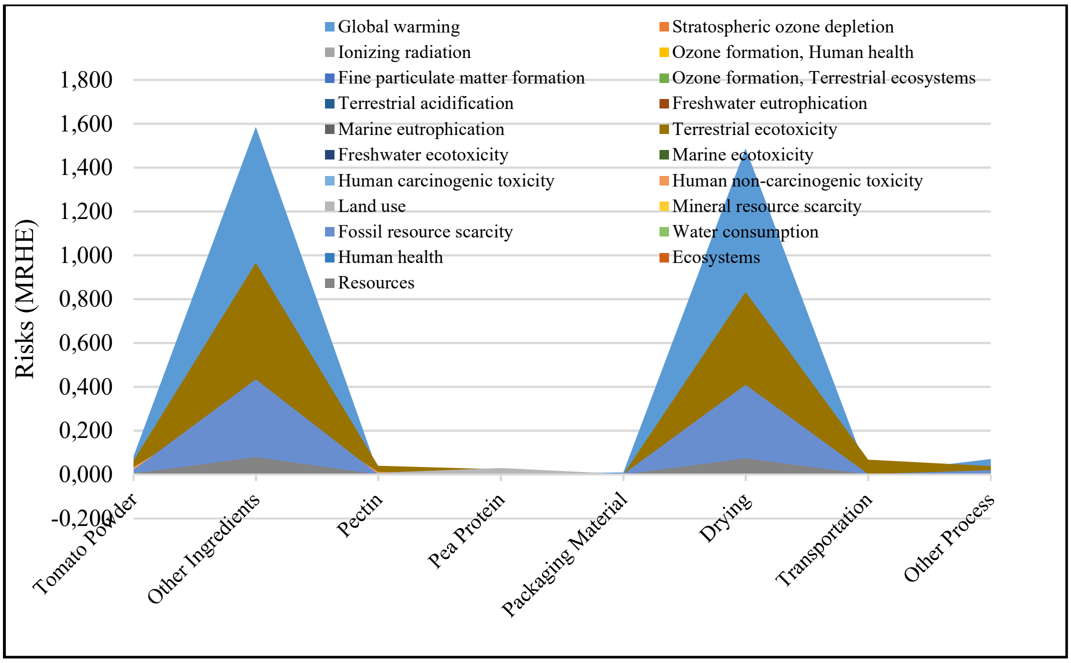

Figure 4.10. The Environmental Hotspots of Tomato Bar Product-4 (Pea protein_Conventional dryer_Bar) According to the Life Cycle Activities

The reason why Rubisco-added products are less sustainable has been investigated. The use of a freeze dryer with a vacuum in the Rubisco manufacturing process increases the environmental impact, especially on global warming, terrestrial ecotoxicity and fossil resources. The water bath isoelectric precipitation step also increases the risk of terrestrial ecotoxicity, as shown in Figure 4.11.

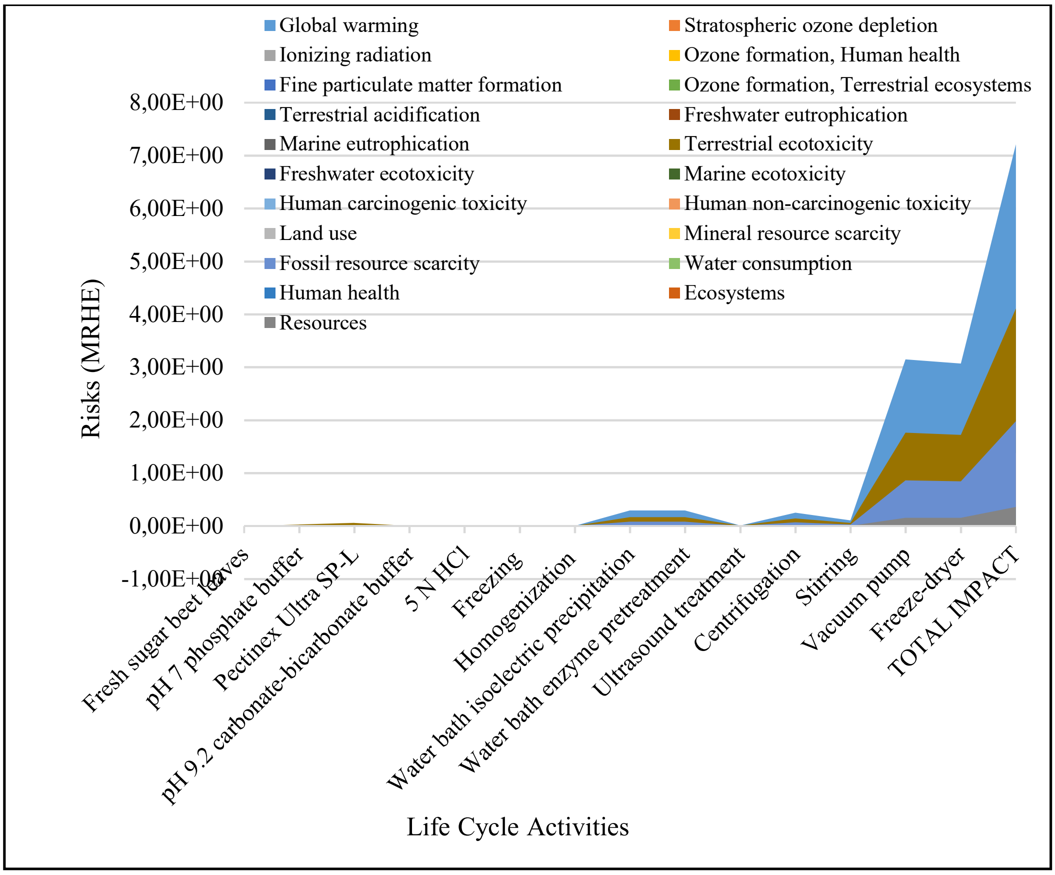

Figure 4.11. The Environmental Hotspots of Rubisco Protein Production According to the Life Cycle Activities

4.1.2.2. Results of Economic Impact

The risks in the economic dimension are evaluated by considering the cost and region of the materials and processes. After normalization of the results by the average of each impact category, the economic impact categories of each product are shown in

Figure 4.12 and 4.13. Apart from the micro level criterion, the cost of the product, which is the highest in leather products (1-2) due to the cost of tray dryer, the highest risks among the macro level criteria are injuries and fatalities due to the Rubisco added protein sources (tomato leather-1, tomato bar-1 and tomato bar-3). In the case of Rubisco-added product 1, which has the highest risk of injuries and fatalities, the risk is shared by Rubisco protein production and olive powder production by freeze-drying.

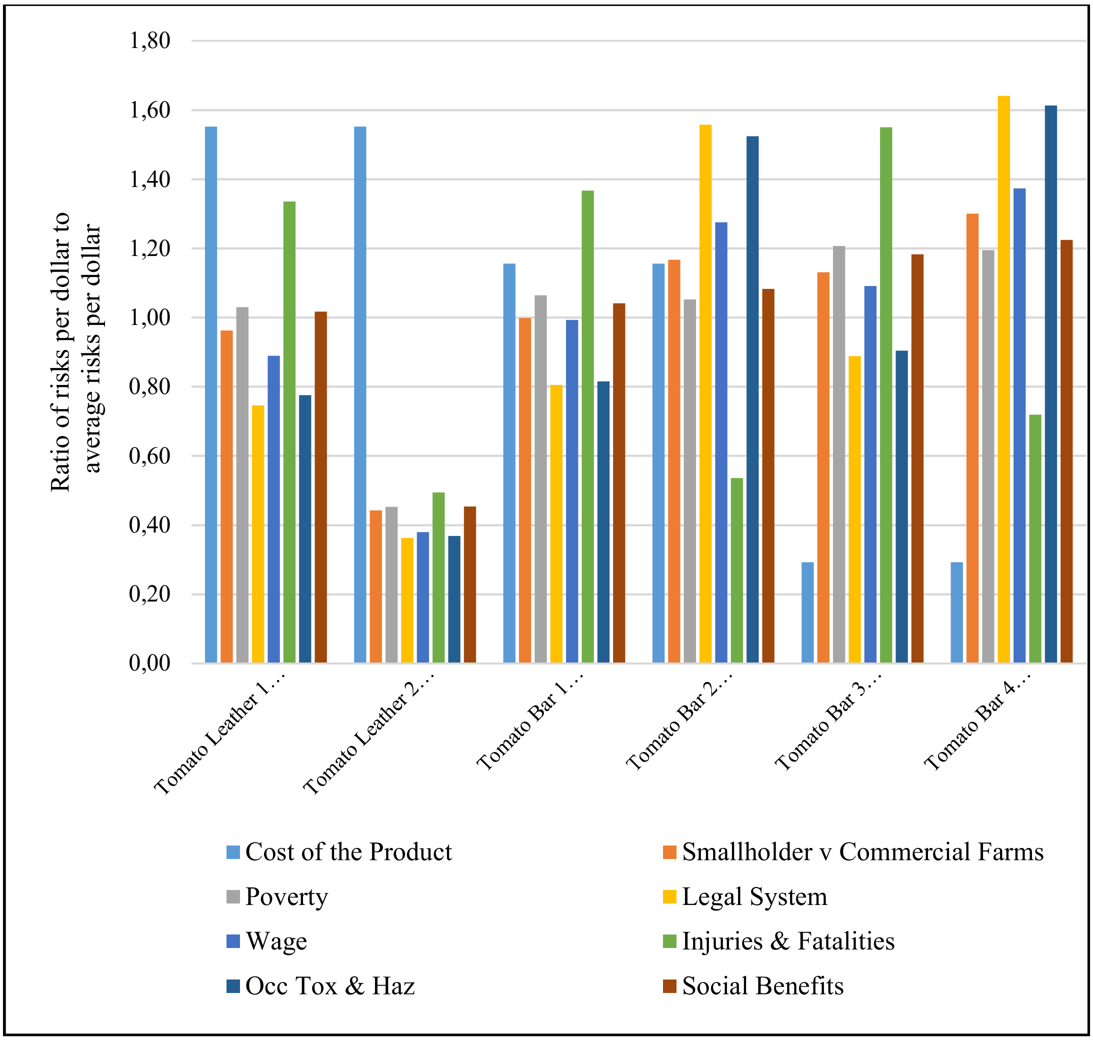

Figure 4.12. Economic Footprints of Products after Normalization by the Average of Each Criterion

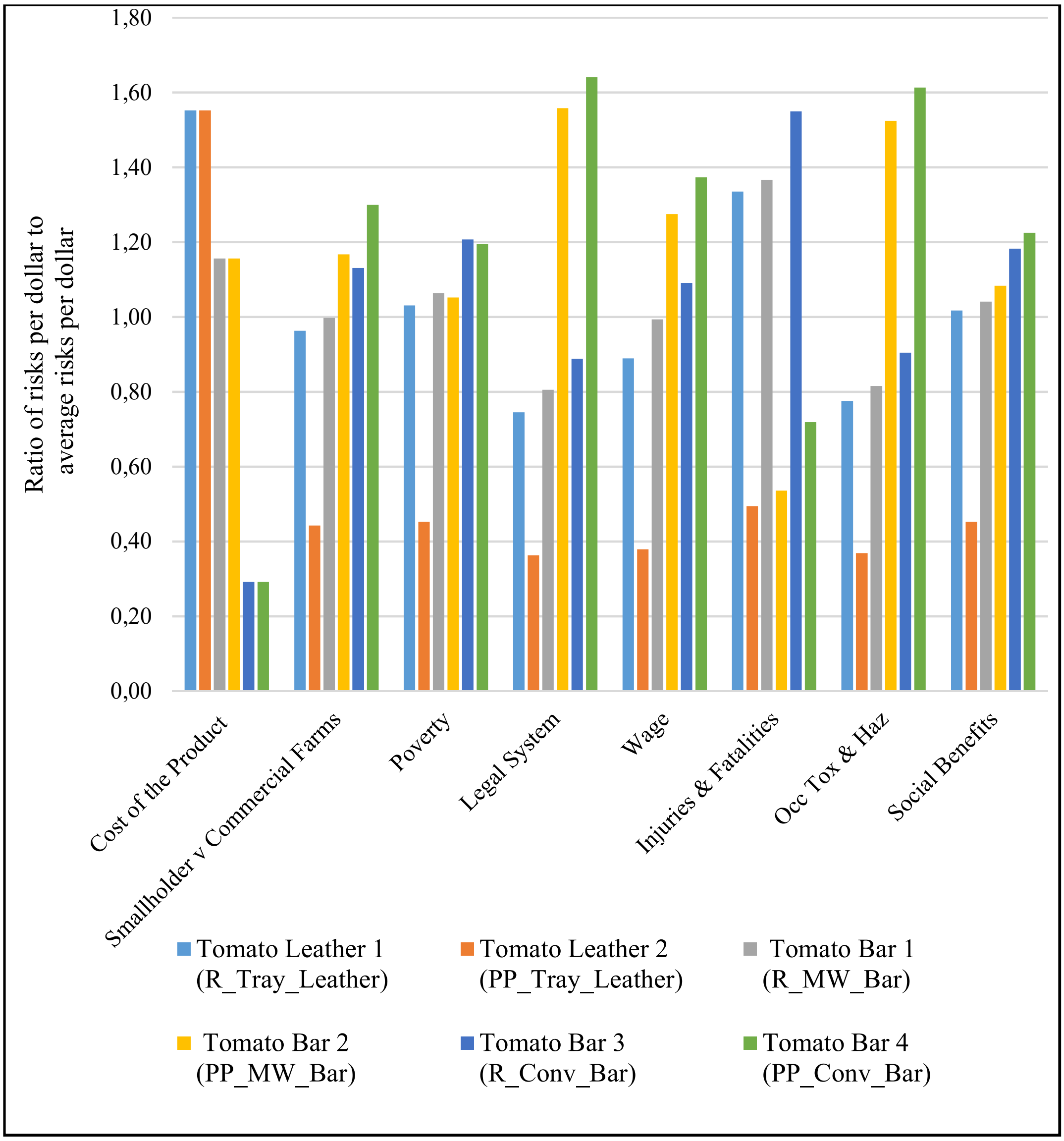

Figure 4.13. Economic Footprints by Impact Subcategory after Normalization by the Average of Each Criterion

On a more detailed examination of the tomato bar products, the legal system, injuries and fatalities, and toxicity and hazards are the greatest risks due to the Pea protein (sector and region, as listed in Table 3.4) in tomato bar-2 (the same for the tomato bar-4 product), as shown in Figure 4.14.

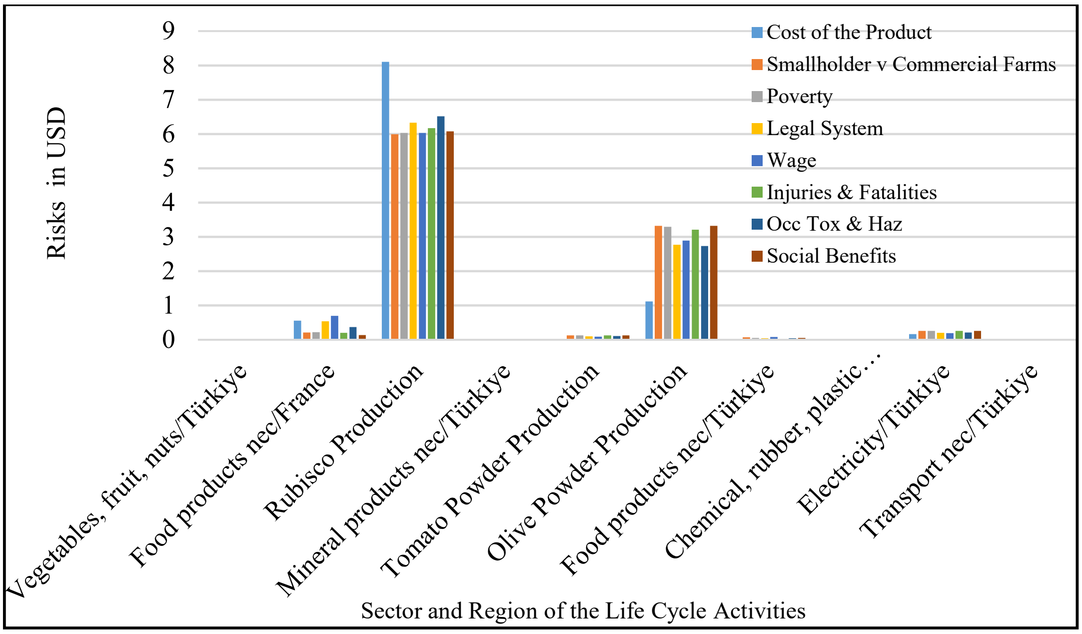

Figure 4.14. Economic Footprint of Tomato Bar Product-1 (R_MW_Bar) by Sector and Region of the Life Cycle Activities

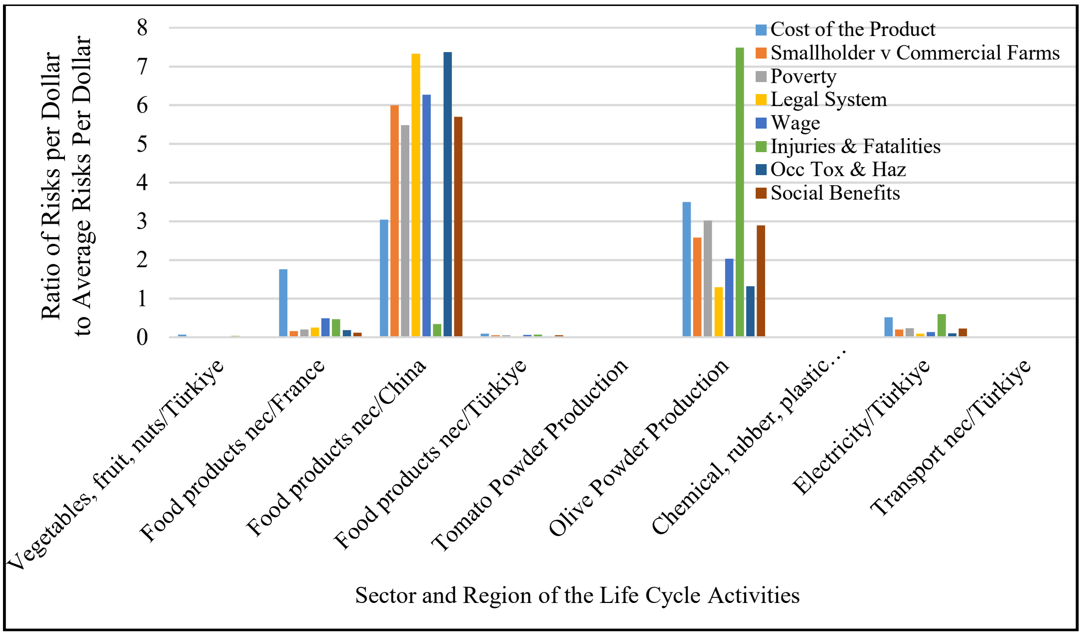

Figure 4.15. Economic Hotspots of Tomato Bar Product-2 (Pea protein_MW vacuum dryer_Bar) According to the Sector and Region of the Life Cycle Activities

In terms of tomato bar products containing Rubisco protein, the economic footprints were concentrated on Rubisco and olive powder production in Figure 4.15. It is necessary to analyze the Rubisco protein production life cycle in terms of economic risk criteria. Injury and fatalities are mostly caused by the Pectinase enzyme (sector and region), the chemical used in buffers and the electricity of the freeze dryer, as shown in Figure 4.16.

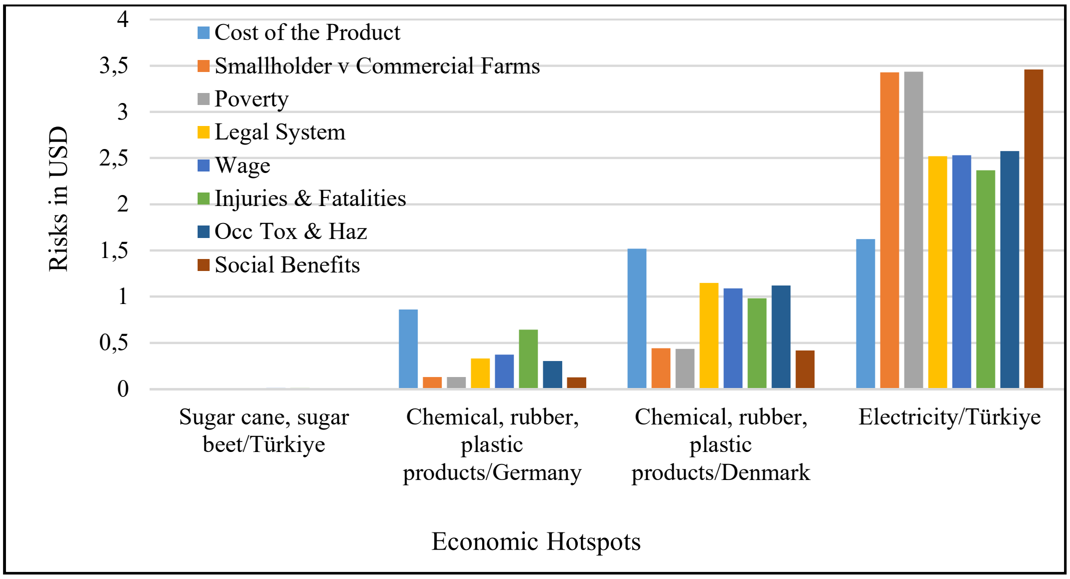

Figure 4.16. Economic Hotspots of Rubisco Protein Production after Normalization by Average

4.1.2.3. Results of Social Impact

Social hotspots indicate the risk levels throughout the life cycle of each activity. Thus, high risks associated with activities can be seen from social hotspots.This step drives the outputs and results of the social LCA, which are designed for opportunities and recommendations to reduce social risks/impacts in the decision-making process. In this step, the regional emergence of risks can be observed. It should be iterated to check and analyze the stages in the supply chain and deeper supply chains in deeper activities. In fact, one can move away from high-risk areas by modifying the supply chain, materials, or stakeholders.

The results were interpreted without giving the specific weights. In the next section, the model is solved by prioritizing the impact categories and taking advantage of the mathematical method of multicriteria decision analysis.

The social risks are shown in Figure 4.17. The categories under which the impact criteria fall are shown in Table 3.7. The risks are mostly prominent in freedom of association, which falls under the impact category of labor rights, and in the criteria of corruption under human rights. The life cycles of the products do not impose a significant burden on the risks of unemployment, access to drinking water, sanitation, or indigenous rights. In fact, there is not much risk of excessive working time.

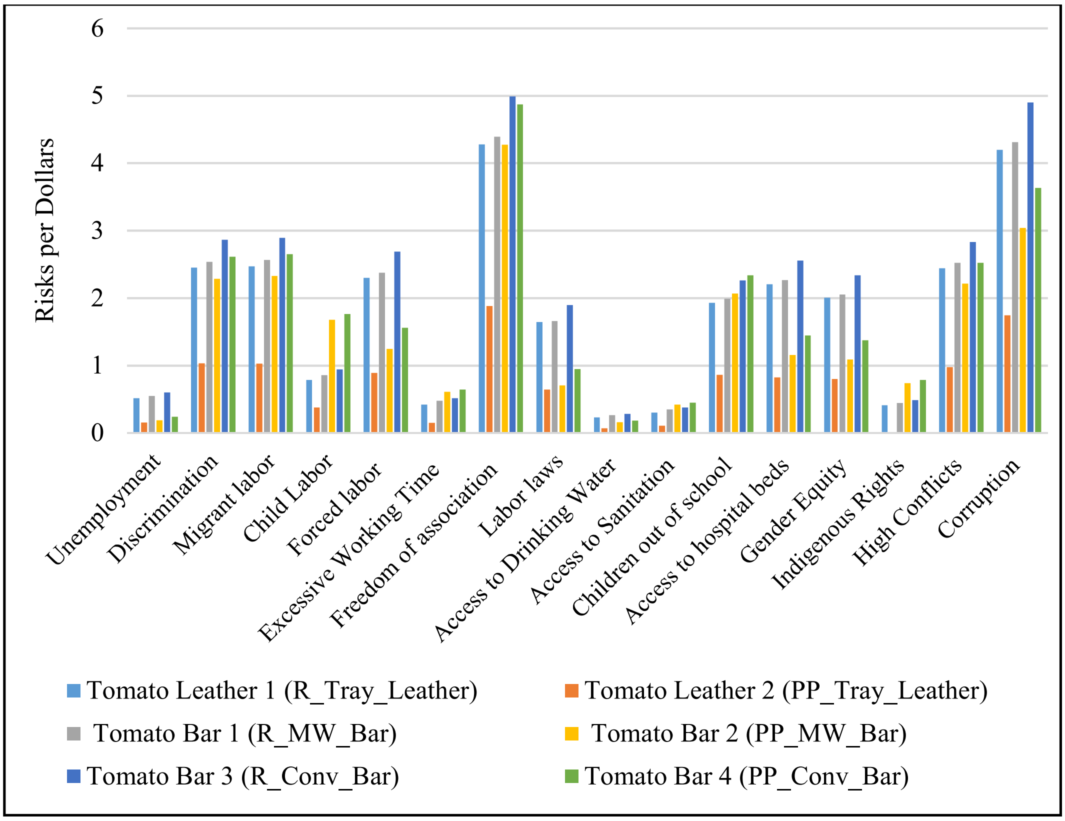

Figure 4.17. Social Risks of the Novel Tomato Products According to the Impact Criteria

Figure 4.18 and Figure 4.19 provide the social hotspots according to the sector and region of the activities given earlier in Table 3.4. Rubisco protein adds more social burdens than does the process. When other alternative protein sources of pea protein are used, the social risks are reduced. In this case, pea protein also has some social risks, although they have less of an impact than does energy.

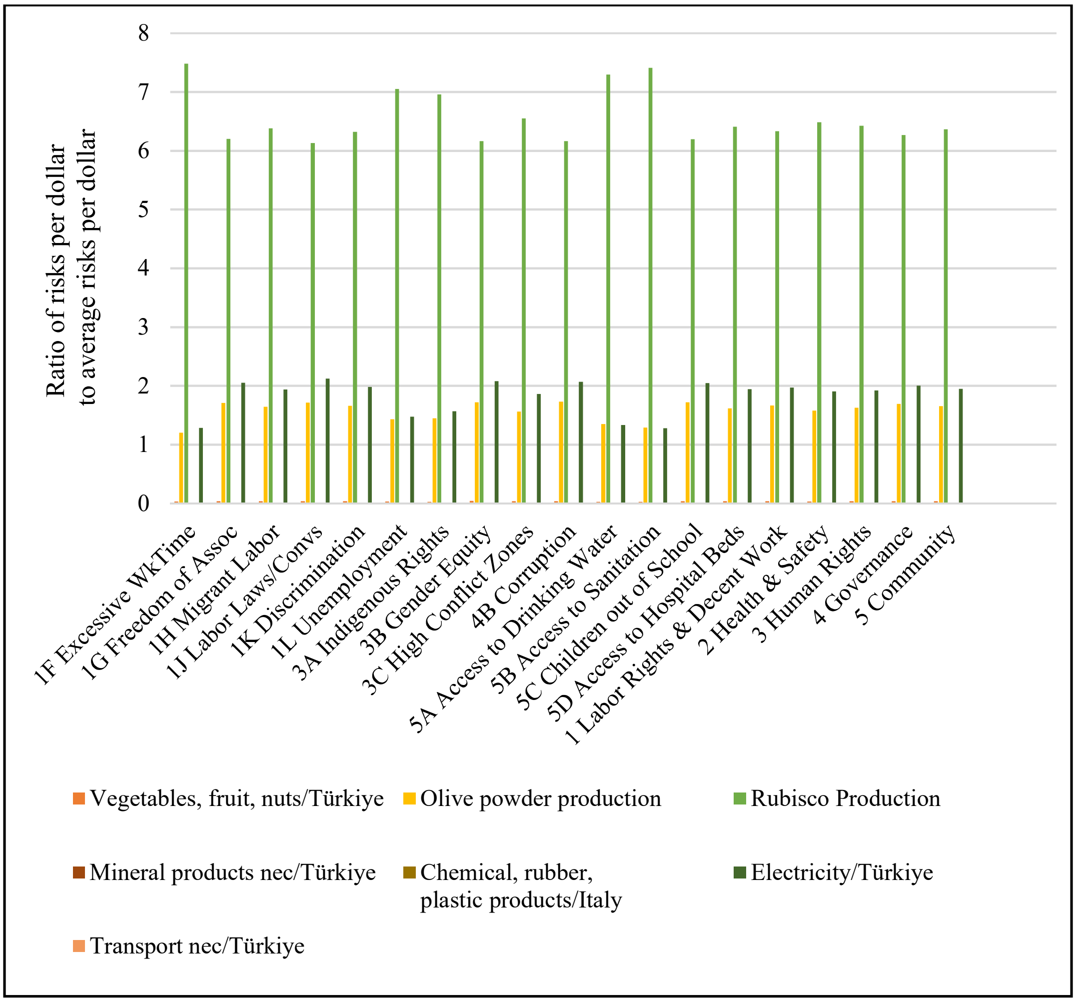

Figure 4.18. Social Footprints of Tomato Leather Product-1 (Rubisco_Tray dryer_Leather) by Sector and Region of the Life Cycle Activities

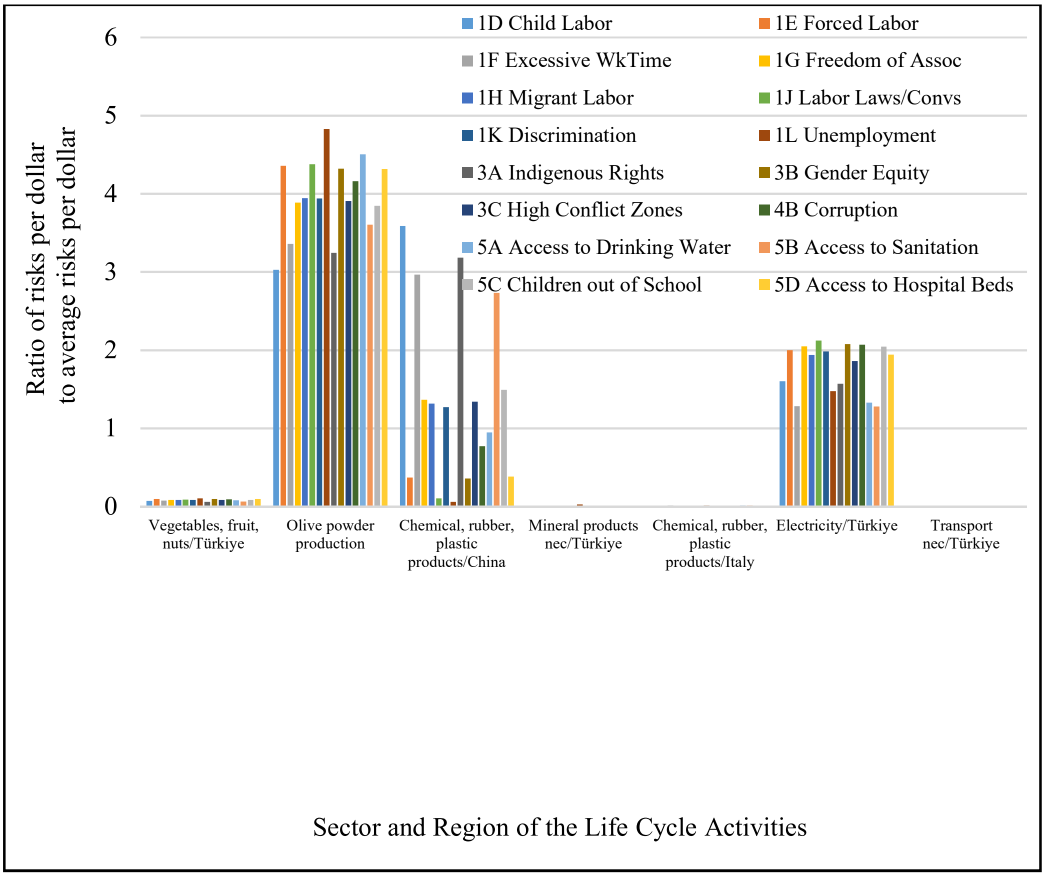

Figure 4.19. Social Footprints of Tomato Leather Product-2 (Pea protein_Tray dryer_Leather) by Sector and Region of the Life Cycle Activities

Among the bar products in the following figures, Rubisco production and olive powder increased the social risks. However, MW vacuum drying is less energy intensive. While this reduces risks and increases sustainability, the impact of Rubisco and olive powder components on social risks is notable in Figure 4.20.

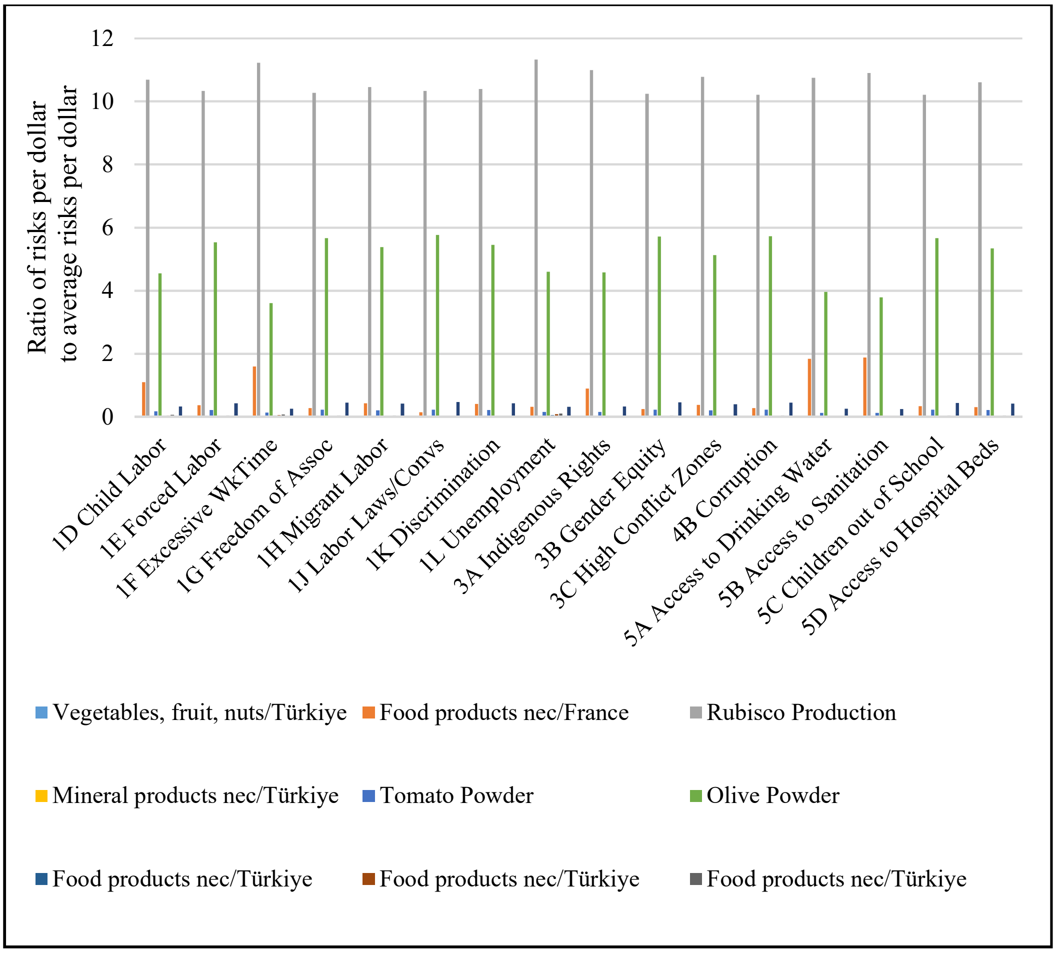

Figure 4.20. Social Footprints of Tomato Bar Product-1 (Rubisco_MW vacuum dryer_Bar) by Sector and Region of the Life Cycle Activities

The bar product with pea protein and MW drying is more sustainable than that with Rubisco. However, it seems hotspots coming from the pea protein purchasing in Figure 4.21. When the hotspots for tomato bar products with pea protein are deeply analyzed, the raw material pea protein is more responsible for social risks (child labor, excessive working time, and access to sanitation are the picks) than is electricity and olive powder production.

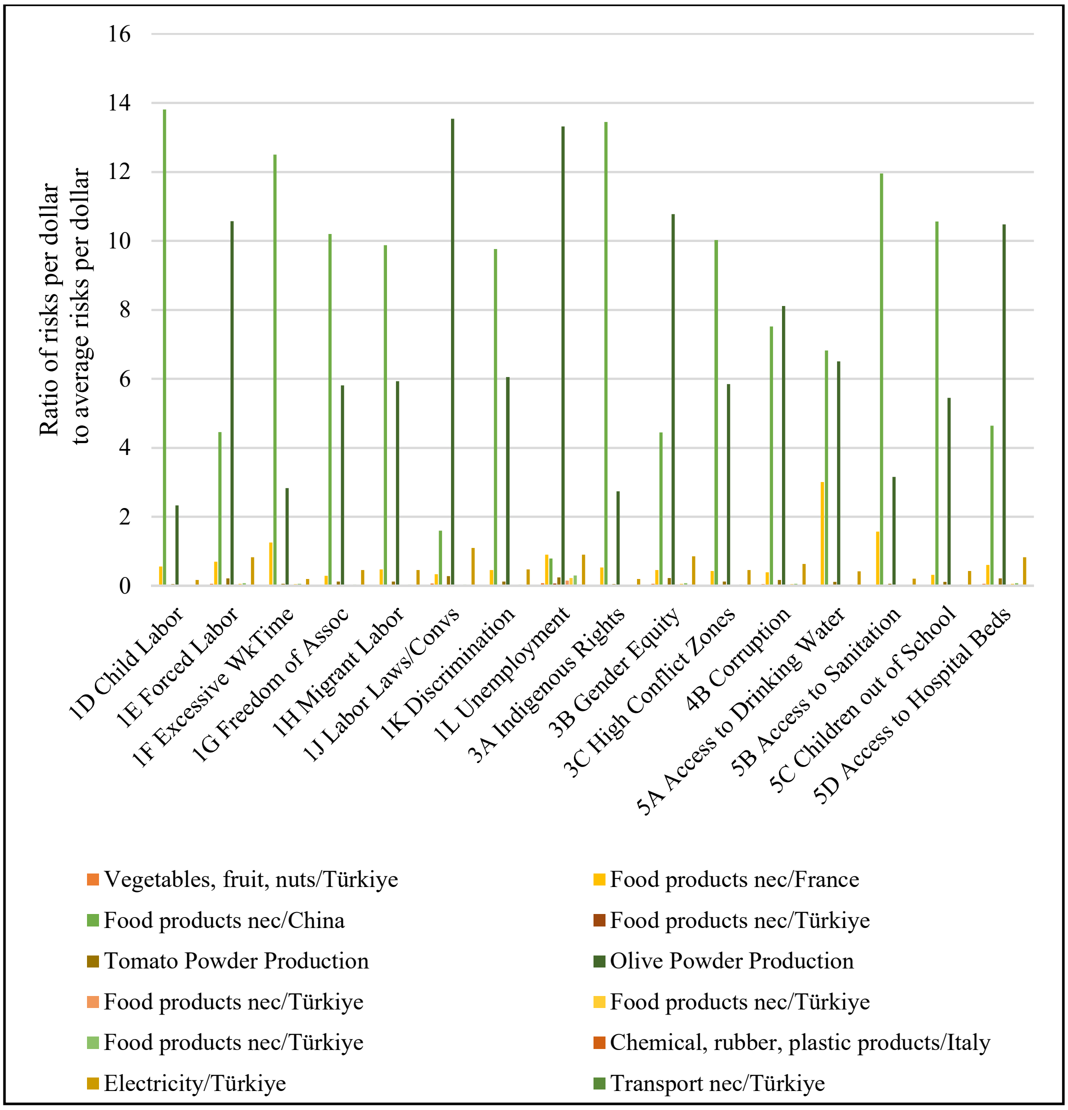

Figure 4.21. Social Footprints of Tomato Bar Product-2 (Pea protein_MW vacuum dryer_Bar) According to the Impact Criteria by Sector and Region of the Life Cycle Activities

The tomato bar dried by a conventional dryer has social risks due to the energy-intensive nature of the process, as shown in Figure 4.22, although the risk is less than that of other hotspots of Rubisco protein production and olive powder production.

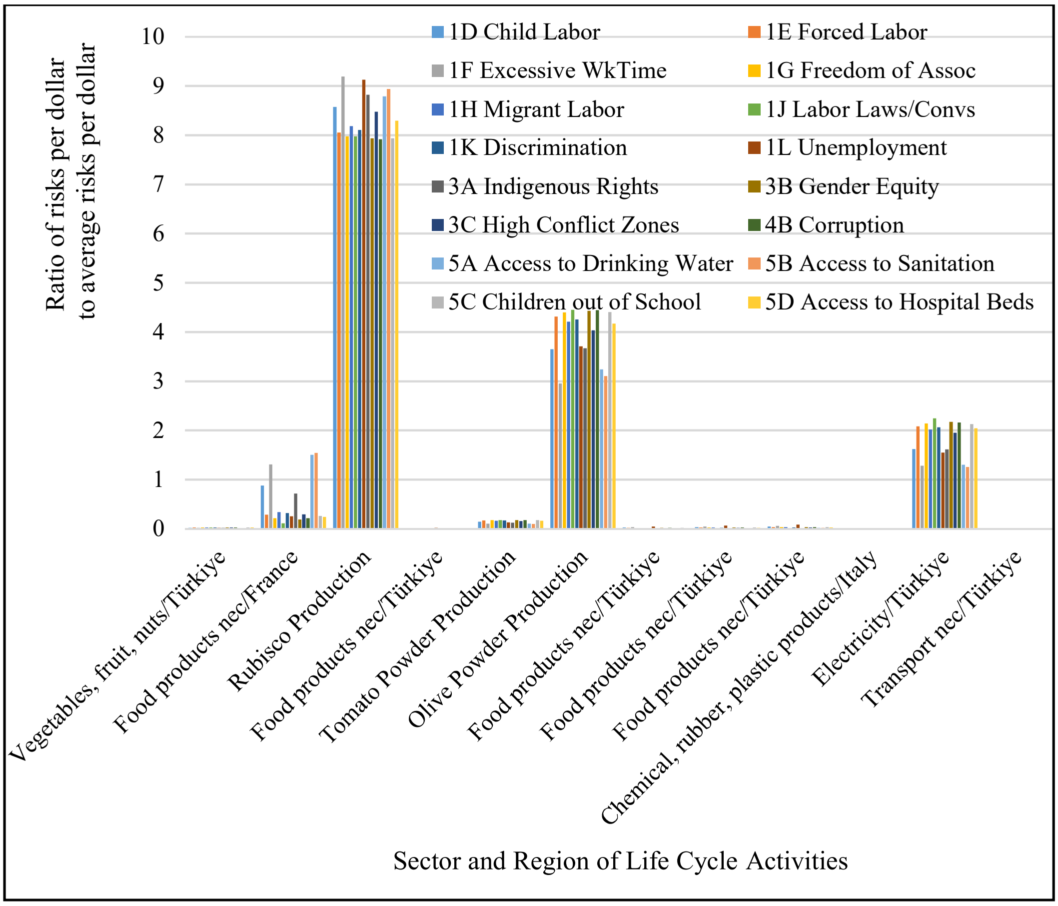

Figure 4.22. Social Footprints of Tomato Bar Product-3 (Rubisco_Conventional dryer_Bar) According to the Sector and Region of the Life Cycle Activities.

Rubisco protein and olive powder production life cycles play a significant role in product sustainability as illustrated in Figure 4.23 and Figure 4.24. Since freeze drying has been used both for olive powder and for Rubisco, it has become increasingly popular. The Pectinase enzyme, which is from Denmark, as shown in Table 3.4, also has a burden on the social risks of Rubisco production.

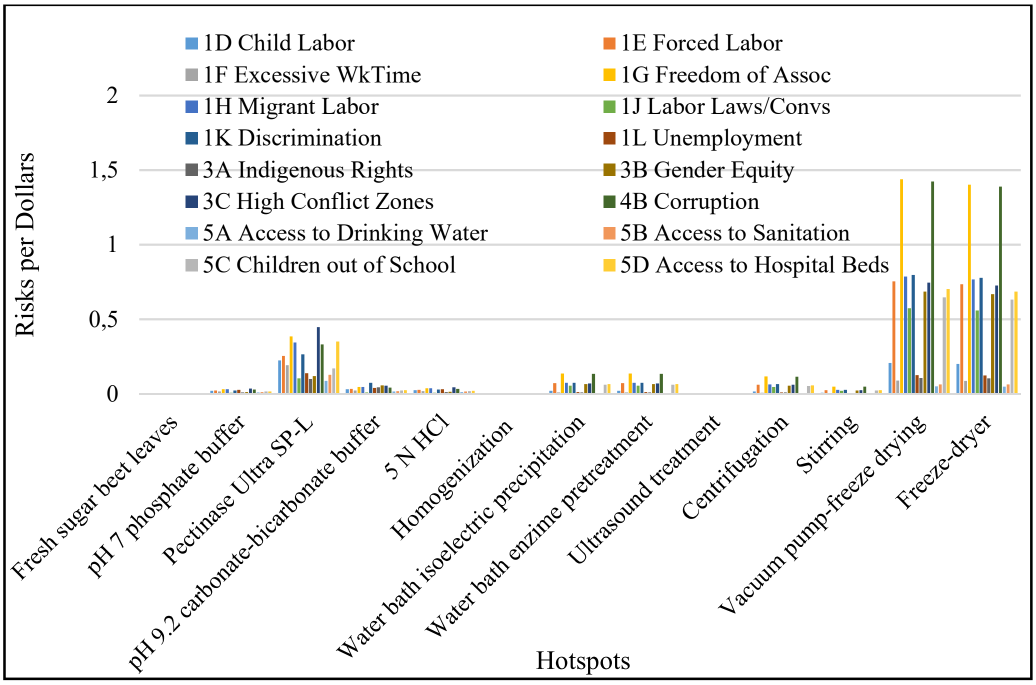

Figure 4.23. Social Footprint of the Rubisco Protein Production

The greatest risks associated with freeze drying of olive powder are corruption and freedom of association in Figure 4.24.

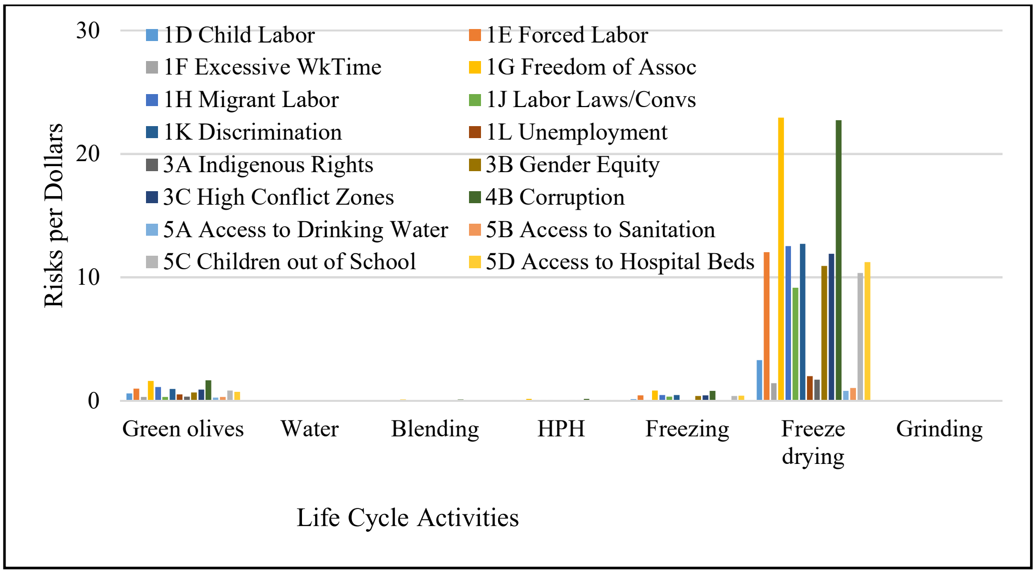

Figure 4.24. Social Footprint of Olive Powder Production According to the Life Cycle Activities

A deep analysis of the hotspots for tomato bar products with pea protein is illustrated in Figure 4.25. The food product nec, which refers to pea protein from China, has the highest risks in terms of child labor, access to sanitation and indigenous rights. Olive powder production in Türkiye also has some drawbacks in terms of unemployment and labor laws. This reveals that the raw material pea protein is more responsible for social risks (e.g., child labor, excessive working time, and access to sanitation) than olive powder production and electricity, even in conventional drying.

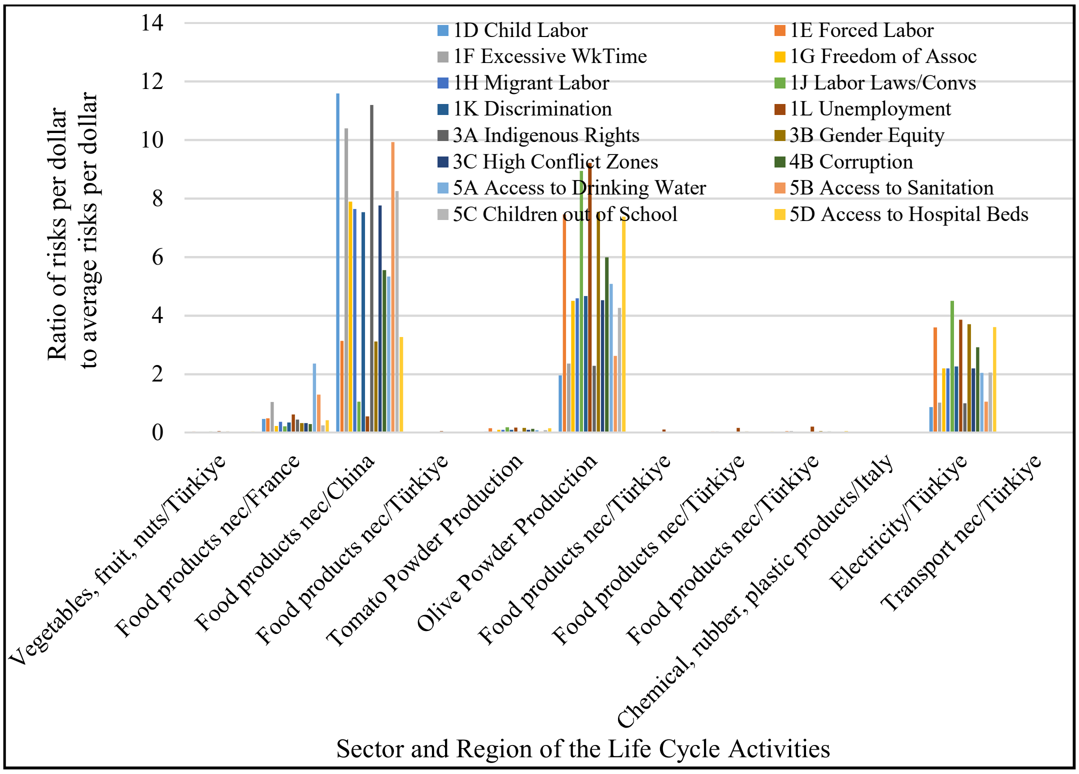

Figure 4.25. Social Footprint of Tomato Bar Product-4 (Pea Protein_Conventional dryer_Bar) According to the Sector and Region of Life Cycle Activities

The difference of the proposed model is that it includes criteria with attributes related to the designed product, including benefits. The benefits of micro level social benefits are analyzed in Figure 4.26. Tomato bars with pea protein dried with a MW vacuum dryer or a conventional drier appear to provide greater benefits to the sustainability score. DPPH antioxidant activity is associated with antioxidant activity. Leather products have greater DPPH capacity. As more protein was added to the bar, the protein content increased. In addition, bar products have a relatively high phenolic content, which is very favorable for a healthy diet.

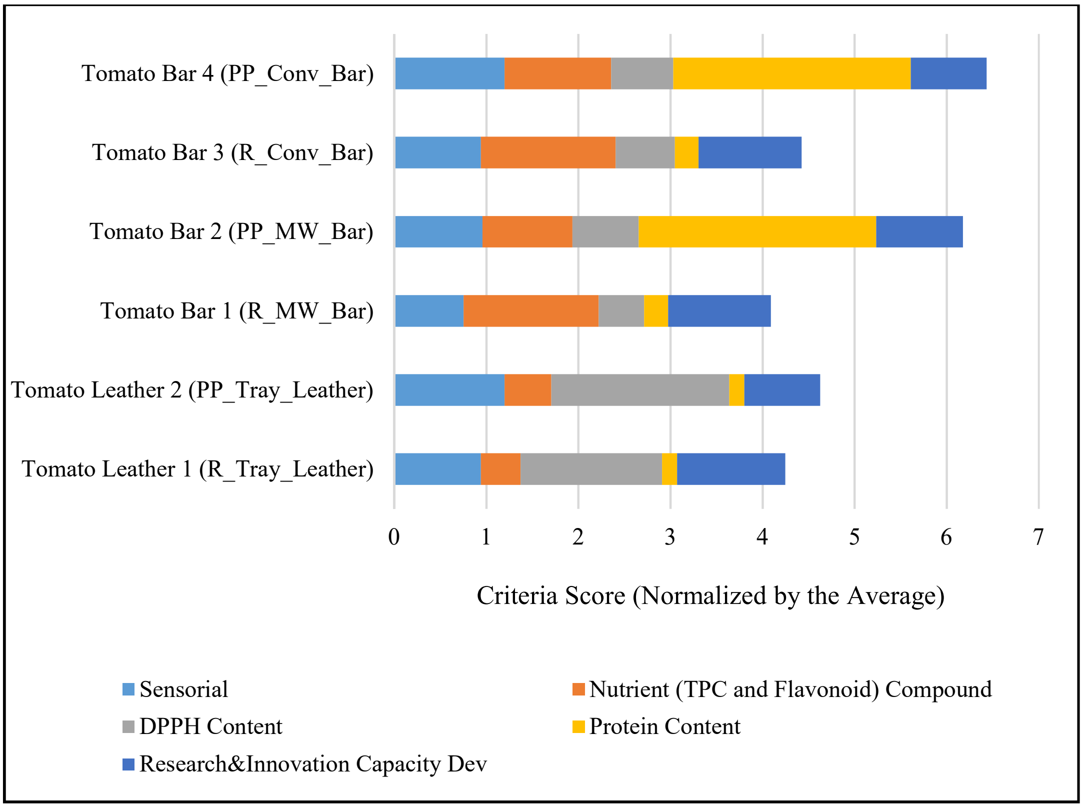

Figure 4.26. The Beneficial Aspects by Product-Specific Impact Criteria after Normalization with Average of Each Criterion

4.1.3. Results of MCDA: Scoring and Ranking of Sustainability

Different from the life cycle impact, the results are weighted in this section. Once the overall weights are calculated for the three dimensions, the environmental footprint, economic footprint and social footprint are multiplied by the AHP weights to obtain the sustainability score. Then, the impacts or risks in addition to the benefits are integrated to calculate the sustainability scores via TOPSIS and SAW, as summarized in Table 4.5. The difference in the ranking results of the two MCDA methods is due to the normalization pattern and weighted scores. TOPSIS also provides the best solution based on the similarity of the ideal solution, and SAW uses the weight averages of the scores. However, the relative importance of TOPSIS for each of the five MCDA techniques is 52% (Sánchez-Garrido et al., 2022), which is the best distinguishable method among the MCDA techniques. SAW had a significance of 9% in the same research.

In the results of each sustainability pillar, while the weights under each pillar were considered, the weights associated with the pillars were not included. These weights are included in finding the overall sustainability score.

Table 4.5. *Sustainability Score of the Tomato Products for Each Pillar by the TOPSIS and SAW Methods*

	TOPSIS Method			SAW Method		
Products	Env	Eco	Soc	Env	Eco	Soc
Tomato Leather 1 (R_Tray_Leather)	0.102	0.244	0.343	0.256	0.359	0.458
Tomato Leather 2 (PP_Tray_Leather)	0.996	0.389	0.536	0.989	0.723	0.811
Tomato Bar 1 (R_MW_Bar)	0.200	0.363	0.317	0.279	0.367	0.444
Tomato Bar 2 (PP_MW_Bar)	0.986	0.297	0.539	0.975	0.350	0.585
Tomato Bar 3 (R_Conv_Bar)	0.000	0.696	0.312	0.236	0.591	0.445
Tomato Bar 4 (PP_Conv_Bar)	0.790	0.624	0.528	0.597	0.570	0.562

4.1.3.1. Environmental Sustainability Score

The TOPSIS method uses the distance from the best and worst solutions. In this context, the optimal products or the products closest to the best solution and the worst solution were calculated for each environmental impact criterion as shown in Table 4.6. The weights in Table 4.1 were used for the environmental sustainability assessment.

Table 4.6. *The Sustainability Performance of Each Product on the Environmental Criteria by the TOPSIS Method*

Products	C1	C2	C3	TOTAL	Ranking
A1	0.09	0.11	0.09	0.102	5
A2	0.99	1.00	0.99	0.996	1
A3	0.20	0.20	0.20	0.200	4
A4	1.00	0.98	1.00	0.986	2
A5	0.00	0.00	0.00	0.000	6
A6	0.80	0.78	0.80	0.790	3

According to the weighted sustainability scores of the environmental dimension, the most sustainable products were identified with pea protein sources. Among the bar products, tomato bar enriched with pea protein and dried with a MW vacuum dryer is the best alternative, followed by tomato bar with pea protein and corn obtained with a conventional dryer. The results are the same when solving the problem via the SAW method, as shown in Table 4.7.

Table 4.7. *The Sustainability Performance of Each Product on the Environmental Criteria by the SAW Method*

	C1	C2	C3	SAW	Ranking
Products	Human health	Natural Environment	Resources	Sustainability Score	
A1	0.07723	0.11491	0.06370	0.2558	5
A2	0.30183	0.43982	0.24768	0.9893	1
A3	0.08500	0.12400	0.07014	0.2791	4
A4	0.30752	0.41526	0.25266	0.9754	2
A5	0.07181	0.10530	0.05927	0.2364	6
A6	0.18476	0.26040	0.15215	0.5973	3

4.1.3.2. Economic Sustainability Score

The economic results were achieved by multiplying the parameters with the weights in Table 4.2 by applying the TOPSIS and SAW procedures. According to the economic results in Table 4.8, leather products are not found to be sustainable in terms of the first criterion (C1), as the tray dryer is more expensive than the MW vacuum dryer and the conventional dryer. In fact, there is not much need to use expensive technologies to increase sustainability in agricultural applications (Davis et al., 2017).

Table 4.8. *The Sustainability Performance of Each Product on the Economic Criteria by the TOPSIS Method*

Product	Cost	Prosperity Generation			Labor Productivity				Eco Sus. Score	Rank
	C1	C2	C3	C4	C5	C6	C7	C8		
A1	0.000	0.393	0.234	0.701	0.487	0.203	0.673	0.269	0.244	6
A2	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.389	3
A3	0.314	0.352	0.189	0.654	0.382	0.173	0.641	0.238	0.363	4
A4	0.314	0.155	0.205	0.065	0.099	0.961	0.072	0.184	0.297	5
A5	1.000	0.197	0.000	0.589	0.284	0.000	0.570	0.055	0.696	1
A6	1.000	0.000	0.016	0.000	0.000	0.788	0.000	0.000	0.624	2

The difference between the bar products is due to the amount of tomato powder, the drying technology, and the protein. The results show that pea protein is more sustainable than Rubisco protein, although Rubisco protein is derived from byproducts of sugar beet leaves. This may be due to the freeze drying of Rubisco, which was previously dried by a spray dryer and was found to be enhanced for sustainability (Skunca et al., 2021). In addition, pea protein is more sustainable because its production has been revised many times in industrial production, unlike that of the Rubisco protein. When solved with the SAW method, the rankings of the tomato leaves and tomato bars do not change, as shown in Table 4.9.

Table 4.9. *The Sustainability Performance of Each Product on the Economic Criteria by the SAW Method*

Product	Cost	Prosperity Generation			Labor Productivity				Eco Sus. Score	Rank
	C1	C2	C3	C4	C5	C6	C7	C8		
A1	0.06	0.06	0.05	0.06	0.03	0.03	0.03	0.03	0.3591	5
A2	0.06	0.12	0.12	0.12	0.07	0.07	0.07	0.07	0.7232	1
A3	0.09	0.05	0.05	0.06	0.03	0.03	0.03	0.03	0.3666	4
A4	0.09	0.05	0.05	0.03	0.02	0.07	0.02	0.03	0.3502	6
A5	0.34	0.05	0.05	0.05	0.02	0.02	0.03	0.03	0.5910	2
A6	0.34	0.04	0.05	0.03	0.02	0.05	0.02	0.03	0.5695	3

The economic sustainability for each impact category is illustrated in Figure 4.27. The best option among the bar products is tomato bar product-3.

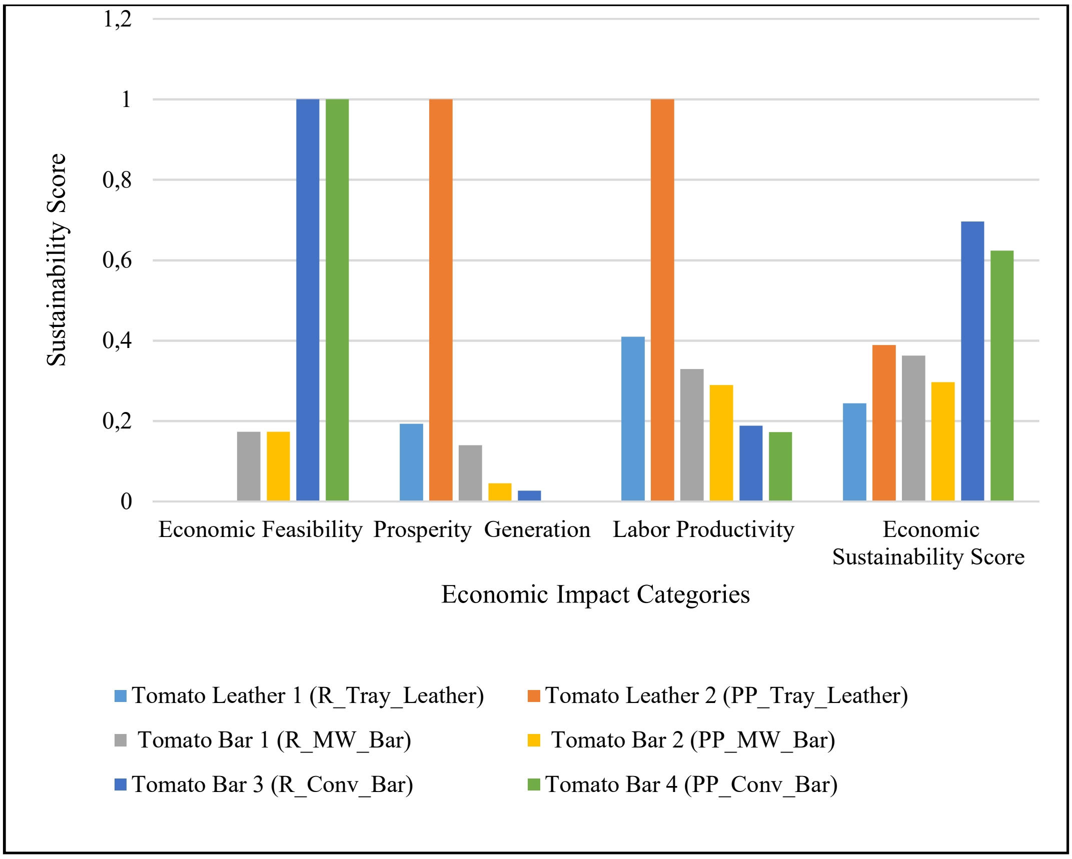

Figure 4.27. Sustainability Score by TOPSIS After Normalization According to the Economic Impact Category

4.1.3.3. Social Sustainability Score

The ranking with TOPSIS in Table 4.10 shows that for each unit of product, in terms of social sustainability, the best product is tomato snack bar with pea protein with MW vacuum drying. Tomato leather containing pea protein has the second highest degree of sustainability.

Table 4.10. *The Social Sustainability Scores By the TOPSIS and SAW Methods after Normalization and Multiplied by AHP Weights*

Products	TOPSIS Sustainability Score	Ranking	SAW Sustainability Score	Ranking
Tomato Leather 1 (R_Tray_Leather)	0.343	4	0.458	4
Tomato Leather 2 (PP_Tray_Leather)	0.536	2	0.811	1
Tomato Bar 1 (R_MW_Bar)	0.318	5-6	0.444	5-6
Tomato Bar 2 (PP_MW_Bar)	0.539	1	0.585	2
Tomato Bar 3 (R_Conv_Bar)	0.312	5-6	0.445	5-6
Tomato Bar 4 (PP_Conv_Bar)	0.528	3	0.562	3

After normalization by TOPSIS and weighting the results in terms of sustainability, Figure 4.28 reveals that the most sustainable product among the bars is tomato bar with pea protein and MW vacuum drying. Compared with the Rubisco product, pea protein is more sustainable for tomato leather.

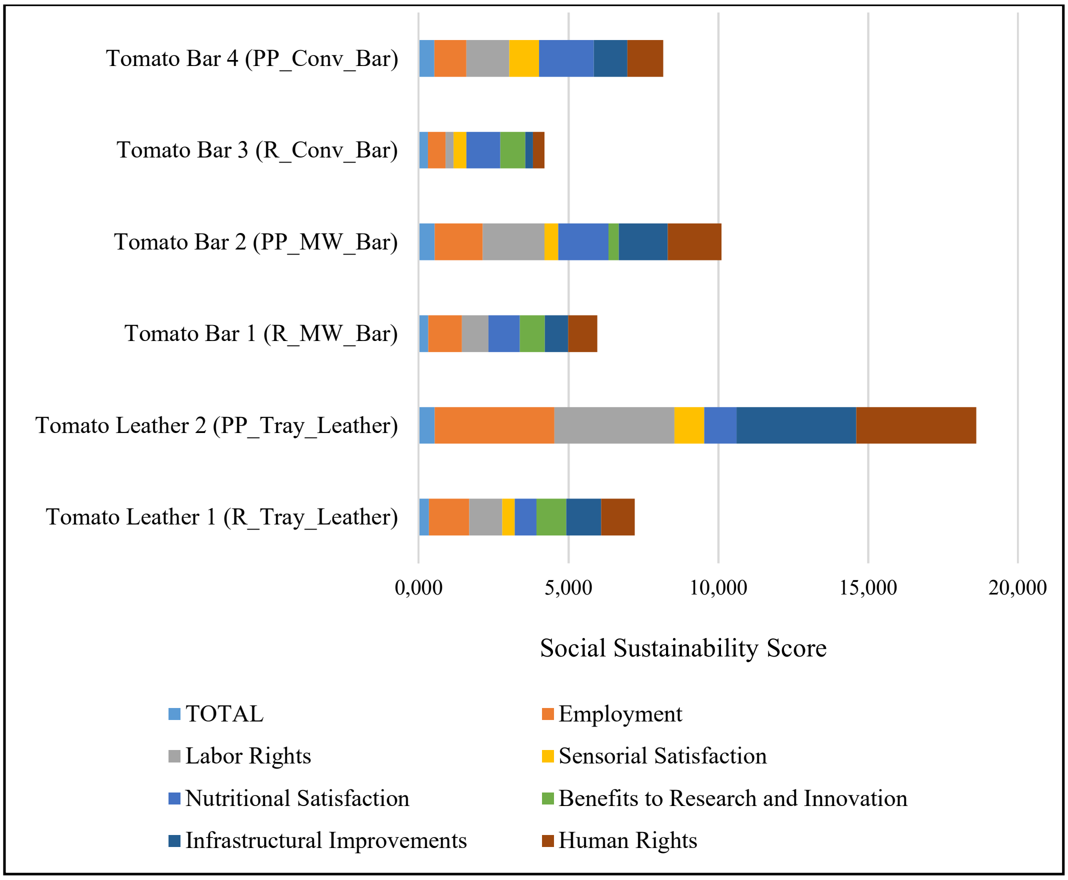

Figure 4.28. Social Sustainability Score of the Products by the TOPSIS Method after Normalization and Weighting

The sustainability score for each impact criterion is given in Figure 4.29. These findings show that the use of sensorial and nutrient compounds, which are embedded in social aspects, is more beneficial for food sustainability. Unemployment, labor laws, sensory and nutritional utility, research and innovation capacity, access to hospitals, gender equality, child labor and forced labor were more sustained among the developed products.

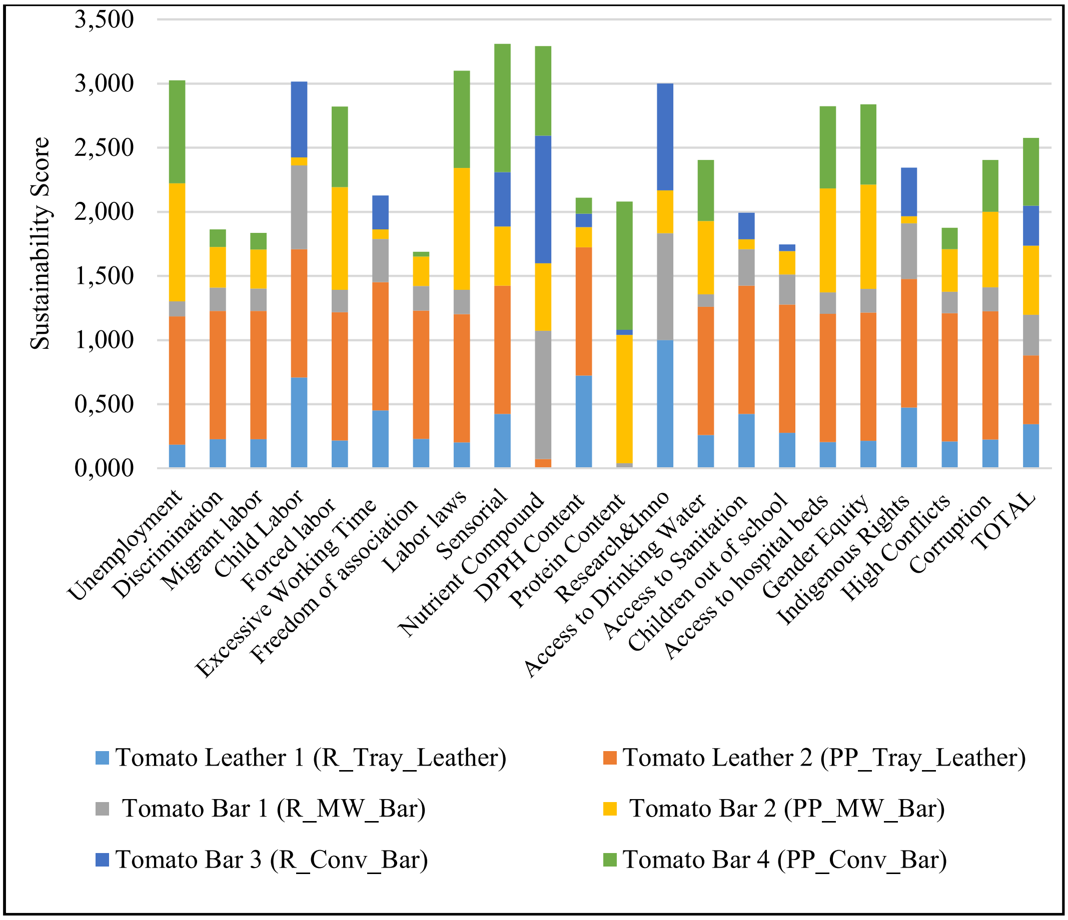

Figure 4.29. The Sustainability of the Products by the TOPSIS Method After Normalization According to the Social Impact Criterion

The results of the impact categories are also summarized for the proposed model and those in the SHDB in Table 4.11. While the results are the same in the first two positions, they change in the next positions. The social LCA model in the SHDB does not perform a product-based analysis. The reason for this is the product-specific criterion "product utility" considered in the model, such as nutrient content, sensory results and research and innovation development capacity.

Table 4.11 *Comparison of the Results of the Proposed Model with the Results of the SHDB Impact Categories*

Metod	Subcategories	A1	A2	A3	A4	A5	A6
Sustainability Scores of the Proposed Model (Better in Positive Direction)	Employment	1.345	4.000	1.125	1.604	0.591	1.070
	Labor Rights	1.098	4.000	0.892	2.055	0.262	1.425
	Sensorial Satisfaction	0.423	1.000	0.000	0.462	0.423	1.000
	Nutritional Satisfaction	0.723	1.072	1.039	1.682	1.138	1.825
	Benefits to Research and Innovation	1.000	0.000	0.833	0.333	0.833	0.000
	Infrastructural Improvements	1.162	4.000	0.782	1.642	0.258	1.118
	Human Rights	1.122	4.000	0.972	1.790	0.378	1.196
Risks Given By SHDB Categories (Better in Negative Direction)	Labor Rights & Decent Work	34.9988	14.7382	36.2917	32.8652	40.9840	37.5576
	Health & Safety	40.6375	16.4299	41.9604	36.8110	47.2346	42.0853
	Human Rights	22.5853	9.1991	23.4504	19.9945	26.3988	22.9429
	Governance	49.5631	21.1455	51.3143	46.3235	58.0714	53.0806
	Community	26.5549	11.0795	27.6643	24.7981	31.1839	28.3176

4.1.3.4. Evaluation of Overall Sustainability

The individual sustainability of each pillar is shown in Figure 4.30. When one is environmentally sustainable, it is not as economically sustainable. For example, tomato bar product 2 (A4), which has a MW vacuum and is processed and enriched with pea protein, is good as an environmental pillar and not as much as an economic pillar.

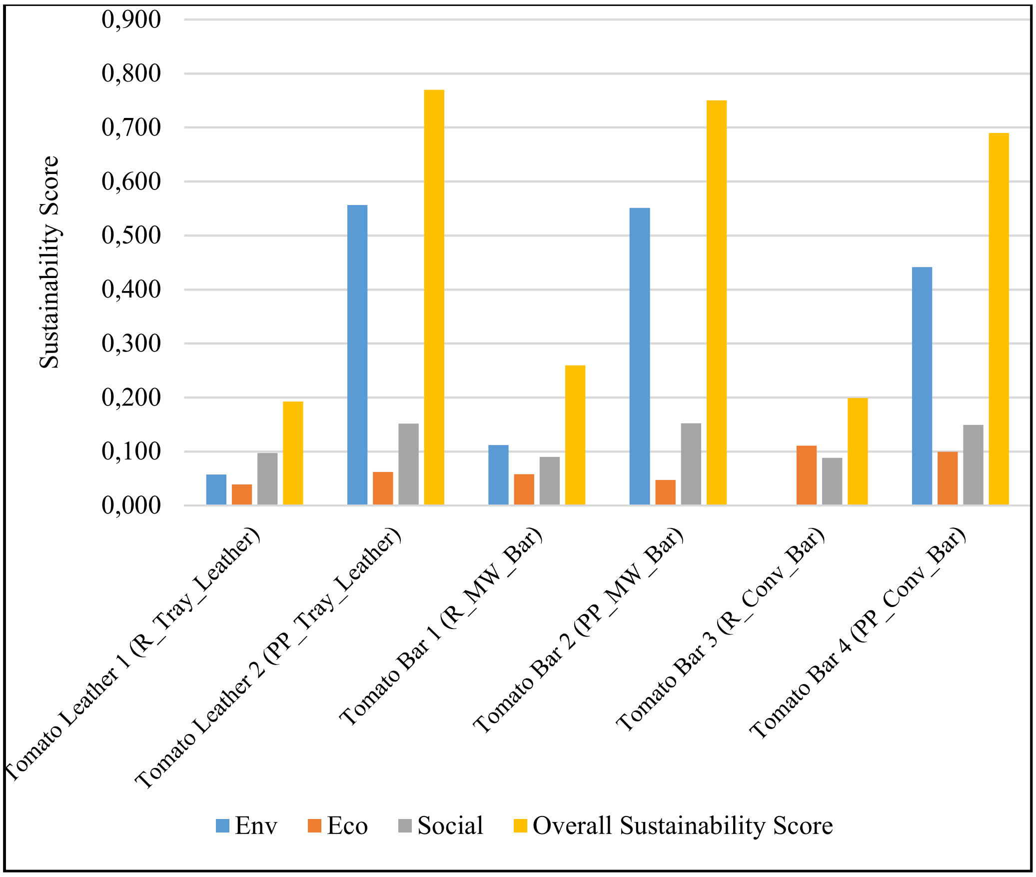

Figure 4.30. The Environmental, Economic, Social, and Overall Sustainability Scores of the Products by the TOPSIS Method after Normalization

Tomato leather with pea protein was superior in each category, as shown in Figure 4.31 according to the SAW method.

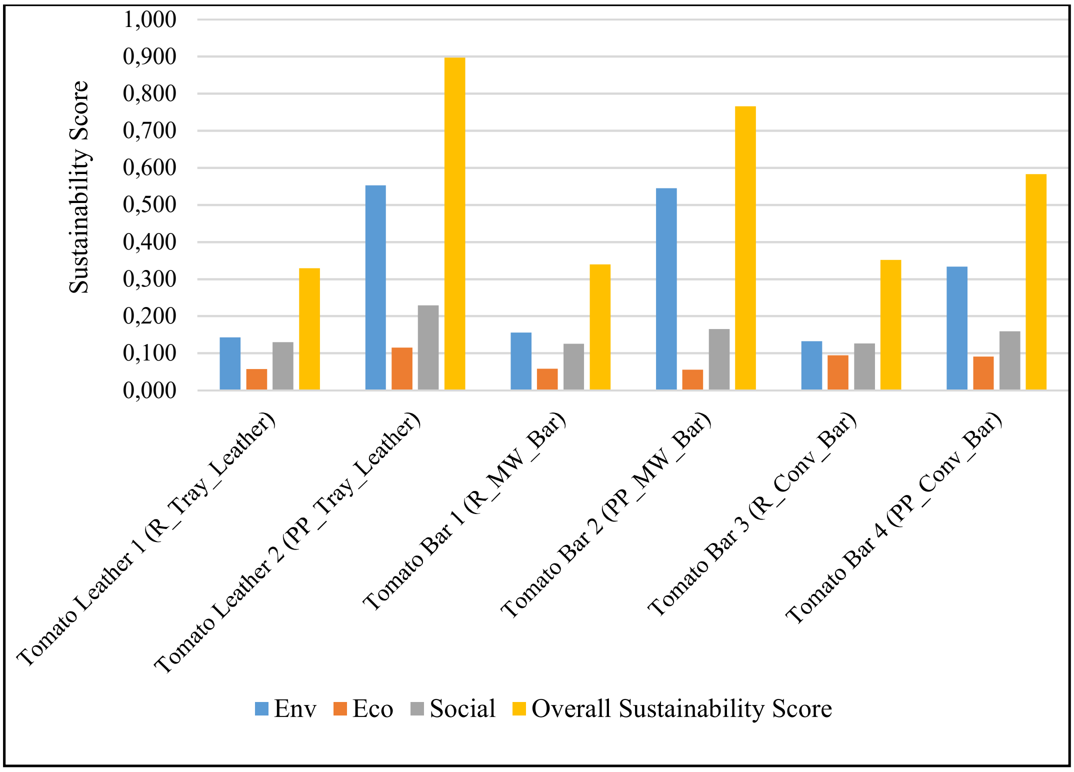

Figure 4.31. The Environmental, Economic, Social, and Overall Sustainability Scores of the Products by the SAW Method after Normalization

Therefore, to find a solution, TOPSIS and SAW solve this mathematical problem to obtain an overall score using the weights of each criterion in Table 4.4. The results in Table 4.12 show that when the weights change, the ranking also changes. For example, in the equal weight TOPSIS solution, A6, tomato bar-4 (pea protein and conventional), is ranked first, while tomato leather-2 (pea protein and tray dryer) is ranked second, and tomato bar-2 (pea protein and MW vacuum) is ranked third. However, in the TOPSIS solution, the products in the first three rankings are the same, but their rankings have changed. This shows that the importance of weights affects the sustainability performance of products. Since TOPSIS is more preferable of discrimination than SAW, the TOPSIS ranking can be accepted more precisely.

Table 4.12 *The Overall Sustainability Score of Products with Equal and AHP weights according to the TOPSIS and SAW Results*

				w1	w2	w3		AHP weights	w1	w2	w3		
				0.333	0.333	0.333			0.559	0.159	0.282		
	Individual Scores			Equal Weights					Weighted Results				
TOPSIS RESULTS	**Env**	**Eco**	**Social**	**Env**	**Eco**	**Social**	**Overall Sustainability Score**	**Ranking**	**Env**	**Eco**	**Social**	**Overall Sustainability Score**	**Ranking**
A1	0.102	0.244	0.343	0.034	0.081	0.114	0.230	6	0.057	0.039	0.097	0.192	6
A2	0.996	0.389	0.536	0.332	0.130	0.179	0.640	**2**	0.556	0.062	0.151	0.770	**1**
A3	0.200	0.363	0.317	0.067	0.121	0.106	0.293	5	0.112	0.058	0.090	0.259	4
A4	0.986	0.297	0.539	0.329	0.099	0.180	0.607	**3**	0.551	0.047	0.152	0.750	**2**
A5	0.000	0.696	0.312	0.000	0.232	0.104	0.336	4	0.000	0.111	0.088	0.199	5
A6	0.790	0.624	0.528	0.263	0.208	0.176	0.647	**1**	0.441	0.099	0.149	0.689	**3**
SAW RESULTS	**Env**	**Eco**	**Social**						**Env**	**Eco**	**Social**	**Overall Sustainability Score**	**Ranking**
A1	0.256	0.359	0.458	0.085	0.120	0.153	0.358	6	0.143	0.057	0.129	0.329	6
A2	0.989	0.723	0.811	0.330	0.241	0.270	0.841	**1**	0.553	0.115	0.229	0.897	**1**
A3	0.279	0.367	0.444	0.093	0.122	0.148	0.363	5	0.156	0.058	0.126	0.340	5
A4	0.975	0.350	0.585	0.325	0.117	0.195	0.637	**2**	0.545	0.056	0.165	0.766	**2**
A5	0.236	0.591	0.445	0.079	0.197	0.148	0.424	4	0.132	0.094	0.126	0.352	4
A6	0.597	0.570	0.562	0.199	0.190	0.187	0.576	**3**	0.334	0.091	0.159	0.583	**3**

CHAPTER 5

DISCUSSIONS AND CONCLUSIONS

This study aimed to assess sustainability and provide some methodological improvements for economic and social assessments. To measure social sustainability for dried tomato products along the cradle-to-market (farm to fork) food value chain, appropriate criteria and indicators related to subcriteria are weighted and then modeled by focusing on product-based micro criteria in addition to macro level data, which are typically examined in the literature. This study determined the optimal approach for revising and attaining the final specifications of dried tomato products. The outcomes are also expected to guide producers to attain deeper supply chains that have a greater beneficial impact.

5.1. Synthesis of the Dissertation and Results

In the first chapter, information about sustainability and background information from the literature was given for each dimension: environmental, economic and social. Gaps in the literature were addressed by means of problem definitions and the objectives of the thesis.

In the second chapter, developments related to sustainability were discussed conceptually in environmental, economic and social dimensions. Information on approaches, tools, applications and methods was given separately. Impact criteria in the literature were discussed; controversial issues in the literature or issues recommended for further study were mentioned; and the ways in which this thesis contributes to the literature were given.

In the third chapter, the materials and methods used in the study were described. The study methodology was diagrammed, and specifications and process diagrams of the products evaluated were given. In addition, the proposed assessment methodology of environmental, economic and social sustainability was presented. The AHP survey was explained in this chapter, and the MCDA methods used for calculations and data analysis were also mentioned.

In the fourth chapter, the results were discussed under three main headings, first, the AHP survey results for criteria weighting were given, and then, the section containing the results of the impacts in environmental, economic and social dimensions were given. In this section, the hotspots were shown with graphs, and the life cycle activities that need to be developed were presented. In the last part of this chapter, the sustainability scores weighted for each dimension and finally, the overall scores of the products were presented with two different MCDA methods.

In the fifth and the final chapter, discussions on the results and comparisons with the results in the literature were given, the information obtained from the results was analyzed in response to the research questions in the first part of this thesis. Projections to the future studies were also mentioned.

5.2. Main Discussions Addressing the Research Questions

This work represents a significant step forward in understanding the environmental, economic and social sustainability of food production systems, with a specific focus on dried tomato products-a key component of the Mediterranean diet. This study employs a comprehensive approach integrating life cycle assessment (LCA), life cycle costing (LCC) and social LCA methodologies, further enhanced by multicriteria decision-making tools such as the AHP, technique for order by preference by similarity to ideal solution (TOPSIS), and simple additive weighting (SAW). It has assessed not only the environmental impact of these products but also their economic and social viability, incorporating both global criteria and product-level costs into our analysis.

The novelty of this research lies in its holistic approach to sustainability, merging environmental considerations with economic and socioeconomic factors, thus offering a broader perspective on sustainability assessments. The findings revealed the significant impact of raw tomato production processes, including product enrichment and texturization, as well as the chosen drying method, on the sustainability of the final products. These insights are crucial for stakeholders across the food value chain, from farmers to food processors and policymakers, in making informed decisions that align with sustainability goals.

By combining environmental science with economic and social analysis and decision-making frameworks, which is also the interdisciplinary nature of the Earth's System Science, this study would be of interest to researchers, practitioners, and policymakers engaged in sustainable food system design and environmental management. Thus, this study addresses the following critical issues related to the sustainability of agricultural systems and food value chains:

- The **environmental footprint** has shown that raw materials and their deeper supply chains are as important as processing technologies. In product comparisons, the Rubisco protein life cycle has shown greater risk even when using a MW vacuum dryer than when using pea protein. Different novel methodologies can be implemented for the production of rubisco and olive powder to reduce the environmental impacts. Furthermore, the extraction methods could be differentiated in terms of the use of Pectinase enzymes. By minimizing energy consumption and reducing the use of chemicals, sustainability rankings can be significantly influenced in further studies. It is also valuable to consider in the analysis that the Rubisco inventory is based on the laboratory scale. Pea protein data are related to the industrial scale, which is expected to be more efficient than small-scale production.
- The SHDB has socioeconomic themes recommended and used in social analysis. In this study, economic and social performance models were built by combining themes from the SHDB. **The impact categories were reclustered under the economic and social categories.** The **economic**

footprint has become more meaningful with product-level costs and broader macroeconomic factors, ensuring the avoidance of double counting between economic and environmental dimensions. The importance of the impact criteria of the economic model has shown that none of the criteria are irrelevant. It also enables a link with social LCA, which needs to be established. In the cradle-to-market case study, while the cost of investment is lower in conventional dryers, the criteria defining economic prosperity and labor productivity are higher in MW vacuum drying, which offers a sustainable, energy-efficient alternative. This approach offers a valuable tool to revise environmental and economic risks in agri-food supply chains with the potential for future expansion into social dimensions.

- This study applied the LCA approach methodologically in the social pillar, **using product-specific micro-level criteria (such as sensory, nutrient and benefit to research and innovation) to ensure that the model covered a comprehensive set of criteria.** Thus, the social LCA model of the SHDB has not been directly used. In the case study section, product-specific data have been included in the sustainability model. The study emphasized that the addition of product-specific criteria changes the sustainability results. In addition, **this hybrid impact pathway should be applied in other cases to visualize its generality as a framework.** These results may also contribute to future research on the Mediterranean diet due to its impact on culture, health, and sustainability.
- Furthermore, **nutritional sustainability** is a very important concept in the SDGs. In addition to the LCA model, the proposed social model includes nutritional and sensory criteria. The importance of these criteria was calculated to be high in AHP responses. Product-based criteria provide a more precise estimate of social potential.
- Nevertheless, the results with impact categories of the proposed social model are **in line with the results of the SHDB impact categories.**

- The importance of impact categories in the SHDB model is equal. However, the importance of stakeholders and impact criteria has been calculated for economic and **social footprints** by applying the **AHP procedure**. Through the AHP weighting of stakeholders, the most important stakeholder is society, followed by consumers and workers.
- Considering the economic and social impacts, **the regional occurrence of risks can be observed**. In fact, by changing the supply chain, materials, or stakeholders, high risks can shift from hotspots. These hotspots can be reduced by selecting stakeholders (i.e., protein sources and their origin of purchase). Thus, sustainability improvements are also possible when changing the ingredient or purchasing country.
- **Sustainability score** between 0-1 was calculated for each pillar and each product with TOPSIS and SAW techniques. This overall score which integrates the three pillars of sustainability also provides the ranking of products in terms of sustainability. All the implementation steps for assessing the sustainability of the **six novel and dried tomato products** are clearly given. **As a framework**, this procedure can be a model for companies planning to measure and improve their value chain. Risks in life cycle activities can be clearly observed. These findings underscore the need to optimize hotspots such as the tomato powder production process (used in the bar) to reduce energy consumption and to explore more sustainable methods for Rubisco protein extraction to achieve more environmentally friendly products.
- Leather products are expected to be more sustainable as they undergo fewer processes. However, the case study results show that **the product content and complexity (raw material life cycle) are also important.** Due to their textural characteristics, bar products require much more raw material than do leather products. Even though this issue places an extra burden on sustainability assessments, bar products produced with MW vacuum dryers have advantages in terms of energy consumption. It has been observed that

olive powder production is a significant burden due to energy consumption. In addition, Rubisco protein is less sustainable because of the high energy and extraction burden. This process should be improved in a green way in future studies.

- In terms of the importance of impact categories, the environmental dimension was found to be the most important by the experts. For the economic pillar, all the impact subcategories were calculated to have almost the same importance. This shows that the economic criteria are strongly related. For the social pillar, the stakeholders of society and consumers were found to be more important than workers and employers. This finding also revealed that the nutrient criteria added to the social model are highly important.

5.3. Improvement Measures and Actions

In the agri-food sector, environmental assessments have been conducted on different types of food. D'Ammaro et al. (2021) examined wines in terms of their environmental footprint and vineyard management. They also considered a category as a regional factor for socioeconomic aspects of sustainability. However, this approach is not based on LCA; instead, human-related impacts on footprints are combined with socioeconomic criteria using Monte Carlo simulation. Wohner et al. (2020) examined environmental and economic dimensions in the sustainability analysis of food packaging systems for tomato ketchups. The emptiness of the packaging is analyzed using the eight impact categories from the Product Environmental Footprint (PEF) Guidelines (EU, 2018).

The minimization of the hotspots is achieved in different case studies (Baiano, 2021; D'Ammaro et al., 2021). The changes in design that produce positive sustainability in this study are summarized in Table 5.1.

Table 5.1. *Negative Aspects of Sustainability in the Product Life Cycle*

Hotspot	**Pillar**	**Critical Aspect**	**Improvement**
Rubisco production	Environmental	Freeze dryer is energy intense	Other drying technology or hybrid drying with MW vacuum dryer may be tried.
Rubisco production	Economic and Social	Pectinase Enzyme	Purchasing stakeholder may be changed. Product recipe may be changed.
Pea Protein	Economic and Social	Protein Content	It increases the product social risks more than energy load dryer as in the case of Tomato bar product 4. The purchasing origin of stakeholder can be changed. Other protein alternatives can be tried.
Olive powder production	Environmental	Freeze dryer and vacuum	Other drying technology or hybrid drying with MW vacuum dryer may be tried.

The results for Rubisco protein production parallel the environmental results of Skunca et al. (2021). The authors showed that mitigation options should consider electricity usage.

The beneficial (maximized) aspects, which affect sustainability positively, were attained by giving the critical points in Table 5.2.

Table 5.2. *Beneficial Aspects of Sustainability in the Product Life Cycle*

Life Cycle Activity	Pillar	Positive Aspects	Critical Point
Raw materials	Social	Nutritional Quality	Protein content has been enriched in the products. The antioxidant activity has increased with the addition of olive powder. However, Rubisco and olive powder life cycle are also a concern to be improved.
	Social	DPPH Antioxidant Activity	Lycopene content may also be analyzed in later activities.
Drying	Social	TPC and Flavonoid Content	MW vacuum dryer protect more TPC and flavonoid content
	Social	Sensory property	Conventional dryer increases the sensory utility of the products, while its energy results are not as bad as a tray dryer.
	Environmental	MW Vacuum Dryer	Environmentally sustainable
Packaging	Environmental	Material	The selection of biodegradable material is environmentally friendly.

While the product designs are not finished in the FunTomP Project, some of the improvements have already been made. For example, tomato powder production is included in the life cycle of tomato bars. Instead, tomato pomace, which is a waste of tomato plants, is preferred. In addition, the time and power of dryer technologies have been optimized to decrease the energy intensity. Packaging material has been selected as a biodegradable alternative; thus, there is no apparent packaging risk in the results.

However, the hotspots still reveal some good improvements. One of them is the drying technology of Rubisco production, since it greatly increases the environmental burden. The other method is to produce tomato powder by hybridization processes. In addition, the production of olive powder by a freeze dryer can cause injuries and fatalities, which increase the number of reports on its health and decrease the productivity of the economic ecosystem.

The social impact results have been compared with licensed social LCA categories in the SHDB. The impact categories in the SHDB show the risks opposite to those in Figure 4.28. Among the bar products, tomato bar with pea protein and MW vacuum drying has a lower risk than other bar products does. Thus, the SHDB model yielded the same results as those shown in Figure 4.28. Thus, the model of SHDB has given the same results of the proposed social model.The best products are tomato leather-2 (PP, tray), tomato bar-2 (PP, MW), tomato leather-1 (R, tray), tomato bar-1 (R, MW), tomato bar-4 (PP, conv), and tomato bar-3 (R, conv).

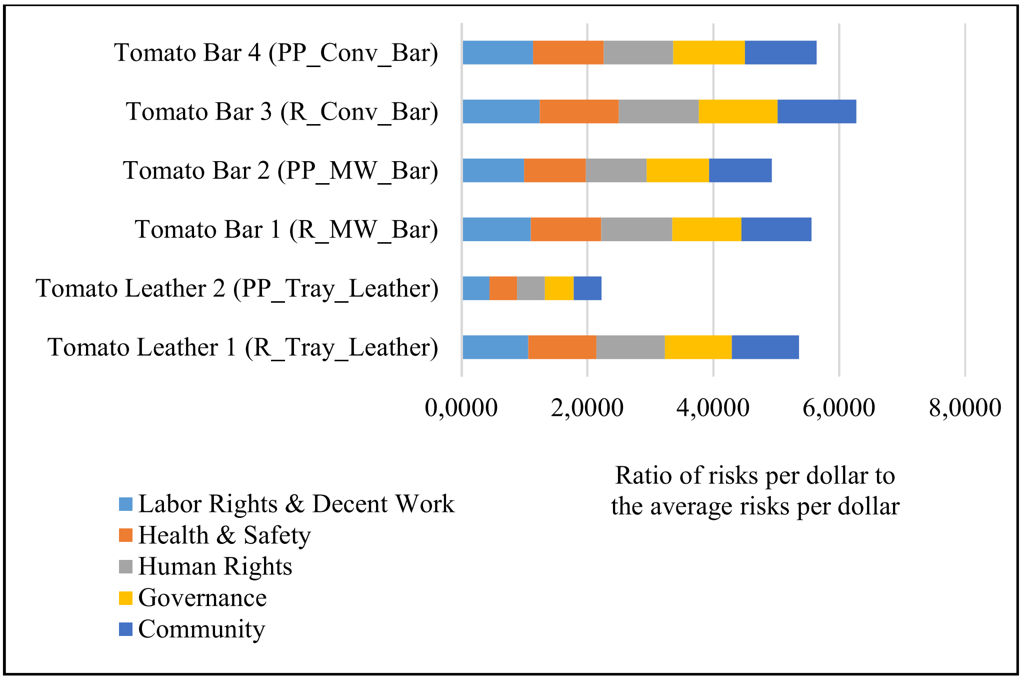

Figure 5.1. The Social Footprint Results According to the Impact Categories of SHDB

This study used the LCA approach methodologically, using product-specific micro criteria to ensure that the results cover a broader life cycle, which captures the product specific aspects. In this way, it has been shown that not only risks but also different criteria, including benefits, can be included in the sustainability model. While the results are the same in the first two positions, they change in the next positions. The reason for this is the product-specific criterion "product utility" considered in the model, such as nutrient content, sensory results and research and innovation development capacity. The social LCA model in the SHDB does not perform a product-based analysis. The other reason is that while the importance of impact categories in the SHDB model are equal, in this model, the AHP weighting has proposed different importance of impact categories. Weighting can be performed by the different segments of the food chain, considering the farmers, sector initiatives, and public authorities.

The health criterion has already been considered in the environmental pillar as damage to human health. The health criteria of the SHDB are not included in the proposed social model or other evaluations to avoid double counting in future complementary environmental studies.

As products are designed for the Mediterranean diet, the aim is also to increase the consumption of these products. Cultural heritage is not included in the criteria because it is also considered an outcome in the literature that is affected not only by social impact but also by the environment. Therefore, it is recommended that the social dimension be examined with more criteria in future studies. Lycopene content was not included since the method was designed to standardize both tomato leather products and tomato bar products. In addition to differences in antioxidant quality, differences in nutrient content, such as lycopene content, can be detected. Other analyses of product utility, such as consumer analysis, can also be added.

Shelf life and food preservation are also important for food products. Different packaging materials can be analyzed by benchmarking not only the time until the product deteriorates but also the production activities of the selected packaging material, which has any impact on sustainability. As an approach for sustainability, instead of processing byproducts, waste can be decreased by mitigation procedures at each activity to achieve zero waste supply chains in food systems. The weighting can be performed with different methods. Different sensibility analysis can also be performed.

It is expected that the results will provide a framework for food companies when designing and assessing the sustainability of their products. The calculated sustainability score may also be an alternative to the ecolabeling of food products (Sengstschmid et al., 2011) by providing an integrated model of environmental, economic and social factors. The gap stated in the recommendation part of the ecolabeling report as “a credible multi-criteria overall outcome-based assessment system” and “a more comprehensive economic assessment” (Sengstschmid et al., 2011) can be answered by this research.

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APPENDICES

A. Social Themes and Issues in SHDB

Table A.1. *Characterized Issues by Social Theme and Category of the Social LCA* (Benoit-Norris et al., 2012)

Category	Social Theme (Name of Table)	Data Indicator	Characterized Issue
Human Rights	Indigenous Rights	Presence of indigenous population, X	Not characterized
		Indigenous Population, %	Amount of Indigenous Population
		ILO Convention adopted for Indigenous, Y or N UN Declaration for Indigenous, endorsed (Y), abstained (A), against (N)	Risk of country not adopting Indigenous ILO convention and UN Declaration
		Number of Laws enacted to protect Indigenous	Risk of country not passing Laws to protect Indigenous
		Qualitative	Risk for Indigenous Rights Infringements by Sector
	Gender Equity	Social Institutions and Gender Index Global Gender Gap World Bank Gender Development Indicator World Bank Gender Empowerment Index CIRI Human Rights Index—Economic CIRI Human Rights Index—Political CIRI Human Rights Index—Social	Risk of Gender Inequity
		Adolescent fertility rate (births per 1000 women ages 15–19)	Not characterized
		Fertility rate, total (births per woman)	Not characterized
		Share of women employed in the nonagricultural sector (% of total nonagricultural employment)	Not characterized
		% Unemployment, (% of female labor force unemployed/% of male labor force unemployed)	Not characterized
		% of women workers *vs.* men by sector	Risk of Gender Inequity by sector
	High Conflict Zones	Heidelberg Conflict Barometer—# of conflicts Heidelberg Conflict Barometer—maximum intensity of conflicts (1–5) Heidelberg Conflict Barometer—change in conflicts (positive = worsening) Number of Refugees—UN Refugee Agency (000's) Center for Systemic Peace Indicator Minority Rights Group Indicator Top Risers from last year in Minority Rights Group Indicator, X	Risk for High Conflict
		Qualitative	Risk for High Conflict specific to sectors

Category	Social Theme (Name of Table)	Data Indicator	Characterized Issue
Labor Rights and Decent Work	Labor Laws/Conventions	Number of Labor Laws	Risk of Country not passing Labor Laws
		Number of Labor Laws by sector	Risk of Country not passing Labor Laws by Sector
		Number of Labor Conventions ratified (out of 81 possible)	Risk of Country not adopting Labor Conventions
		Number of Labor Conventions ratified by sector	Risk of Country not adopting Labor Conventions by Sector
		Year of last Minimum Wage Update	Risk of Minimum Wage not being updated
	Wage Assessment	Minimum Wages (USD) Average Unskilled Wages (USD) in country	Risk of Country Average Wage being < Minimum Wage
		Non-Poverty Guideline (USD) Average Unskilled Wages (USD) in country	Risk of Country Average Wage being < Non-Poverty Guideline
		Minimum Wages (USD) Average Unskilled Wages (USD) by sector	Risk of Sector Average Wage being < Minimum Wage
		Non-Poverty Guideline (USD) Average Unskilled Wages (USD) by sector	Risk of Sector Average Wage being < Non-Poverty Guideline
	Population living in Poverty	Percent of Population living on <$2/day	Risk of Population living on <$2/day
	Child Labor	Child Labor % in country	Risk of Child Labor in country
		Child Labor % by sector	Risk of Child Labor by sector
	Forced Labor	Qualitative	Risk of Forced Labor in country
		Qualitative	Risk of Forced Labor by sector
	Excessive Working Time	Percent working >48 hours/week in country	Risk of Population working >48 hours/week in country
		Qualitative	Risk of Population working >48 hours/week by Sector
	Freedom of Association, Collective Bargaining, Right to Strike	Qualitative	Risk of not having Freedom of Association Rights
		Qualitative	Risk of not having Collective Bargaining Rights
		Qualitative	Risk of not having the Right to Strike
	Unemployment	Unemployment Average % from 2000–2009	Risk of High Unemployment in country
		Unemployment % by sector	Risk for High Unemployment by sector
Governance	Legal System	World Bank Worldwide Governance Indicator—Rule of Law Bertelsmann Transformational Index - Rule of Law, Independent Judiciary CIRI Human Rights Index—Independent Judiciary Global Integrity Index—Judicial Accountability Global Integrity Index—Rule of Law Global Integrity Index—Law Enforcement World Justice Project—Average	Risk of Fragility in Legal System

Table A.1. *Characterized Issues by Social Theme and Category of the Social LCA* (Benoit-Norris et al., 2012) *(cont'd)*

Category	Social Theme (Name of Table)	Data Indicator	Characterized Issue
Human Rights	Human Health - Communicable Diseases & Other Health Risks besides Disease	Life expectancy at birth (years) 2008	Risk of low life expectancy
		Mortality rates for injuries (per 100,000 population) 2004	Risk of high mortality rates due to injury
		Proportion of undernourished % of total population, (−) = <5% 2005–2007	Risk of high undernourishment
		Deaths due to indoor and outdoor air and water pollution, per million 2004	Risk of death due to air and water pollution
		Population affected by natural disasters, ave per year per million 2000–2009	Risk of death due to natural disasters
		Cases of HIV (per 1000 adults 15–49 years) 2010	Risk of HIV 2010
		Cases of Tuberculosis (per 100,000 population) 2008	Risk of Tuberculosis 2008
		Cases of Malaria (per 100,000 population) 2008	Risk of Malaria 2008
		Cases of Dengue Fever (per 100,000 population) 2005	Risk of Dengue Fever, 2005
		Cases of Cholera 2008	Risk of Cholera 2008
		Mortality rates from communicable diseases (per 100,000 population) 2004	Risk of mortality from communicable diseases
Community Infrastructure	Children Out of School	Children out of School—male	Risk of Children not attending School–male
		Children out of School—female	Risk of Children not attending School–female
		Children out of School—total	Risk of Children not attending School–total
	Access to Improved Drinking Water	Access to Improved Drinking Water, %—rural	Risk of not having access to Improved Drinking Water–rural
		Access to Improved Drinking Water, %—urban	Risk of not having access to Improved Drinking Water–urban
		Access to Improved Drinking Water, %—total	Risk of not having access to Improved Drinking Water–total
	Access to Improved Sanitation	Access to Improved Sanitation, %—rural	Risk of not having access to Improved Sanitation–rural
		Access to Improved Sanitation, %—urban	Risk of not having access to Improved Sanitation–urban
		Access to Improved Sanitation, %—total	Risk of not having access to Improved Sanitation–total
	Access to Hospital Beds	Access to Hospital Beds—# beds/1000 pop	Risk of not having Access to Hospital Beds

B. AHP Survey

The Questionnaire

Model Development for the Sustainability Assessment of Novel Tomato Products

AHP Survey for Experts

This survey was prepared under the scope of a PhD study titled "Sustainability of Dried Tomato Products in the 'Farm to Fork' Value Chain Approach" of the Earth System Science Graduate Programme of Middle East Technical University.

The survey will be used in the model of sustainability by Dilber Ayhan under the supervision of Prof. Dr. Hami Alpas (Earth System Science, Food Engineering, METU) and Prof. Dr. Halil Mecit Öztop (Food Engineering, METU). The information collected here will only be used for academic purposes, and the answers will not be published with the names open.

Thank you for your interest and contribution.

Information

This survey was conducted to assess the sustainability score of dried tomato food products. The well-known dimensions of sustainability are environmental, economic and social. A sustainable food system should constitute a balance of food production and consumption and no pressure on the environment while receiving economic and social benefits. The entire value chain in the food system was considered to identify the criteria under each dimension. For this purpose, the sustainability problem is complex and has multiple objectives in the field of food and agriculture: the key to achieving the 2030 Agenda for Sustainable Development (FAO, 2016).

AHP is a well-based tool to make decisions on multiple objectives in countless areas (Winston, 2003). This allows us to compare the alternatives in pairs and choose the most superior one (Saaty, 1990).

The target audience of this survey is professionals or researchers from the food sector, sustainability technologists, and specialists in environmental, economic, or social sciences. The survey was conducted via face-to-face interviews to ensure that the questions and procedures were well understood. The structure of the model is presented in Table 1 in three impact categories:

Table 1: Sustainability Assessment Model

Environmental Impacts	Economic Impacts	Social Impacts

• Damage to Human Health
• Damage to Natural Environment
• Damage to Natural Resources
	• Economic Feasibility and Affordability
	• Prosperity Generation
	• Labor Productivity
		• Employer/Worker
		  • Emloyment
		  • Labor Rights
		• Consumer
		  • Sensorial Satisfaction
		  • Nutritional Quality
		• Society
		  • Benefits to Research and Innovation Cap.
		  • Infrastructural Improvements
		  • Human Rights

Explanation of Criteria:

Environmental Performance Score: This score consists of the environmental pressures in three categories of health, environment, and resources.

- Damage to human health includes particulate matter, ionizing radiation, toxicity, ozone depletion, global warming, and water use.
- Damage to natural environment or ecosystem pressures include the indicators of freshwater pollution, biodiversity of species, and land use change, which is related to deforestation as well as global warming and water use.
- Damage to natural resources is related to the depletion of mineral and fossil resources.

Economic Performance Score: This score consists of economic feasibility and affordability, prosperity generation and labor productivity.

- Economic feasibility and affordability relate with product cost in the life cycle (investment, labor and operational costs), distribution cost (to the retail and markets) and retail cost. It also relates to the investment that contributes to the GDP.
- Prosperity generation also contributes to GDP by increasing the standards of the local community and society. This can be measured

by indicators such as localized production, the legal system and decreased poverty.

- Labor productivity, which also contributes to GDP, can be linked to wage assessment, social benefits to workers, and occasional labor health.

Social Performance Score: The subcriteria are identified by considering stakeholders as impact categories:

1. Employers/workers (local community),
    - Employment (unemployment, discrimination, migrant employment, child labor),
    - Labor rights (excessive working hours, forced labor, freedom of association, labor laws)
2. Consumers
    - Sensory satisfaction
    - Nutritional quality
3. Society;
    - Benefits to Research and Innovation Capacity (R&D improvements for the benefit of people)
    - Infrastructural improvements (access to fresh water, sanitation, hospital beds, children out of school)
    - Human rights (gender equity, indigenous rights, high conflicts, corruption)

The proposed model is designed to calculate the following:

1. Environmental Performance Score

2. Economic Performance Score

3. Social Performance Score

In this research, the weight of each subcategory in the sustainability score is determined by experts via the AHP method:

1. The three main categories are compared. In the first stage, there are 3 questions in which three criteria ("Environmental Performance Score", "Economical Performance Score", and "Social Performance Score") are evaluated.
2. After the three main categories are evaluated, each performance category will be examined among its own subcriteria, as shown in Figure.
3. In the score calculation, each subcategory is weighted according to its importance and contributes to the total sustainability score according to its weight.

The Weighting Scale of the AHP

Criteria will be compared in pairs on the following scale (Saaty & Vargas, 2013):

- 1=Equally important
- 3= Moderately important
- 5= Strongly Important
- 7= Very strongly important
- 9=Extremely important

SURVEY PAGE

The survey will be answered by experts. The pairwise comparison will be executed step by step for scoring the sustainability of dried tomato products in the PRIMA FunTomP Horizon Project (https://funtomp.com) coordinated by Prof. Dr. Mecit Halil Öztop.

Since the relevance of the experts is an important part of determining the weights of the criteria, they are determined under the circumstances below.

Information about the expert:

Name, Surname:

Gender:

Male	
Female	

Education:

Prof. Dr.	
Assoc. Dr.	
PhD	
Master of science	
Bachelor of science	

Working at:

University	
Private-Industry	
Research Center	
Food Plant	
Public Institution	

Professional at:

Social or Education	
Biology or Chemistry	
Environmental or Civil Eng.	
Economy	
Health	
Food or Chemical Engineering	
Sustainability	

How many years of experience have you been in your profession?

5-10	
10-15	
15-20	
20-25	
25-	

	Yes/No
Author of peer-reviewed journal articles	
Invited to speak at a conference	
A proceeding or poster in a sustainability conference	

SURVEY QUESTIONS

The survey contains 17 questions and can be completed in 15 minutes.

If criterion-A is seven more important than criterion-B, select from criterion-A. If criterion-B is more important, select the degree of importance from criterion-B.

Sample: Criterion A is 7 times more important than Criterion B

Criterion A versus Criterion B

9		7		5		3		1		3		5		7		9

Sample: Criterion B is 7 times more important than Criterion A

Criterion A versus Criterion B

9		7		5		3		1		3		5		7		9

Step – 1: Weighting the Environmental, Economic and Social Dimensions

There are three questions in this section.

Question 1: Compare "Environmental" and "Economic" dimensions. A score of 1-9 was assigned for the degree of importance.

Environmental versus Economic

9		7		5		3		1		3		5		7		9

Question 2: Compare "Economic" and "Social" dimensions. A score of 1-9 was assigned for the degree of importance.

Environmental versus Social

9		7		5		3		1		3		5		7		9

Question 3: Compare "Economic" and "Social" dimensions. Decide and select a score of 1-9 for the importance degree.

Economic versus Social

9		7		5		3		1		3		5		7		9

Step – 2: Weighting the sub-criteria in the Environmental Performance Score

Environmental Performance

Subcategory 1: The effect of pressure on human health is related to particulate matter, ionizing radiation, toxicity, ozone depletion, global warming and water use.

Subcategory 2: The effect of pressure on the natural environment (or ecosystem pressure) is related to freshwater pollution, the biodiversity of species, and land use change, which is related to deforestation as well as global warming and water use.

Subcategory 3: The effect of pressure on natural resources is related to the depletion of mineral and fossil resources.

There are three questions in this section.

Question 1: Compare "Damage to Human Health" and "Damage to the Natural Environment". A score of 1-9 was assigned for the degree of importance.

Damage to Human Health versus Damage to Natural Environment

9		7		5		3		1		3		5		7		9

Question 2: Compare "Damage to Human Health" and "Damage to Natural Resources". A score of 1-9 was assigned for the degree of importance.

Damage to Human Health versus Damage to Natural Resources

9		7		5		3		1		3		5		7		9

Question 3: Compare "Damage to Natural Environment" and "Damage to Natural Resources". A score of 1-9 was assigned for the degree of importance.

Damage to the Natural Environment versus Damage to Natural Resources

9		7		5		3		1		3		5		7		9

Step 3: **Weighting the subcriteria in the economic performance score**

Economic Performance

Subcategory 1: Economic feasibility and affordability (cost of the product)

Subcategory 2: Prosperity generation (increasing standards for local work, decreasing poverty)

Subcategory 3: Labor productivity (wage assessment, social benefits, risky or safe conditions of labor)

There are 3 questions in this section.

Question 1: Compare "economic feasibility and affordability" with "property generation". A score of 1-9 was assigned for the degree of importance.

Economic feasibility and affordability versus Prosperity generation

9		7		5		3		1		3		5		7		9

Question 2: Compare "Economic feasibility and affordability" with "Labor productivity". A score of 1-9 was assigned for the degree of importance.

Economic feasibility and affordability versus Labor productivity

9		7		5		3		1		3		5		7		9

Question 3: Compare "property generation" with "labor productivity". A score of 1-9 was assigned for the degree of importance.

Prosperity generation versus Labor productivity

9		7		5		3		1		3		5		7		9

Step-4: Weighting the Impact Categories of the Social Performance Score

The importance of impact categories as stakeholders in the food value chain will be compared by experts:

1. Employers/workers (local community),
   - Employment (unemployment, discrimination, migrant employment, child labor),
   - Labor rights (excessive working hours, forced labor, freedom of association, labor laws)
2. Consumers
   - Sensory satisfaction
   - Nutritional quality
3. Society;
   - Benefits to Research and Innovation Capacity (R&D improvements for the benefit of people)
   - Infrastructural improvements (access to fresh water, sanitation, hospital beds, children out of school)
   - Human rights (gender equity, indigenous rights, high conflicts, corruption)

Three questions will be answered.

Question 1: Compare "Worker/Employer" category importance with "Consumer" importance. A score of 1-9 was assigned for the degree of importance.

Worker/Employer versus Consumer

9		7		5		3		1		3		5		7		9

Question 2: Compare "Worker/Employer" category importance with "Society" importance. A score of 1-9 was assigned for the degree of importance.

Worker/Employer versus Society

9		7		5		3		1		3		5		7		9

Question 3: Compare the importance of the "consumer" category with that of the "society" category. A score of 1-9 was assigned for the degree of importance.

Consumer versus Society

9		7		5		3		1		3		5		7		9

Step 5: Weights the Social Performance Score Criteria

1. Employers/workers (local community),
   - Employment (unemployment, discrimination, migrant employment, child labor),
   - Labor rights (excessive working hours, forced labor, freedom of association, labor laws)
2. Consumers
   - Sensory satisfaction
   - Nutritional quality
3. Society;
   - Benefits to Research and Innovation Capacity (R&D improvements for the benefit of people)
   - Infrastructural improvements (access to fresh water, sanitation, hospital beds, children out of school)
   - Human rights (gender equity, indigenous rights, high conflicts, corruption)

There are five questions in this section.

Question 1: Compare "Employment" with "Labor rights". A score of 1-9 was assigned for the degree of importance.

Employment versus Labor rights

9		7		5		3		1		3		5		7		9

Question 2: Compare "Sensory satisfaction" with "Nutritional quality". A score of 1-9 was assigned for the degree of importance.

Sensory satisfaction versus Nutritional quality

9		7		5		3		1		3		5		7		9

Question 3: Compare "Benefits to Research and Innovation Capacity" with "Infrastructural improvements". A score of 1-9 was assigned for the degree of importance.

Benefits to Research and Inn. Cap. Dev. versus Infrastructural improvements

9		7		5		3		1		3		5		7		9

Question 4: Compare "Benefits to Research and Innovation Capacity" with "Human Rights". A score of 1-9 was assigned for the degree of importance.

Benefits to Research and Innovation Capacity versus Human Rights

9		7		5		3		1		3		5		7		9

Question 5: Compare the importance of "Infrastructural Improvements" with that of "Human Rights". A score of 1-9 was assigned for the degree of importance.

Infrastructural Improvements versus Human Rights

9		7		5		3		1		3		5		7		9

Table B.1. *Specifications of the Experts in the AHP Survey*

Specifications	Attributes	Expert1	Expert2	Expert3	Expert4	Expert5	Expert6	Expert7	Expert8	Expert9	Expert10	Expert11
1. Gender	F/M	M	M	F	F	F	M	M	F	F	M	F
2. Education	BS, MS, PhD	PhD	MS	MS	BS	PhD	PhD	PhD	PhD	BS	PhD	MS
3. Working at	U:University I:Private-Industry R:Research Center F: Food Plant P: Public Institution	U	I	I	I	I	P	U	U	F	U-P	F
4. Professional at	1: Social science, 2: Biology/Chemistry, 3: Environmental or Civil Eng., 4: Economy, 5: Health, 6: Food or Chemical Eng., 7: Sustainability	3-7	7	7	3	7	4	7	4	6	1	6
5. Professional Experience	years (at least 5 years)	15-20 years	5-10 years	5-10 years	10-15 years	15-20 years	20-25 years	25- years	25- years	15-20 years	15-20 years	10-15 years
6. Author of peer-reviewed journal articles	Yes/No	Y	N	N	N	Y	Y	Y	Y	N	Y	Y
7. Invited to speak at a conference	Yes/No	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
8. A proceeding or poster in a sustainability conference	Yes/No	Y	Y	Y	Y	Y	Y	Y	N	N	N	N

Table B.2. *Criterion Weighting through AHP-G (Geometric Mean)*

Dimension	Aspect	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	AHP-G	Seperate	Final Weight
Pillar	Env	0.14	0.64	0.64	0.71	0.43	0.48	0.69	0.63	0.72	0.63	0.19	0.56		
	Eco	0.43	0.07	0.07	0.14	0.43	0.11	0.14	0.11	0.19	0.11	0.08	0.16		
	Soc	0.43	0.28	0.28	0.14	0.14	0.41	0.18	0.26	0.08	0.26	0.72	0.28		
Env	C1	0.72	0.19	0.07	0.26	0.26	0.14	0.47	0.43	0.43	0.11	0.18	0.31	0.31	0.17
	C2	0.08	0.72	0.28	0.11	0.63	0.43	0.47	0.43	0.43	0.26	0.75	0.44	0.44	0.25
	C3	0.19	0.08	0.64	0.63	0.11	0.43	0.07	0.14	0.14	0.63	0.07	0.25	0.25	0.14
Eco	C1	0.43	0.19	0.63	0.11	0.63	0.20	0.60	0.11	0.11	0.20	0.64	0.34	0.34	0.05
	C2	0.43	0.72	0.11	0.26	0.26	0.60	0.20	0.63	0.63	0.20	0.07	0.37	0.37	0.06
	C3	0.14	0.08	0.26	0.63	0.11	0.20	0.20	0.26	0.26	0.60	0.28	0.29	0.29	0.05
Soc	IC1	0.14	0.11	0.26	0.57	0.20	0.20	0.45	0.19	0.11	0.07	0.06	0.27		
	SC1	0.75	0.25	0.25	0.75	0.25	0.50	0.50	0.05	0.50	0.75	0.17	0.63	0.17	0.05
	SC2	0.25	0.75	0.75	0.25	0.75	0.50	0.50	0.14	0.50	0.25	0.83	0.37	0.10	0.03
	IC2	0.43	0.11	0.63	0.14	0.60	0.20	0.09	0.08	0.63	0.64	0.65	0.36		
	SC3	0.75	0.75	0.25	0.17	0.25	0.17	0.25	0.02	0.75	0.17	0.25	0.28	0.10	0.03
	SC4	0.25	0.25	0.75	0.83	0.75	0.83	0.75	0.06	0.25	0.83	0.75	0.72	0.25	0.07
	IC3	0.43	0.78	0.11	0.29	0.20	0.60	0.45	0.72	0.26	0.28	0.29	0.38		
	SC5	0.43	0.07	0.08	0.26	0.26	0.11	0.20	0.07	0.11	0.08	0.26	0.18	0.07	0.02
	SC6	0.43	0.28	0.49	0.11	0.63	0.26	0.20	0.64	0.26	0.72	0.63	0.46	0.17	0.05
	SC7	0.14	0.64	0.44	0.63	0.11	0.63	0.60	0.28	0.63	0.19	0.11	0.35	0.13	0.04

C. USD Inflation Factor

A deflator of 1.39 is used from January 2024 to February 2011 (since the SHDB requires costs of 2011 USD). All the prices have been divided by 1.39 to the value in 2011 USD (U.S. Bureau of Labor Statistics, 2024).

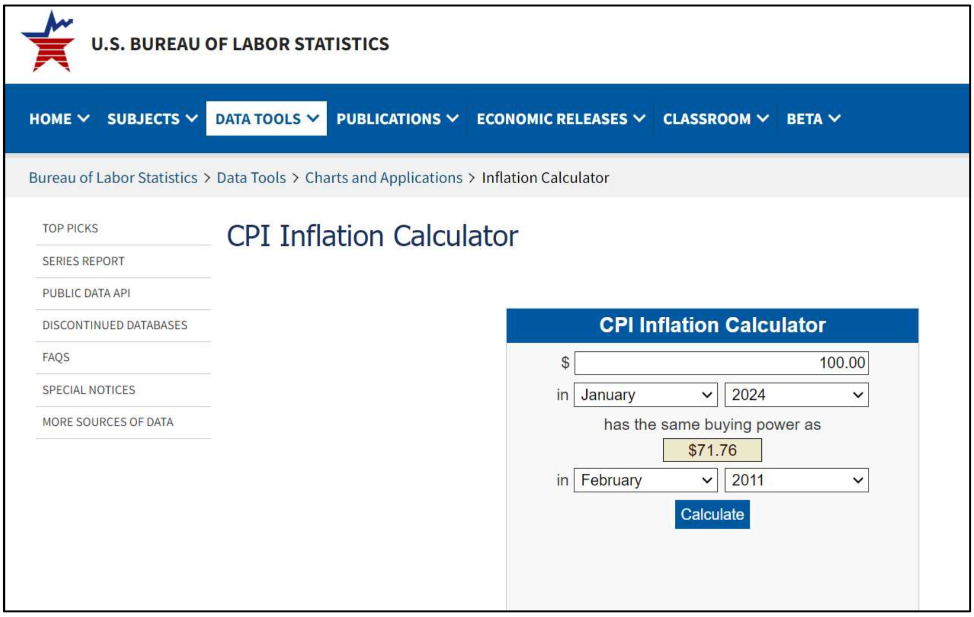

Figure C.1. Deflator for USD from 2024 to 2011 (U.S. Bureau of Labor Statistics, 2024).

D. Electricity Price

The electricity prices are taken from one of the energy distributors in Türkiye (Enerji Atlası, 2024).

enerjiatlasi.com/elektrik-fiyatlari/

Dağıtım Bedeli	(b)	0,878175 TL	210,76 TL
BTV * (a,%5)	(c)	0,095611 TL	22,95 TL
KDV Matrahı (a+b+c)	(d)	2,886006 TL	692,64 TL
KDV (d,%20)	(e)	0,577201 TL	138,53 TL
Elektrik Fiyatı (d+e)		**3,463207 TL**	**831,17 TL**

Sanayi Elektrik Tarifesi

Tek terimli alçak gerilim sanayi grubu aboneleri için geçerli tarife

Sanayi Aboneleri Elektrik Tarifesi			
Tüketim Miktarı		1 kWh	240 kWh
Elektrik Ücreti	(a)	3,053828 TL	732,92 TL
Dağıtım Bedeli	(b)	0,647998 TL	155,52 TL
BTV * (a,%1)	(c)	0,030538 TL	7,33 TL
KDV Matrahı (a+b+c)	(d)	3,732364 TL	895,77 TL
KDV (d,%20)	(e)	0,746473 TL	179,15 TL
Elektrik Fiyatı (d+e)		**4,478837 TL**	**1.074,92 TL**

Figure D.1. Electricity Price of Industry Use (Enerji Atlası, 2024)

E. Cost Calculations for the Economic Pillar

Table E.1. *Cost Calculation* (Peters et al., 2003)

Preliminary Method (Peters et al., 2003)	Purchased Equipment cost	Purchased-equipment installation	Instrumentation (installed)	Piping (installed)	Electrical (installed)	Buildings (including services)	Yard improvements	Service facilities (new plant installed)	Engineering and supervision	Construction expense	Legal Expense	Constructor's fee	Contingency	Total	Fixed Capital Investment (FCI)	Working Capital Investment (WCI)	Total Capital Investment (TCI)
Percentage of Fixed-Capital Investment	25.00	9.00	10.00	8.00	5.00	5.00	2.00	15.00	8.00	10.00	2.00	2.00	8.00	109.00			
Normalized percentage of FCI	22.94	8.26	9.17	7.34	4.59	4.59	1.83	13.76	7.34	9.17	1.83	1.83	7.34	100.00	85.00	15.00	100.00
Tomato Leather 1 (R_Tray_Leather)	30616.67	11022.00	12246.67	9797.33	6123.33	6123.33	2449.33	18370.00	9797.33	12246.67	2449.33	2449.33	9797.33	133488.67	133488.67	23556.82	157045.49
Tomato Leather 2 (PP_Tray_Leather)	30616.67	11022.00	12246.67	9797.33	6123.33	6123.33	2449.33	18370.00	9797.33	12246.67	2449.33	2449.33	9797.33	133488.67	133488.67	23556.82	157045.49
Tomato Bar 1 (R_MW_Bar)	22783.33	8202.00	9113.33	7290.67	4556.67	4556.67	1822.67	13670.00	7290.67	9113.33	1822.67	1822.67	7290.67	99335.33	99335.33	17529.76	116865.10
Tomato Bar 2 (PP_MW_Bar)	22783.33	8202.00	9113.33	7290.67	4556.67	4556.67	1822.67	13670.00	7290.67	9113.33	1822.67	1822.67	7290.67	99335.33	99335.33	17529.76	116865.10
Tomato Bar 3 (R_Conv_Bar)	5683.33	2046.00	2273.33	1818.67	1136.67	1136.67	454.67	3410.00	1818.67	2273.33	454.67	454.67	1818.67	24779.33	24779.33	4372.82	29152.16
Tomato Bar 4 (PP_Conv_Bar)	5683.33	2046.00	2273.33	1818.67	1136.67	1136.67	454.67	3410.00	1818.67	2273.33	454.67	454.67	1818.67	24779.33	24779.33	4372.82	29152.16

Table E.1. *Cost Calculation* (Peters et al., 2003) *(cont'd)*

Preliminary Method (Peters et al.. 2003)	Inventory tables	17000 TRY	%15 labor cost	Inventory tables	%7 FCI	%15 Maintenance	%20 operating cost	%80 of TPC	%10 TPC	%10 TPC	Total Production Cost (TPC)	Total Capital Investment (TCI)	Total Cost (TPC+TCI)
Percentage of Fixed-Capital Investment	Raw materials (functional unit)	Labor cost	Labor Supervision	Utilities (energy)	Maintenance and repair	Operating supplies	Laboratory charges	Operating Costs	Tax. insurance	Plant Overhead Cost			
Normalized percentage of FCI	50.00	0.50											
Tomato Leather 1 (R_Tray_Leather)	4.35	283.33	42.50	0.58	9344.21	1401.63	2769.15	13845.75	1730.72	1730.72	17307.19	157045.49	174352.68
Tomato Leather 2 (PP_Tray_Leather)	0.64	283.33	42.50	0.58	9344.21	1401.63	2768.22	13841.11	1730.14	1730.14	17301.39	157045.49	174346.88
Tomato Bar 1 (R_MW_Bar)	4.64	283.33	42.50	0.08	6953.47	1043.02	2081.76	10408.80	1301.10	1301.10	13011.00	116865.10	129876.10
Tomato Bar 2 (PP_MW_Bar)	1.33	283.33	42.50	0.08	6953.47	1043.02	2080.93	10404.67	1300.58	1300.58	13005.84	116865.10	129870.94
Tomato Bar 3 (R_Conv_Bar)	5.10	283.33	42.50	0.47	1734.55	260.18	581.54	2907.68	363.46	363.46	3634.60	29152.16	32786.75
Tomato Bar 4 (PP_Conv_Bar)	1.73	283.33	42.50	0.47	1734.55	260.18	580.69	2903.46	362.93	362.93	3629.32	29152.16	32781.48

F. TOPSIS and SAW Decision Matrices

TOPSIS Results

Table F.1. *Environmental Decision Matrix of TOPSIS after Weighting and Normalization*

Criteria	A1	A2	A3	A4	A5	A6
Human Health	0.12706	0.00080	0.11154	0.00000	0.13985	0.02831
Natural Env.-Ecosystems	0.17649	0.00000	0.15897	0.00369	0.19829	0.04301
Natural Resources	0.10426	0.00071	0.09146	0.00000	0.11468	0.02322
Total	0.05816	0.00000	0.04608	0.00001	0.07203	0.00319
S*	0.24117	0.00107	0.21466	0.00369	0.26838	0.05648
S^-	0.02734	0.26766	0.05372	0.26567	0.00000	0.21195
Env. Sus. Score	0.10183	0.99602	0.20017	0.98630	0.00000	0.78959

Table F.2. *Economic Decision Matrix of TOPSIS after Weighting and Normalization*

Criteria	A1	A2	A3	A4	A5	A6
C1	0.1552	0.1552	0.1064	0.1064	0.0000	0.0000
C2	0.0254	0.0000	0.0271	0.0354	0.0336	0.0419
C3	0.0283	0.0000	0.0300	0.0294	0.0370	0.0364
C4	0.0176	0.0000	0.0204	0.0550	0.0242	0.0589
C5	0.0142	0.0000	0.0171	0.0250	0.0199	0.0277
C6	0.0227	0.0000	0.0235	0.0011	0.0284	0.0060
C7	0.0109	0.0000	0.0120	0.0310	0.0144	0.0334
C8	0.0160	0.0000	0.0167	0.0179	0.0207	0.0219
Total	0.0269	0.0241	0.0147	0.0184	0.0049	0.0090
S^*	0.1641	0.1552	0.1210	0.1356	0.0702	0.0946
S^-	0.0530	0.0988	0.0689	0.0572	0.1606	0.1568
Eco Sus. Score	0.2439	0.3891	0.3627	0.2966	0.6958	0.6237

Table F.3. *Social Decision Matrix of TOPSIS after Weighting and Normalization*

Criteria	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**
C1	0.01512	0.00000	0.01638	0.00148	0.01854	0.00364
C2	0.01036	0.00000	0.01099	0.00914	0.01340	0.01156
C3	0.01042	0.00000	0.01111	0.00937	0.01346	0.01172
C4	0.00595	0.00000	0.00707	0.01911	0.00833	0.02037
C5	0.00723	0.00000	0.00763	0.00183	0.00923	0.00343
C6	0.00546	0.00000	0.00660	0.00921	0.00734	0.00995
C7	0.00565	0.00000	0.00592	0.00565	0.00733	0.00706
C8	0.00745	0.00000	0.00756	0.00047	0.00933	0.00224
C9	-0.01040	0.00000	-0.01804	-0.00971	-0.01040	0.00000
C10	-0.03325	-0.03085	0.00000	-0.01576	-0.00019	-0.01002
C11	-0.01220	0.00000	-0.04404	-0.03715	-0.03945	-0.03846
C12	-0.05591	-0.05591	-0.05370	0.00000	-0.05370	0.00000
C13	0.00000	-0.00981	-0.00164	-0.00654	-0.00164	-0.00981
C14	0.01358	0.00000	0.01658	0.00784	0.01833	0.00959
C15	0.00988	0.00000	0.01228	0.01580	0.01362	0.01714
C16	0.00967	0.00000	0.01023	0.01092	0.01266	0.01336
C17	0.01330	0.00000	0.01388	0.00318	0.01668	0.00598
C18	0.00964	0.00000	0.01001	0.00231	0.01227	0.00458
C19	0.01032	0.00000	0.01111	0.01853	0.01221	0.01964
C20	0.00857	0.00000	0.00904	0.00723	0.01084	0.00903
C21	0.00882	0.00000	0.00923	0.00466	0.01135	0.00679
S^*	0.07772	0.06460	0.08379	0.05734	0.08432	0.06062
S^-	0.04053	0.07473	0.03898	0.06694	0.03826	0.06788
Social Sus. Score	0.34272	0.53632	0.31750	0.53862	0.31210	0.52825

SAW Results

Table F.4. *Environmental Decision Matrix of SAW after Weighting and Normalization*

Products	C1 Damage to Human Health	C2 Damage to Natural Environment (Ecosystems)	C3 Damage to Natural Resources	SAW Environmental Sustainability Score
Tomato Leather 1 (R_Tray_Leather)	0.07723	0.11491	0.06370	0.2558
Tomato Leather 2 (PP_Tray_Leather)	0.30183	0.43982	0.24768	0.9893
Tomato Bar 1 (R_MW_Bar)	0.08500	0.12400	0.07014	0.2791
Tomato Bar 2 (PP_MW_Bar)	0.30752	0.41526	0.25266	0.9754
Tomato Bar 3 (R_Conv_Bar)	0.07181	0.10530	0.05927	0.2364
Tomato Bar 4 (PP_Conv_Bar)	0.18476	0.26040	0.15215	0.5973

Table F.5. *Economic Decision Matrix of SAW after Weighting and Normalization*

Criteria	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**
Cost of the Product (Dollar)	0.0641	0.0641	0.0860	0.0860	0.3408	0.3409
Smallholder v Commercial Farms	0.0569	0.1240	0.0549	0.0470	0.0485	0.0422
Poverty	0.0544	0.1240	0.0527	0.0533	0.0465	0.0470
Legal System	0.0603	0.1240	0.0558	0.0289	0.0506	0.0274
Wage	0.0306	0.0718	0.0274	0.0213	0.0249	0.0198
Injuries & Fatalities	0.0266	0.0718	0.0260	0.0663	0.0229	0.0494
Occ Tox & Haz	0.0341	0.0718	0.0324	0.0174	0.0293	0.0164
Social Benefits	0.0320	0.0718	0.0312	0.0300	0.0275	0.0266
Economic Score	0.3591	0.7232	0.3666	0.3502	0.5910	0.5695

Table F.6. *Social Decision Matrix of SAW after Weighting and Normalization*

Criteria	A1	A2	A3	A4	A5	A6
C1	0.0126	0.0425	0.0119	0.0345	0.0109	0.0270
C2	0.0179	0.0425	0.0173	0.0192	0.0153	0.0168
C3	0.0177	0.0425	0.0170	0.0188	0.0151	0.0165
C4	0.0206	0.0425	0.0188	0.0096	0.0171	0.0092
C5	0.0095	0.0245	0.0092	0.0175	0.0081	0.0140
C6	0.0088	0.0245	0.0077	0.0061	0.0072	0.0057
C7	0.0108	0.0245	0.0105	0.0108	0.0092	0.0095
C8	0.0096	0.0245	0.0095	0.0223	0.0083	0.0167
C9	0.0788	0.1003	0.0631	0.0803	0.0788	0.1003
C10	0.0249	0.0293	0.0850	0.0565	0.0846	0.0669
C11	0.0674	0.0850	0.0217	0.0316	0.0283	0.0297
C12	0.0054	0.0054	0.0085	0.0850	0.0085	0.0850
C13	0.0688	0.0482	0.0654	0.0550	0.0654	0.0482
C14	0.0130	0.0437	0.0113	0.0186	0.0105	0.0164
C15	0.0156	0.0437	0.0135	0.0113	0.0125	0.0106
C16	0.0195	0.0437	0.0189	0.0182	0.0167	0.0161
C17	0.0163	0.0437	0.0159	0.0312	0.0141	0.0249
C18	0.0132	0.0333	0.0129	0.0244	0.0114	0.0194
C19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C20	0.0133	0.0333	0.0129	0.0146	0.0114	0.0129
C21	0.0138	0.0333	0.0135	0.0191	0.0118	0.0160
Social Sustainability Score	0.4576	0.8108	0.4443	0.5845	0.4452	0.5616

CURRICULUM VITAE

DİLBER AYHAN

EDUCATION

Degree	Institution	CumGPA	Years
PhD	METU Earth System Science	3.64/4.00	February 2019-
MSc	METU Industrial Engineering	3.21/4.00	2006-2009
BS	METU Food Engineering (First year is for English prep. school)	3.57/4.00	2000-2005
High School	Kaya Bayazıtoğlu Anadolu High School, Mat-Science, Ankara	5.00/5.00 (1st Rank)	1998-2000

BACKGROUND

While studying PhD in Earth System Science, the core courses of Earth System, Environmental Economics and elective courses of Environmental Philosophy, Global Environmental Issues, Energy Policy and Finance, Nature and Human Use, Sustainable Development, Environment, Society & Technology were completed.

The master's degree in industrial engineering allowed to apply engineering principles and methods to complex problems, which stems from the core courses of Operations Research I-II, Production and Service Operations Planning I-II, Linear Optimization, Stochastic Models, and elective courses of Multiobjective Decision Making, Design of Experiments Analysis, Quality Planning & Control, Total Quality Management.

RESEARCH PROJECTS

- For doctoral study, the project under grant agreement #2032 titled Functionalized Tomato Products (FunTomP) supported by the European Union's Horizon 2020 PRIMA Section I Program.
- For master's study, the project under grant agreement #105M138 titled Use and Development of Data Mining in Quality Improvement supported by TÜBİTAK's 1001 Programme.

WORK EXPERIENCE

2006-up to now, Researcher, Scientific and Technological Research Council of Türkiye (TÜBİTAK)

LANGUAGE

- Native in Turkish
- English- very good command in reading and writing, fluent in speaking
- French- elementary in speaking and writing and reading (French Cultural Center speaking courses, Ankara)
- German- elementary in speaking, writing, and reading (I took the elective courses up to advanced level given by METU Foreign Languages Dept.)

COMPUTER SKILLS AND CERTIFICATES

- Certificated by Advanced Project Management and Applications, Project Management Institute, Issued in Feb 2014, Credential ID 29009
- Certificated by Preparation for PMP (Project Management Professional) Examination, Project Management Institute, Issued in Jan 2014, Credential ID 29632
- MATLAB, C programming, Python, MS Excel

AWARDS

- 2210- TÜBİTAK National MSc Scholarship Program, September 2005.
- 2224- TÜBİTAK Grant Program for Participation in Scientific Meetings Abroad, July 2009.
- A short-term LCA training in Lomartov Sustainability Firm, Valencia, Spain, November 2023.
- Participation in the 37th EFFoST International Conference held in Valencia, Spain, 6-8 November 2023.
- Dean's High Honor Roll, METU, Food Engineering Dept., 2002-2003 Spring, 2003-2004 Spring, 2004-2005 Fall and 2004-2005 Spring.
- Dean's Honor Roll, METU, Food Engineering Dept., 2001-2002 Fall and Spring, 2002-2003 Fall, 2003-2004 Fall.

PUBLICATIONS

A. Research Articles (Submitted)

Two research articles from the dissertation have been submitted to two journals.

- The first article is about the environmental and economic sustainability of novel tomato products in the context of value addition, multi-criteria decision, and process technology.
- The second article is about the social sustainability assessment of the products according to the product-specific criteria and social impacts of food technology.

B. Theses:

- MSc. Thesis, Multi-Class Classification Methods Utilizing Mahalanobis Taguchi System (MTS) and A Re-Sampling Approach for Imbalanced Data Sets, Advised by Prof. Dr. Gülser Köksal, Industrial Engineering, METU, 2009.
- TÜBİTAK Chief Expertise Thesis, Investigation of International Cooperation Projects in TÜBİTAK In Terms of Cooperation Benefits and Process Improvements, 2021.

- TÜBİTAK Expertise Thesis, Monitoring of Application-Oriented Research and Development Projects: Türkiye and World Applications, 2010.

C. Conference Proceedings:

1. Ayhan, D., Alpas, H., Oztop, M. H., Integrating Environmental, Economic and Social Sustainability of Tomato Products Using LCA and Multi-Criteria Decision Analysis, 38th. EFFoST International Conference, 2024, Belgium (submitted).
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