Ref. Ares(2026)8295818 - 31/08/2026

NEW VALUE LANDSCAPES FOR PLANT PROTEIN PATHWAYS

# D4.2 Life Cycle Sustainability Assessment (LCSA) of the proposed IPSs

valpropath.eu

Co-funded by the European Union

| | |
|---|---|
| **Author(s)/Organisation(s)** | Tryfon Kekes, Fotini Drosou (NTUA), Dimitra Fragkouli (DNY) |
| **Contributor(s)** | All IPS partners |
| **Work Package** | WP4 |
| **Delivery Date (DoA)** | 31/08/2026 |
| **Actual Delivery Date** | 31/08/2026 |
| **Abstract:** | This document aims to present he evaluation of the environmental, economic and social sustainability of the business cases developed within the framework of the VALPRO Path project. Additionally, the overall sustainability of business cases aiming to improve the efficiency of conventional agri-food systems is presented. This deliverable represents the sustainability evaluation of the solutions implemented during the project's lifetime. |

| **Document Revision History** | | | |
|---|---|---|---|
| **Date** | **Version** | **Author/Contributor/ Reviewer** | **Summary of main changes** |
| 28/07/2026 | 0.1 | Tryfon Kekes, Fotini Drosou, Dimitra Fragkouli | Initial version |
| 11/08/2026 | 0.2 | Ewen Mullins | Reduce content and document size |
| 28/08/2026 | 1.0 | Tryfon Kekes, Fotini Drosou, Richard Lynch | Final version |
| | | | |

| **Dissemination Level** | | |
|---|---|---|
| **PU** | Public, fully open, e.g. web | **X** |
| **SEN** | Sensitive, limited under the conditions of the Grant Agreement | |
| **Classified R-UE/EU-R** | EU RESTRICTED under the Commission Decision No2015/444 | |
| **Classified C-UE/EU-C** | EU CONFIDENTIAL under the Commission Decision No2015/444 | |
| **Classified S-UE/EU-S** | EU SECRET under the Commission Decision No2015/444 | |

VALPRO Path

| Participant Number | Participant organisation name | Short name | Country |
|---|---|---|---|
| 1 | TEAGASC - AGRICULTURE AND FOOD DEVELOPMENT AUTHORITY | TEAGASC | Ireland |
| 2 | AARHUS UNIVERSITET | AU | Denmark |
| 3 | UNIVERSITA DEGLI STUDI DI TORINO | UNITO | Italy |
| 4 | NATIONAL TECHNICAL UNIVERSITY OF ATHENS - NTUA | NTUA | Greece |
| 5 | LEIBNIZ-ZENTRUM FUER AGRARLANDSCHAFTSFORSCHUNG (ZALF) e.V. | ZALF | Germany |
| 6 | AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS | CSIC | Spain |
| 7 | CONFEDERAZIONE GENERALE DELL AGRICOLTURA ITALIANA | CONFAGRICOLTURA | Italy |
| 8 | AGRICOLUS S.R.L. | AGRICOLUS | Italy |
| 9 | WAGENINGEN UNIVERSITY | WU | Netherlands |
| 10 | BEOTANICS LIMITED | BEOTANICS | Ireland |
| 11 | PepsiCo | PEPSICO | Ireland |
| 12 | DIGNITY IDIOTIKI KEFALAIOUXIKI ETAIREIA | DNY | Greece |
| 13 | Moorepark Technology Ltd | MTL | Ireland |
| 14 | MOLINO PEILA SPA | MP | Italy |
| 15 | Global networks gUG | GN | DE |
| 16 | FARMB DIGITAL AGRICULTURE PRIVATE COMPANY | FARMB | Greece |
| 17 | Fattoria Soidale del Circeo cooperativa sociale | FSDC | Italy |
| 18 | Antignano prodotto tipico di Tealdi Roberto | APT | Italy |
| 19 | Kerry Luxembourg S.á.r.l. | KERRY | Luxembourg |
| 20 | UDRUZENJE ZA PREDUZETNISTVO I INOVACIJE FOODSCALE HUB | FSH | Serbia |
| 21 | Wide Open Agriculture | WOA | Germany |

## Disclaimer

The information and views set out in this application form are those of the author(s) and do not necessarily reflect the official opinion of the European Union. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

Co-funded by the European Union

Title: new VALue landscapes for plant PROtein Pathways
Type of action: HORIZON Innovation Actions ● Topic: HORIZON-CL6-2021-FARM2FORK-01-02
Start date of project: 01 September 2022 ● Duration: 48 months

© VALPRO Path Consortium, 2022.
Reproduction is authorised provided the source is acknowledged.

**Table of Contents**

Executive Summary ..... 10
1. Introduction ..... 12
2. Methodology ..... 13
2.1. Life Cycle Assessment (LCA) ..... 13
2.1.1. LCA Standarized Methodology ..... 13
2.2. Life Cycle Costing (LCC) Analysis ..... 14
2.3. Social Life Cycle Assessment (s-LCA) ..... 15
2.4. Overall Susainability Factor (OSF) ..... 16
2.5. Studied Business Cases ..... 17
3. Results ..... 18
3.1. Vegan Burger Production ..... 18
3.1.1. Goal & Scope ..... 18
3.1.2. Life Cycle Inventory (LCI) ..... 19
3.1.3. LCA Results ..... 19
3.1.4. LCC Results ..... 22
3.1.5. s-LCA Results ..... 23
3.1.6. LCSA of Vegan Burger Business Case ..... 25
3.2. European Cultivated Peanuts Exploitation ..... 27
3.2.1. Goal & Scope ..... 27
3.2.2. Life Cycle Inventory (LCI) ..... 28
3.2.3. LCA Results ..... 28
3.2.4. LCC Results ..... 30
3.2.5. s-LCA Results ..... 32
3.3. Intercropping of Peas and Faba Beans ..... 36
3.3.1. Goal & Scope ..... 36
3.3.2. Life Cycle Inventory (LCI) ..... 36
3.3.3. LCA Results ..... 36
3.3.4. LCC Results ..... 37
3.3.5. s-LCA Results ..... 38
3.3.6. Results from Intercropping Questionnaire ..... 40
3.3.7. LCSA of European Intercropping Peas and Faba Beans Business Case ..... 40
3.4. Plant-based Beverage Production ..... 42
3.4.1. Goal & Scope ..... 42
3.4.2. Life Cycle Inventory (LCI) ..... 43
3.4.3. LCA Results ..... 43

3.4.4. LCC Results ..... 45
3.4.1. s-LCA Results ..... 46
3.5. Energy Bar Production ..... 48
3.5.1. Goal & Scope ..... 48
3.5.2. Life Cycle Inventory (LCI) ..... 48
3.5.3. LCA Results ..... 48
3.5.4. LCC Results ..... 51
3.5.5. s-LCA Results ..... 52
3.6. Legume-based Pasta Production ..... 55
3.6.1. Goal & Scope ..... 55
3.6.2. Life Cycle Inventory (LCI) ..... 55
3.6.3. LCA Results ..... 55
3.6.4. LCC Results ..... 57
3.6.5. s-LCA Results ..... 57
3.6.6. Results from Consumer Acceptance Questionnaire ..... 60
3.6.7. LCSA of Legume-based Pasta Production Business Case ..... 61
4. References ..... 63
5. Supplementary Material ..... 64
5.1. Vegan Burger Production ..... 65
5.2. European Cultivated Peanuts Exploitation ..... 76
5.3. Intercropping of Peas and Faba Beans ..... 82
5.4. Plant-based Beverage Production ..... 86
5.5. Energy Bar Production ..... 95
5.6. Legume-based Pasta Production ..... 98

## List of tables

Table 1: List of abbrevioations and acronyms ..... 9
Table 2: CaPex analysis ..... 14
Table 3: OpEx analysis ..... 14
Table 4: Social risk subcategories per stakeholder ..... 15
Table 5: The Risk Level categories and their Factor, based on PsiLCA Handbook ..... 15
Table 6: Selected studied business cases ..... 17
*Table 7: Overview of the studied scenarios* ..... 19
Table 8: Results of the economic performance of peanuts cultivation and deshelling ..... 31
Table 9: Total cost for producing the legume-based and wheat pasta per 1 kg of pasta and 1 kg of protein content ..... 57
*Table 10: Life Cycle Inventory of the base case scenario* ..... 65
*Table 11: Life Cycle Inventory of the base case scenario* ..... 65

*Table 12: LCA results of the base case scenario* ..... 66
*Table 13: LCA results of the different studied scenarios regarding the transportation of lentils flour* . 67
*Table 14: LCA results of the different studied scenarios regarding the transportation of pea protein* 68
*Table 15: LCA results of the different studied scenarios regarding the transportation of pea flour* .... 69
*Table 16: LCA results of the different studied scenarios regarding the utilization of alternative packaging materials* ..... 70
*Table 17: LCA results of the optimum scenario* ..... 70
Table 18: LCC data for the production of the vegan burger ..... 72
Table 19: Cost breakdown across all differet studied scenaios ..... 73
Table 20: Life Cycle Inventory of peanuts cultivation and deshelling ..... 76
Table 21: Life Cycle Inventory of peanut milk production ..... 77
Table 22: Life Cycle Inventory of peanut butter production ..... 77
Table 23: Life Cycle Inventory of peanut oil production ..... 78
Table 24: LCA results of the different peanut products ..... 78
Table 25: LCC data for the cultivation and deshelling of peanuts ..... 79
Table 26: LCC data for the production of peanut milk ..... 79
Table 27: LCC data for the production of peanut butter ..... 80
Table 28: LCC data for the production of peanut oil ..... 81
Table 29: LCC analysis of the different studied peanut products ..... 81
Table 30: Life Cycle Inventory of peas and faba beans intercropping ..... 82
Table 31: Life Cycle Inventory of intercrop flour production ..... 82
Table 32: Life Cycle Inventory of intercrop cake production ..... 82
Table 33: LCA results of intercrop cake production ..... 83
Table 34: LCC inventory of peas and faba beans intercropping ..... 83
Table 35: LCC inventory of peas and faba beans intercrop flour production ..... 84
Table 36: LCC inventory of intercrop cake production ..... 84
Table 37: Life Cycle Inventory of faba beans cultivation ..... 86
Table 38: Life Cycle Inventory of faba protein isolate production ..... 87
Table 39: Life Cycle Inventory of beverage production ..... 88
Table 40: LCA results of plant-based beverage production ..... 89
Table 41: LCC inventory of faba beans cultivation ..... 91
Table 42: LCC inventory of faba protein isolate production ..... 91
Table 43: LCC inventory of beverage production ..... 91
Table 44: Life Cycle Inventory of energy bar production ..... 95
Table 45: LCA results of energy bar production ..... 96
Table 46: LCC inventory of energy bar production ..... 97
Table 47: Life Cycle Inventory of legume-based pasta production ..... 98
Table 48: Life Cycle Inventory of legume-based pasta production ..... 99
Table 49: LCA results of the base case scenario ..... 100
Table 50: Overview of osts associated with the production of the legume-based pasta ..... 100
Table 51: Overview of osts associated with the production of the conventional wheat pasta ..... 100

## List of figures

Figure 1: Flowchart of legume-based vegan burger production ..... 19
Figure 2: Comparison of base case and optimum scenario in selected midpoint categories ..... 21
Figure 3: Comparison of base case and optimum scenario in enddpoint categories ..... 22

Figure 4: Total costs associated with the production of 2 pieces of the legume-based vegan burger in all studied scenarios....23
Figure 5: Comparison of social risks associated with the base and optimum scenarios Optimum Scenario involves the integration of the Bio-PE packaging and the 10km distance of Pea Flour. ....25
Figure 6: Overall Sustainability of the different sudied scenarios in the vegan burger business case.26
Figure 7: Flowchart of peanut milk production ....27
Figure 8: Flowchart of peanut butter production....27
Figure 9: Flowchart of peanut oil production ....28
Figure 10: Comparison of the different peanut products in selected midpoint categories ....29
Figure 11: Results of the economic performance of peanuts cultivation and deshelling ....31
Figure 12: LCC analysis of the different studied peanut products....32
Figure 13: Social LCA Results of the peanut use case: Mean Social Risks per stakeholder per peanut product....33
Figure 14: Social LCA Results of the peanut use case: Mean Social Risks of the three Peanut products per stakeholder....34
Figure 15: Social LCA Results of the peanut use case: Base scenario mean social impacts composition per stakeholder....35
Figure 16: Comparison of the wheat and intercrop cakes in selected environmental midpoints ....37
Figure 17: Total cost and cost per production component for producing 1 cake using peas and faba beans intercrops ....38
Figure 18: Distribution of total social impacts across stakeholder groups (Value Chain Actors, Workers, Society, and Local Communities), expressed as percentage contribution to total medium risk hours for 1 cake produced with intercropped of pea and fava share....39
Figure 19: Overall Sustainability of the Intercropping business case ....41
Figure 20: Flowchart of plant-based beverage production ....43
Figure 21: LCA results of plant-based beverage production in selected midpoint indicators....44
Figure 22: ReCiPe endpoints of the beverage production....44
Figure 23: Total cost and cost per production component for producing 330 mL of beverage....45
Figure 24: Distribution of total social impacts across stakeholder groups (Value Chain Actors, Workers, Society, and Local Communities), expressed as percentage contribution to total medium risk hours for 1 kg of fava bean–based protein beverage....46
Figure 25: LCA results of plant-based energy bar production in selected midpoint indicators ....49
Figure 26: ReCiPe endpoints of the energy bar production ....50
Figure 27: Total cost and cost per production component for producing 330 mL of beverage....51
Figure 28: Total social risks of energy bar production per stakeholder [medium risk hours ....52
Figure 29: Total social risks of energy bar production per stakeholder [med risk hours] ....53
Figure 30: LCA results of pasta production in selected midpoint indicators ....56
Figure 31: ReCiPe endpoints of the pasta production ....56
Figure 32: Total risk hours for wheat and legume pasta per stakeholder....58
Figure 33: Total risk hours for wheat pasta per process ....59
Figure 34: Total risk hours for legume pasta per proces ....59
Figure 35: Overall Sustainability of the Legume-based Pasta business case per kg of pasta ....61
Figure 36: Overall Sustainability of the Legume-based Pasta business case per kg of protein....61
Figure 37: ReCiPe 2016 – overview of impact caegories ....64
Figure 38: Comparison of base case and optimum scenario in midpoint categories....71
Figure 39: Vegan Burger Production Base Case – Social Risks by Stakeholder Category ....74
Figure 40: Total Social Impacts of Vegan Burger Production Associated to the Transportation Scenarios ....74

Figure 41: Social Risks by Stakeholder Category Across Packaging Scenarios ..... 75
Figure 42: Total Social Risks Across Packaging Scenarios ..... 75
Figure 43: LCC analysis of the different studied peanut products with a 10fold increase in the volume of harvesed peanuts ..... 81
Figure 44: Contribution of life cycle stages to total social impacts on Local Communities, expressed in medium risk hours ..... 84
Figure 45: Contribution of life cycle stages to total social impacts on Society, expressed in medium risk hours ..... 85
Figure 46: Contribution of life cycle stages to total social impacts on Workers, expressed in medium risk hours ..... 85
Figure 47: Contribution of life cycle stages to total social impacts on Value Chain Actors, expressed in medium risk hours ..... 86
Figure 48: Relative contribution of each life cycle stage to total social impacts across stakeholder groups, expressed as percentage of medium risk hours ..... 86
Figure 49: LCA results of the plant-based beverage ..... 90
Figure 50: Contribution of life cycle stages (Fava Cultivation, Fava Flour Production, Protein Precipitate Production, and Beverage Processing) to total social impacts on workers, expressed in medium risk hours ..... 92
Figure 51: Contribution of life cycle stages to total social impacts on society, expressed in medium risk hours ..... 92
Figure 52: Contribution of life cycle stages to total social impacts on value chain actors, expressed in medium risk hours ..... 93
Figure 53: Contribution of life cycle stages to total social impacts on local communities, expressed in medium risk hours ..... 93
Figure 54: Relative contribution of each life cycle stage to total social impacts across stakeholder groups, expressed as percentage of medium risk hours ..... 94

| List of Abbreviations and Acronyms | |
|---|---|
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| s-LCA | Social Life Cycle Assessment |
| LCSA | Life Cycle Sustainability Assessment |
| CaPex | Capital Expenditures |
| OpEx | Operating Expenditures |

*Table 1: List of abbrevioations and acronyms*

# Executive Summary

Deliverable 4.2 presents the Life Cycle Sustainability Assessment (LCSA) of the business cases developed within the VALPRO Path project. The assessment evaluates the environmental, economic, and social sustainability of the proposed innovative production systems (IPSs), identifying key hotspots, opportunities for improvement, and potential trade-offs associated with the valorisation of protein crops and the development of innovative food products. Six business cases were assessed, with Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (s-LCA) being applied to provide an integrated assessment of the three sustainability dimensions.

Overall, the results demonstrate that the sustainability performance of the investigated systems is strongly influenced by the specific characteristics of each value chain. Processing activities, energy consumption, raw material sourcing, packaging, and agricultural practices were identified as important contributors to environmental, economic, and/or social impacts.

For the vegan burger business case, the combination of local sourcing of pea flour and Bio-PE packaging provided substantial sustainability benefits. The optimised scenario reduced the carbon footprint from 1.30 to 0.51 kg $CO_2$-eq. per package, corresponding to a reduction of approximately 60%, while also reducing production costs and social risks. This scenario achieved the best Overall Sustainability Factor (OSF) among the alternatives assessed, highlighting the importance of simultaneously optimising ingredient sourcing and packaging.

The European cultivated peanut business case demonstrated the potential for developing new European value chains based on peanut milk, peanut butter, and peanut oil. Peanut milk presented the lowest environmental impacts, while oil and butter showed comparatively higher environmental and social impacts, mainly due to its greater processing complexity and energy and resource requirements. From an economic perspective, peanut cultivation and deshelling were found to be feasible, while peanut milk and butter were profitable under the assessed conditions. Although peanut oil was not economically viable at the small scale considered, a tenfold increase in production volume resulted in profitability for all three products, demonstrating the importance of scale-up.

The pea–faba bean intercropping business case showed that intercrop flour can be incorporated into cake production without compromising the overall sustainability performance of the final product. Environmental differences compared with the conventional wheat-based cake were generally small, while production costs were virtually identical (€0.1539 versus €0.1538 per cake), and the OSF was also comparable.

For the faba bean-based beverage and energy bar, downstream processing was identified as a major sustainability hotspot. In particular, protein isolate production is associated with significant energy requirements for extraction, purification, and drying. In the energy bar case, protein isolate production accounted for approximately 64% of greenhouse gas emissions, while downstream manufacturing represented the main contributor to production costs and social risks. Improving process efficiency, increasing the use of renewable energy, and optimising ingredients and packaging therefore represent important opportunities for improving sustainability.

Finally, the legume-based pasta demonstrated particularly strong performance when assessed on a nutritional basis. Per kg of protein, greenhouse gas emissions were approximately 30% lower, fossil depletion approximately 42% lower, and social risks approximately 79% lower than for conventional wheat pasta. Although its production cost per kg of product was higher (€1.20 versus €0.91), its cost

per kg of protein was approximately 15% lower (€6.01 versus €7.10), demonstrating its favourable nutritional-economic performance.

Overall, the LCSA results confirm the potential of the VALPRO Path solutions to contribute to more sustainable and diversified European agri-food systems. The findings highlight the importance of local and responsible sourcing, sustainable packaging, efficient processing, renewable energy, production scale-up, and the wider use of legumes in value-added food products. Importantly, sustainability improvements should be evaluated simultaneously across environmental, economic, and social dimensions to ensure that improvements in one dimension do not result in unintended trade-offs in another. The results provide a basis for further development of business plans, value-chain strategies, and recommendations supporting climate-smart, resource-efficient, and socially responsible European protein crop value chains.

# 1. Introduction

VALPRO Path is advancing sustainable, locally sourced food innovation to meet rising demand for healthy and environmentally responsible products. The project focuses on developing scalable business models around high-protein crops such as peas, lupins, chickpeas, faba beans, and lentils, strengthening the agri-food value chain while reducing environmental impact.

Through five Innovation Production Systems (IPSs) operating as Living Labs in Germany, Ireland, Italy, Portugal, and Denmark, VALPRO Path combines advanced technologies with strategic collaboration to deliver practical, future-ready solutions for consumers, producers, and the wider agri-food sector. Specifically, the development of innovation through the IPSs forcussed on several business cases, which through Deliverable 4.2 (D4.2) underwent a comprehensive sustainability assessment , in accordance with the activities and outcomes of WP2 and WP3.

The developed business cases are evaluated in the current deliverable through Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and social Life Cycle Assessment (s-LCA). This deliverable allows for a cross-cutting comparison with baseline scenarios in case they were developed before VALPRO Path or in the assessment of business cases developed during the implementation of the project, by combining the social, economic, and environmental performance of each intervention. The findings are intended to aid in the creation of transformative pathways, such as business plans and policy suggestions, in the direction of a climate-smart and sustainable EU agri-food industry.

# 2. Methodology

## 2.1. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) evaluates the possible environmental effects of products or services across their entire life cycle. This encompasses everything from resource extraction and production to transportation, product use, and end-of-life scenarios such as reuse, recycling, or disposal. Environmental impacts considered may include resource consumption, effects on human health, and ecological ramifications, such as contributions to global warming.

LCA serves as a pivotal tool in enhancing sustainability within supply chains by offering concrete benefits. Firstly, it provides a holistic overview of a product's environmental impacts, allowing for the identification of key areas for improvement throughout its life cycle. This aids in pinpointing hotspots and directing efforts towards enhancing sustainability. Secondly, LCA enables the measurement and monitoring of environmental performance, facilitating the identification of trends and progress over time. By quantifying impacts, organizations can set targets and track their achievements effectively. Moreover, LCA serves as a basis for decision-making, guiding investments and efforts towards areas with the greatest potential for improvement. Whether in strategic planning or day-to-day operations, the insights gained from LCA inform various aspects of sustainable supply chain management, including strategy development, organizational structuring, product and process innovation, supplier engagement, and marketing strategies.

The International Organization for Standardization (ISO) has standardized the methodology for conducting LCA through its ISO 14040 series of standards. These standards establish principles, frameworks, and methodological requirements for LCA studies. Additionally, the series includes a standardized format for documenting LCA data, as well as two technical reports containing illustrative examples of LCA applications.

### 2.1.1. LCA Standarized Methodology

LCA analysis is conducted in accordance to the ISO 14040 and 14044 series and consists of four different phases (Finkbeiner et al., 2006; International Organization for Standardization [ISO], 2006).

- Goal and Scope. Adequate time investment in this phase is recommended to clarify the study's purpose, intended use of results, and inclusion criteria
- Life Cycle Inventory which includes data collection and aggregation of data from individual unit processes into an inventory result for the entire product system
- Life Cycle Impact Assessment aims to assess the potential environmental impact of a product system based on its inventory results. In accordance with ISO 14040, the impact assessment comprises both mandatory and optional elements. In practice, the impact assessment in LCA is typically conducted using a pre-established impact assessment method, such as ReCiPe2016, which offers a state-of-the-art methodology for converting life cycle inventories into a concise set of life cycle impact scores at both midpoint and endpoint levels. It includes three endpoint categories (human health, ecosystem quality, and resource scarcity) and 18 midpoint categories as outlined in (Huijbregts et al., 2017) (see Supplementary Fig 1)
- Interpretation, which derives conclusions and recommendations aligned with the study's defined goal and scope by integrating and analyzing results from both the inventory (LCI) and environmental impact assessment (LCIA). Interpretation occurs iteratively alongside other phases of the LCA, with each intermediate result being interpreted as part of the overall process. The interpretation phase of an LCA consists of three main elements as per ISO 14040:

(i) Identification of significant issues based on LCI and LCIA results (ii) Evaluation of results, including checks for completeness, sensitivity, consistency, and consideration of uncertainty and data quality analysis findings and (iii) Drawing conclusions, outlining limitations, and providing recommendations.

## 2.2. Life Cycle Costing (LCC) Analysis

Life Cycle Cost (LCC) aims to evaluate not just the procurement costs but also the operational, maintenance, and disposal expenses, allowing decision-makers to enhance the economic performance across the system's life cycle. Additionally, LCC studies may encompass the costs of externalities, such as environmental impacts attributable to the system or product, often guided by the "polluter pays" principle.

Considering the significance of LCA and LCC methodologies, a notable challenge for companies in adopting Life Cycle Assessment (LCA) is comprehending the implications of its findings on their economic metrics. While LCA relies on a comprehensive dataset derived from mass and energy balances identified during the Life Cycle Inventory (LCI) phase, LCC necessitates monetary data concerning financial resources, including expenditures and revenues. LCC is usually applied for the comparison of products, processes, or projects, utilizing economic aspects to highlight those that excel in specific environmental-economic criteria. Variations in cost categories, including direct and indirect costs, internal and external costs, and operational and non-operational costs, are evident across studies.

Unlike LCA, there is no globally accepted standard guiding the organization of LCC studies. Nevertheless, most studies express LCC results as the sum of costs per functional unit, similar to LCA, where the functional unit serves as a parameter (Bachmann et al., 2024).

While various approaches and practical applications of Life Cycle Costing (LCC) tools exist, the underlying economic methodology at the heart of LCC calculations remains consistent. Here, LCC costs were computed using the general formula:

$$LCC = \sum CAPEX + \sum OPEX$$

The analysis of CaPex and OpEx to the various cost categories is presented in Tables 2 & 3.

| Direct Costs | Indirect Costs |
|---|---|
| Equipment – purchase, delivery | Engineering and supervision |
| Equipment – installation | Construction expenses |
| Instrumentation & Controls (installed) | Legal expenses |
| Piping (installed) | Contractor’s fee |
| Electrical systems (installed) | Contigency |
| Buildings (including services) | |
| Yard improvements | |
| Service facilities (installed) | |

*Table 2: CaPex analysis*

| Direct Costs | Indirect Costs |
|---|---|
| Raw materials | Taxes |
| Labor | Insurance |
| Utilities | Rent |
| Maintenance and repairs | Administration |

*Table 3: OpEx analysis*

## 2.3. Social Life Cycle Assessment (s-LCA)

Social Life Cycle Assessment (S-LCA) is an analytical tool designed to evaluate the social impacts of products, processes, or services throughout their entire life cycle, from raw material extraction to production, distribution, use and final disposal. The methodology follows the framework provided by the UNEP Guidelines for Social Life Cycle Assessment.These guidelines establish a structured approach for identifying and assessing social impacts associated with a product's life cycle. The S-LCA methodology follows the structure of Environmental LCA, encompassing four sequential phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation.

S-LCA categorizes stakeholders into four main groups, each associated with distinct impact categories as seen in Table 4.

| Stakeholder Category | Subcategories |
|---|---|
| Workers | Child and forced labor, fair salary, working hours, discrimination, health and safety, social benefits, and workers' rights. |
| Local Community | Access to resources, respect for indigenous rights, safe and healthy living conditions, local employment, migration, and environmental/labor footprints. |
| Value Chain Actors | Fair competition, corruption prevention, social responsibility promotion, and contribution to economic development. |
| Society | Prevention and mitigation of conflicts, social equity, and overall societal well-being. |

*Table 4: Social risk subcategories per stakeholder*

For the inventory completion data were collected on input and output flows of the involved processes, while also qualitative information was collected from international databases for the European Union, to assess key social indicators. The qualitative data is then attributed based on PSILCA handbook to a corresponding Risk Level. In the next Table the Risk Levels and their scaling factors are available.

| Risk Level | Factor |
|---|---|
| Very Low Risk | 0.01 |
| Low Risk | 0.1 |
| Medium Risk | 1 |
| High Risk | 10 |
| Very High Risk | 100 |
| No Risk | 0 |
| No Data | 0.1 |

*Table 5: The Risk Level categories and their Factor, based on PsiLCA Handbook*

Each indicator with defined Risk Level, and thus scaling factor, should now be multiplied by the Worker Hours, which is the activity variable. In S-LCA, the activity variable is a key concept used to link the functional output of a product system to its social impacts. It essentially represents a quantifiable measure of the activity that generates the social impact.

The activity variable used for all the IPS cases is worker hours, defined by the following formula:

$$Worker\ Hours = ((Price\ of\ product) \times (Unit\ labour\ costs)) \div (Mean\ hourly\ labor\ cost\ (per\ employee))$$

Workers hours are expressed in h, unit labour costs in USD/USD, mean hourly labour cost in USD/h and the price of the product in USD, following the units used in the PSILCA manual. Since the

calculation is based on a ratio between the mean hourly labour cost and the product price, the currency does not affect the resulting ratio, provided that both values are expressed in the same currency. Thus, the same ratio would be obtained if the mean hourly labour cost and product price were expressed in EUR/h and EUR, respectively, resulting in a EUR/EUR ratio. More details can be found about the different terms of the formula in the PSILCA manual (Maister, Noi, Ciroth, & Srocka, 2020) and the S-LCA Guidelines (LIFE CYCLE INITIATIVE, 2020).The analysis took place on OpenLCA Software using Soca V3 database and the Social Impacts Weighting Method.Instead of reporting results for specific subcategories or indicators, S-LCA reports results at the stakeholder level. Rather than measuring each individual social aspect in detail, the primary goal is to evaluate the overall social impacts on impacted groups. Stakeholder-level result aggregation avoids placing too much emphasis on ambiguous or extremely specific data while clearly and interpretably capturing the combined impact of several indicators. .

## 2.4. Overall Susainability Factor (OSF)

Within the framework of the VALPRO Path, the overall sustainability assessment of the Innovative Production Systems (IPSs) was based on three key indicators, selected as the most representative metrics of the environmental, economic, and social dimensions of sustainability. Specifically, the carbon footprint (climate change default, excluding biogenic carbon) was selected to represent the environmental dimension, the total production cost was used as the economic indicator, and the total social risks were adopted as the social indicator. These indicators were chosen to provide a concise yet comprehensive evaluation of the sustainability performance of each CSA practice.

Since these indicators originate from different assessment methodologies (LCA, LCC, and s-LCA) and are expressed in different units, a direct comparison or aggregation is not possible. Therefore, a harmonised, dimensionless equation was developed to quantify the relative performance of each studied scenario with respect to its corresponding baseline scenario. To ensure a balanced assessment, the three sustainability dimensions were considered equally important and were assigned equal weighting factors (1/3 each). This approach resulted in the calculation of the Overall Sustainability Factor, which integrates the environmental, economic, and social performance into a single, easily interpretable metric while preserving the equal contribution of each sustainability pillar.

The Overall Sustainability Factor was developed to evaluate whether the interventions implemented within the project effectively promote sustainability compared with conventional production systems. Consequently, the proposed methodology is intended for scenarios involving improvements or modifications to existing production practices, where a direct comparison with a baseline is possible. It is not intended for the assessment of entirely novel products or production systems, including the formulation of the energy-bar and the plant-based beverage, for which no equivalent conventional baseline exists.

The Overall Sustainability Factor (OSF) is calculated using the following equation:

$$OSF = \frac{1}{3} * \frac{Carbon\ Footprint_{Studied\ Scenario}}{Carbon\ Footprint_{Base\ Scenario}} + \frac{1}{3} * \frac{Cost\ of\ Production_{Studied\ Scenario}}{Cost\ of\ Production_{Base\ Scenario}} + \frac{1}{3} * \frac{Total\ Social\ Risks_{Studied\ Scenario}}{Total\ Social\ Risks_{Base\ Scenario}}$$

The resulting OSF values provide a relative interpretation of sustainability performance compared to the baseline scenario. An OSF value lower than 1 indicates an enhanced overall sustainability performance, meaning that the CSA practice performs better than the baseline when considering the

weighted contribution of the selected pillars and indicators. Conversely, an OSF value higher than 1 indicates reduced sustainability performance relative to the baseline.

## 2.5. Studied Business Cases

The main objective of WP4 was to apply the above methodologies to evaluate the overall sustainability of the developed business cases from the respective IPSs. Table 6 presents key information regarding the studied business cases.

| Business Case | Involved Partners | Involved IPSs |
|---|---|---|
| Vegan Burger Production | FSDC, UNITO, AU | IPS 1, 2 |
| European Cultivated Peanuts Exploitation | BEOTANICS, TEAGASC | IPS 1, 2 |
| Intercropping of Peas and Faba Beans | TEAGASC | IPS 2, 3 |
| Plant-based Beverage Production | TEAGASC, PEPSICO | IPS 2, 4 |
| Energy Bar Production | BEOTANICS, TEAGASC | IPS 2, 4 |
| Legume-based Pasta Production | MP, APT, UNITO, AU | IPS 2, 5 |

*Table 6: Selected studied business cases*

# 3. Results

## 3.1. Vegan Burger Production

### 3.1.1. Goal & Scope

The main goal of the vegan burger production business case was to assess the environmental, economic, and social performance of a legume-based vegan burger (base case scenario) as well as to evaluate different scenarios that utilize local sourcing of ingredients and the use of sustainable packaging materials. For this purpose, the production of a legume-based vegan burger was assessed using data provided by Fattoria Solidale del Circeo, a partner of the VALPRO Path project that specializes in the production of legume-based food products. Subsequently, different scenarios were studied based on the transportation distances of the basic legume ingredients (pea protein, pea flour, and lentil flour used in a ratio of 1:2.4:1, respectively) and on the utilization of alternative packaging materials.

#### *3.1.1.1. Product System*

The product system consists of the production and transportation to the FSDC facilties of all the ingredients, along with all the processes involved in the production of the vegan burger. Moreover, the product system includes the transportation of the final products to the retail centers along with the end of life of the product. Figure 1 presents the flowchart of the vegan burger production business case.

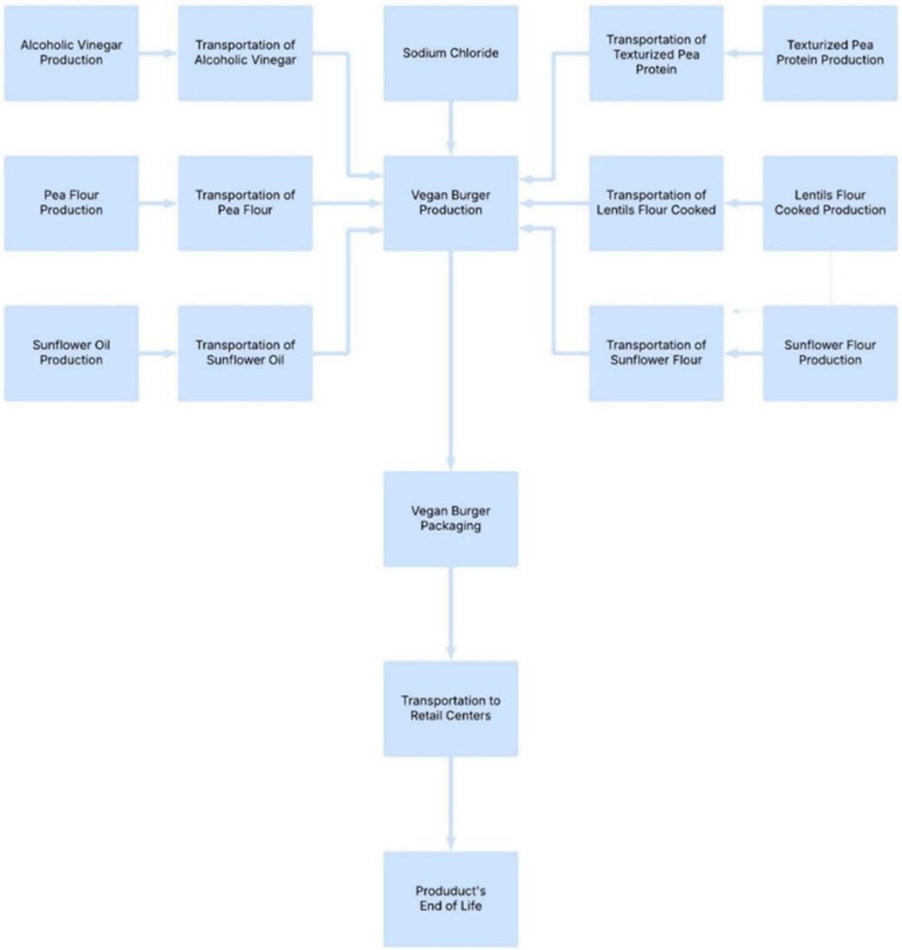


*Figure 1: Flowchart of legume-based vegan burger production*

#### *3.1.1.2. Functional Unit, System Boundaries, Data Requirements, Assumptions and Limitations*

The functional unit was defined as one package of legume-based vegan burgers containing two patties (0.4 kg total weight of the two burgers). A cradle-to-grave system boundary was adopted, covering raw material extraction and production, burger manufacturing and packaging, transportation to retail centers, and end-of-life.

Primary data for production, packaging, transportation, end-of-life, and shelf-life were obtained through collaboration with Fattoria Soidale del Circeo, while data for raw ingredients and alternative packaging materials were sourced from LCA for Experts and Ecoinvent scientific databases.

Four packaging scenarios were assessed: Polyethylene tetrapthalate (PET), Biopolyethylene (bio-PE), Polyethylene (PE), and Polylactic acid (PLA). For PET, bio-PE, and PE, a shelf-life of 40 days was assumed, whereas PLA was assumed to provide a 20-day shelf-life. A 50% recycling rate was assumed for all packaging materials, based on recent European data reported by Statista Research Department (2025). The core production processes and other assumptions remained consistent across scenarios, with packaging material being the main variable.

### 3.1.2. Life Cycle Inventory (LCI)

Table 7 presents studied scenarios of the legume-based vegan burger business case, while information related to the inventory utilized in the analysis are presented in further detail in the Supplementary material (Tables 10 and 11).

| Scenario | Studied Parameter | New Value |
|---|---|---|
| Base Case | Based on Tables 10 and 11 | |
| 1 | Distance of lentil flour (cooked) | 300 km |
| 2 | | 150 km |
| 3 | | 10 km |
| 4 | Distance of pea protein (texturized) | 400 km |
| 5 | | 200 km |
| 6 | | 10 km |
| 7 | Distance of pea flour | 400 km |
| 8 | | 200 km |
| 9 | | 10 km |
| 10 | Packaging material | Bio-PE |
| 11 | | PLA |
| 12 | | PE |
| 13 | Optimum conditions (Distance of pea flour: 10 km a nd Packaging material: Bio-PE) | |

*Table 7: Overview of the studied scenarios*

### 3.1.3. LCA Results

#### *3.1.3.1. Base Case Scenario*

The environmental assessment of the legume-based vegan burger package identified climate change, fossil depletion, and fine particulate matter formation as the areas being most impacted. These are mainly driven by the production stage and the transportation of imported legume ingredients, which increase greenhouse gas emissions. Fossil-based packaging materials, such as PET, also contribute substantially to resource depletion and the overall environmental burden, even when recycled. The

product's carbon footprint is estimated at 1.30 kg $CO_2$-equivalent per package of two patties, with transportation playing a key role. Fine particulate matter and photochemical ozone formation are linked to fossil fuel combustion and nitrogen oxide emissions during production and transport, while metal resource depletion is associated with industrial machinery use. Overall, transportation and conventional packaging are the main environmental hotspots, highlighting local ingredient sourcing and sustainable packaging as effective strategies to improve environmental performance.

#### *3.1.3.2. Transportation of Lentils Flour Scenarios*

The analysis of different transportation scenarios for lentil flour shows that shorter transport distances can reduce the environmental impacts of the vegan burger, particularly in climate change, fossil depletion, and fine particulate matter formation. Reducing the transportation distance from 426 km to 10 km lowers transportation-related carbon emissions by more than 85%, while also decreasing diesel fuel use and air pollution from truck emissions. However, because lentil flour is used in relatively small quantities, reducing its transportation distance does not significantly improve the overall environmental sustainability of the final product.

#### *3.1.3.3. Transportation of Pea Protein Scenarios*

The transportation distance of pea protein significantly affects the environmental footprint of the legume-based vegan burger. Reducing the transport distance from 604 km to 10 km substantially lowers impacts related to climate change, fossil depletion, and fine particulate matter formation. In the optimized scenario, transportation-related $CO_2$ emissions decrease by more than 85%, while reduced diesel fuel consumption also lowers dependence on non-renewable resources and decreases air pollution. However, despite these improvements, the overall effect on the burger's total environmental sustainability remains limited because pea protein represents a relatively small share of the final product. Therefore, although local sourcing offers environmental benefits, its overall contribution must be evaluated within the context of the entire supply chain.

#### *3.1.3.4. Transportation of Pea Flour Scenarios*

Pea flour is a major contributor to the environmental footprint of the legume-based vegan burger due to both its high proportion in the formulation and its transportation distance. In the base case, pea flour is transported 678 km, resulting in significant greenhouse gas emissions, fossil fuel consumption, and air pollution. Reducing the transportation distance to as little as 10 km leads to substantial environmental improvements, particularly in climate change impact, fossil depletion, and photochemical ozone formation. In the optimized scenario, emissions from pea flour transportation decrease by more than 80%, reducing the product's total carbon footprint to 1.25 kg $CO_2$-eq., a 3.8% reduction compared to the base case. Unlike lentil flour and pea protein, whose lower quantities limit their overall influence, pea flour has a much greater effect on the product's sustainability. These findings highlight local sourcing of pea flour as one of the most effective strategies for reducing the environmental burden of the vegan burger.

#### *3.1.3.5. Alernative Packaging Materials Scenarios*

Packaging materials significantly influence the environmental impact of the legume-based vegan burger. The base case uses conventional PET packaging, which contributes to greenhouse gas emissions, fossil resource depletion, and waste generation. To identify more sustainable options, the study evaluates Bio-PE, PLA, and PE packaging alternatives. The results show that these alternatives reduce environmental burdens compared to PET, with bio-based materials lowering the packaging carbon footprint by approximately 61%. Bio-PE, produced from renewable biomass, and PLA, a biodegradable polymer derived from plant starch, both reduce dependence on fossil fuels and

decrease fine particulate matter formation. However, challenges related to the cost, limited availability, and end-of-life management of bio-based materials remain important considerations. Overall, Bio-PE emerges as the most balanced solution, offering improved environmental performance while maintaining packaging functionality and durability.

### *3.1.3.6. Optimum Scenario*

To improve the environmental performance of the legume-based vegan burger, a final optimized scenario combined the most effective transportation and packaging strategies. Reducing the transportation distance of pea flour was identified as the most impactful measure, as pea flour represents a major component of the burger formulation and significantly influences transportation costs and emissions. In terms of packaging, Bio-PE was selected as the optimal alternative due to its lower greenhouse gas emissions and reduced fossil fuel depletion compared to conventional PET, while still maintaining functionality and durability. Together, these strategies substantially improved the product's sustainability, although further research on end-of-life management and food waste reduction is needed to determine the best long-term biomaterial solution. The detailed results of the optimum scenario are depicted in the Supplementary Materials, while a direct comparison in some key environmental indicators between the optimum scenario and the base case is presented in Figure 2.

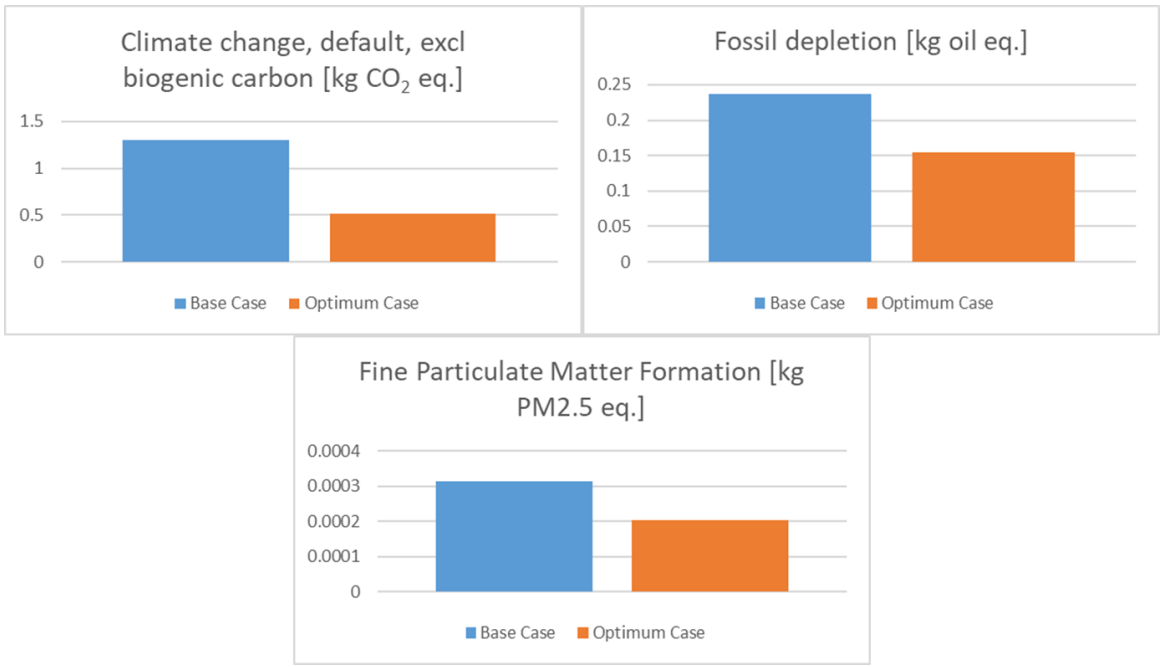



*Figure 2: Comparison of base case and optimum scenario in selected midpoint categories*

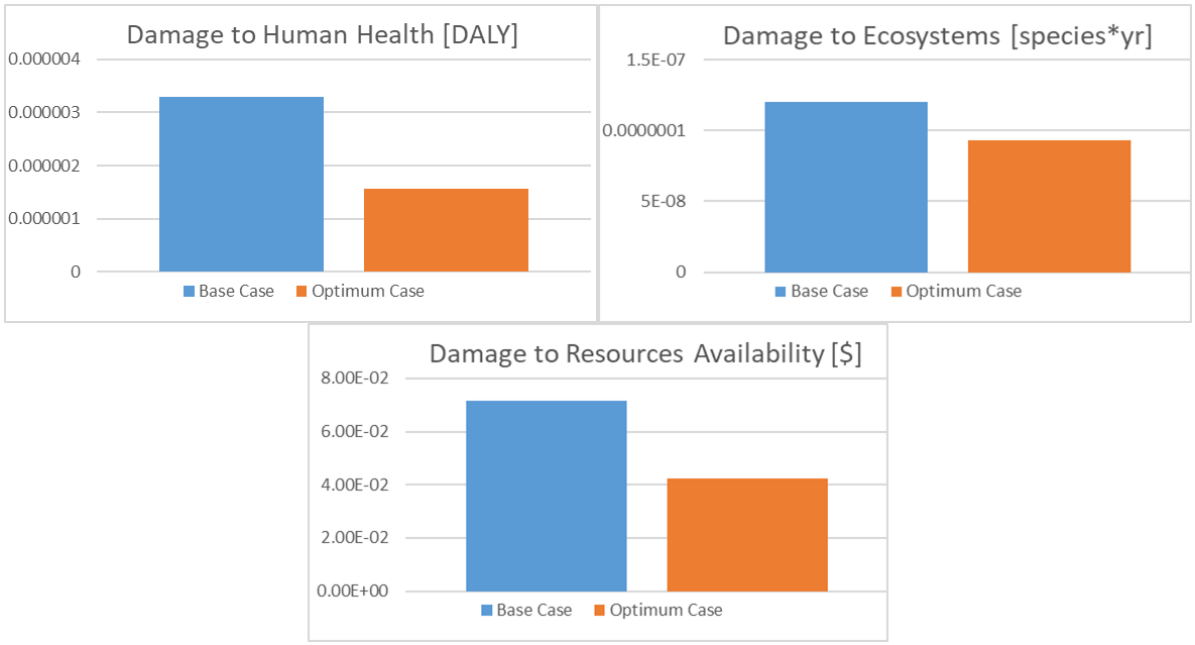



*Figure 3: Comparison of base case and optimum scenario in enddpoint categories*

The comparative analysis between the base case and the optimized scenario demonstrates that local ingredient sourcing and the adoption of Bio-PE packaging can substantially improve the sustainability of the legume-based vegan burger. The optimized scenario reduced the product's carbon footprint from 1.30 kg $CO_2$-eq. to 0.51 kg $CO_2$-eq. per package, achieving a 60% reduction in greenhouse gas emissions through shorter transportation distances and bio-based packaging. Significant reductions were also observed in fossil depletion and fine particulate matter formation, highlighting the environmental benefits of localized supply chains and sustainable packaging materials. The ReCiPe endpoint analysis further confirmed these improvements, showing a 55% reduction in impacts on human health, a 50% reduction in ecosystem damage, and over a 60% decrease in resource depletion. These findings emphasize the importance of integrating circular economy principles, local sourcing, and sustainable packaging strategies into plant-based food production to reduce environmental impacts while maintaining economic feasibility. Detailed explanations and analyses of all studied scenarios have been published under the umbrella of the VALPRO Path project (Kekes et al., 2025).

Further details on LCA results are contained in the Supplementary Materials, Tables 12-17 and Figure 38.

### 3.1.4. LCC Results

The economic assessment of the legume-based vegan burger production identifies labor and raw material acquisition as the primary contributors to total production costs. Key ingredients, particularly pea flour and texturized pea protein, account for a substantial share of expenses, while transportation costs, although smaller, remain significant due to long sourcing distances. The total production cost for two burger patties is estimated at approximately 2.43€.

Transportation optimization analyses reveal that reducing the sourcing distance of lentil flour and pea protein provides only marginal economic savings because these ingredients are used in relatively small quantities. Nevertheless, local sourcing still offers environmental advantages and contributes to incremental reductions in logistics-related emissions and costs. In contrast, pea flour transportation has a more pronounced financial impact because pea flour represents a larger proportion of the burger formulation. Reducing transport distances from several hundred kilometers to local sourcing

scenarios significantly lowers logistics expenses, highlighting the importance of prioritizing locally sourced, high-volume ingredients to improve both economic and environmental performance.

Packaging costs represent a smaller proportion of total expenses; however, their environmental footprint is considerable due to the use of conventional plastics such as PET. The evaluation of alternative materials, including Bio-PE, PLA, and PE, demonstrates that bio-based packaging options currently involve higher costs because of limited supply chains and end-of-life infrastructure. Among the alternatives, Bio-PE emerges as the most balanced option, offering improved sustainability with only a moderate increase in packaging costs.

Overall, the comparison between the base case and the optimized scenario demonstrates that combining local ingredient sourcing with Bio-PE packaging can simultaneously improve sustainability and reduce production costs. The optimized scenario decreases the total life cycle cost from EUR 2.43 to EUR 2.37 per package, mainly through savings in transportation and logistics. These findings emphasize that targeted supply chain and packaging optimizations can enhance both the environmental and economic performance of legume-based vegan burgers. Detailed explanations and analyses of all studied scenarios have been published under the umbrella of the VALPRO Path project (Kekes et al., 2025).

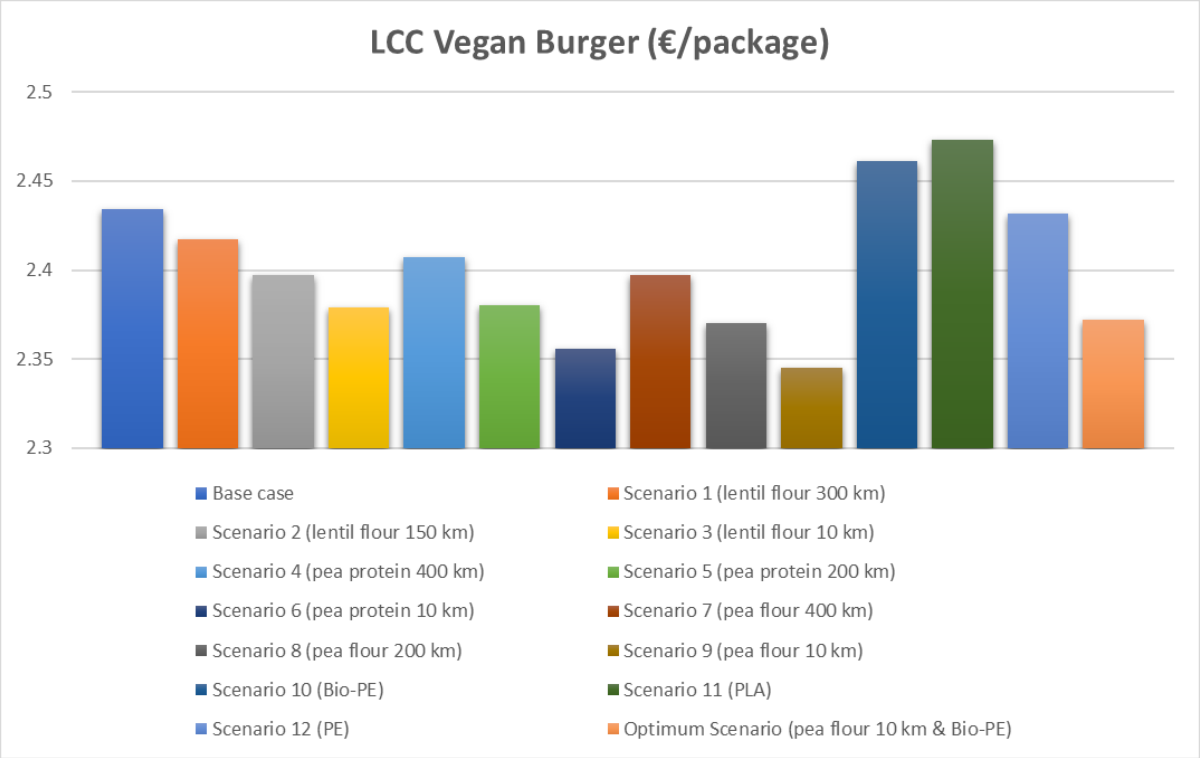



*Figure 4: Total costs associated with the production of 2 pieces of the legume-based vegan burger in all studied scenarios*

Further details on LCC results are contained in the Supplementary Materials, Tables 18 and 19.

## 3.1.5. s-LCA Results

### *3.1.5.1. Results of the Base Scenario*

High risks in vegan burger production are primarily linked to a few critical factors. In the processing phase, electricity consumption emerges as a major contributor, reflecting the dependence on energy-intensive industrial practices. During the cultivation phase, water consumption represents a significant source of risk, as agricultural production often places heavy demands on freshwater resources,

intensifying competition with local communities and ecosystems. Packaging materials also play a role, particularly when they rely on resource-intensive pulp and paper production or other materials that contribute to deforestation and challenging labor conditions. Together, these factors highlight that while vegan burgers reduce overall risks compared to meat burgers, attention to energy use, agricultural water demand, and sustainable packaging remains essential to further improve social and environmental performance.

#### *3.1.5.2. Transportation Scenarios*

Transportation impacts are assessed using the unit kg-km, which represents the product of weight and distance traveled. Shorter transport distances directly translate into lower social impacts, as they reduce exposure to labor risks, lessen energy consumption, and limit the occurrence of social hotspots along supply routes. Among the different ingredients considered, pea flour shows the most notable reduction in social risks when supply distances are shortened, since long-distance transportation of bulk agricultural products often involves high energy demand, multiple handling stages, and greater reliance on labor across extended logistics chains.

#### *3.1.5.3. Packaging Scenarios*

Social risks were generally reduced when alternative packaging materials were introduced, highlighting the influence of material choice on broader sustainability outcomes. Bio-PE packaging demonstrates particularly favorable results, as it not only reduces overall social risks but also contributes positively to multiple stakeholder groups. By supporting bio-based practices in the production of bioethanol, Bio-PE helps foster more sustainable value chains and creates opportunities for local communities and workers engaged in agricultural feedstock production. At the same time, it minimizes conflicts over limited natural resources and decreases dependence on fossil fuels, which are often associated with labor rights issues, geopolitical tensions, and environmental pressures. Compared to conventional plastic packaging, biobased alternatives such as Bio-PE offer a pathway toward improved societal well-being, enhanced worker conditions, and stronger community resilience.

Compared to the base scenario, using PLA results in a 5.9% reduction in social risks, indicating a moderate improvement likely linked to its biobased origin and potentially safer production processes. Conventional PE shows only a 0.1% reduction, suggesting minimal impact on social factors such as labor conditions, community health, or local economic effects. Bio-PE demonstrates the greatest benefit, with a 6.7% reduction in social risks, reflecting the additional advantages of renewable resource sourcing, sustainable agricultural practices, and positive impacts on communities involved in biomass production. Overall, these results highlight that biobased alternatives, like PLA and Bio-PE, can meaningfully reduce social risks, whereas conventional PE offers little improvement over the baseline.

#### *3.1.5.4. Comparison of Base to Optimum*

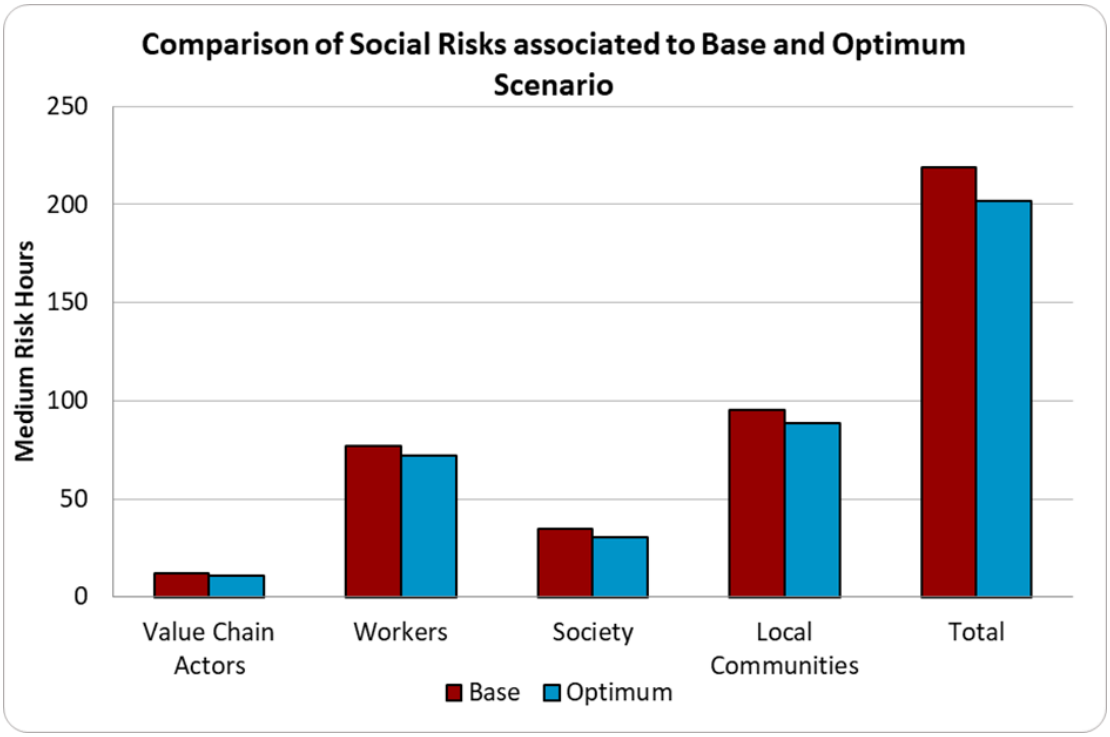



*Figure 5: Comparison of social risks associated with the base and optimum scenarios Optimum Scenario involves the integration of the Bio-PE packaging and the 10km distance of Pea Flour.*

In the optimum scenario, social risks were reduced across all stakeholder groups, with value chain actors experiencing an 11.7% decrease, society seeing a 13.4% reduction, local communities benefiting from a 7.2% decline, and workers experiencing a 5.8% decrease. These improvements collectively resulted in an overall reduction of 7.9% in social risks.

Please note that the use of cardboard packaging is associated with significant social risks, highlighting the need to explore alternative solutions in this area. Further details on social LCA results are contained in the Supplementary Materials, Figures 40-42.

### 3.1.6. **LCSA of Vegan Burger Business Case**

The results regarding the overall sustainability of the Vegan Burger Business Case are presented in the following Figure.

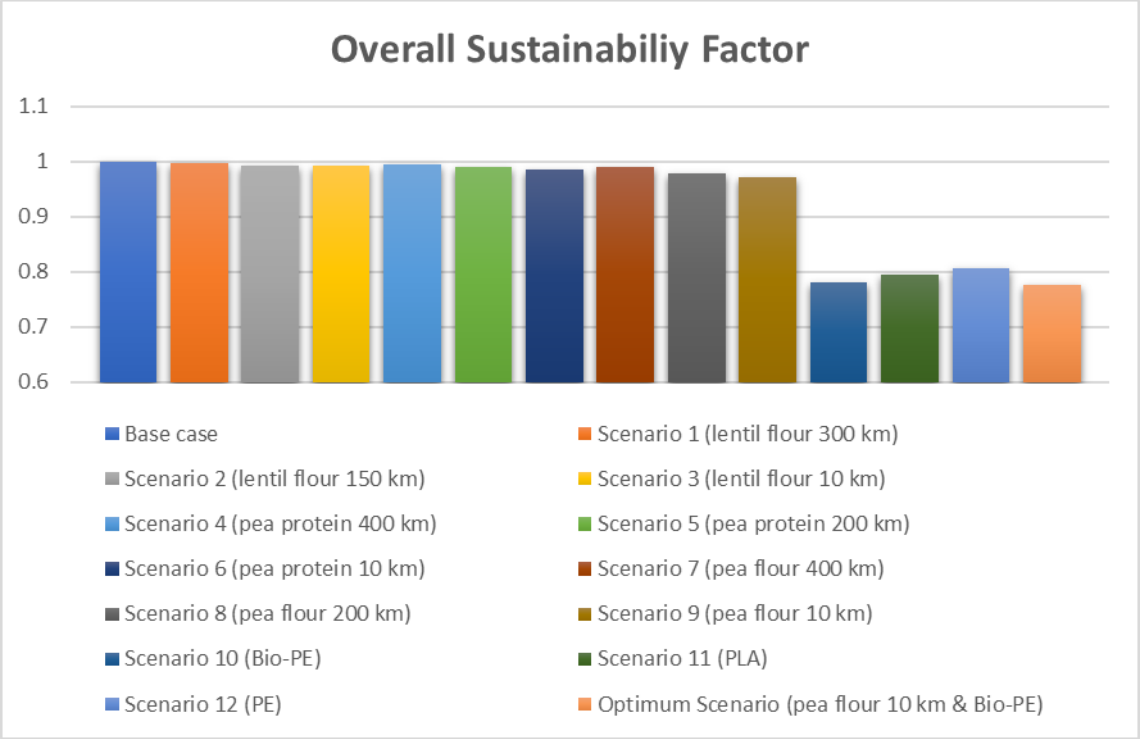



*Figure 6: Overall Sustainability of the different sudied scenarios in the vegan burger business case*

The Overall Sustainability Factor (OSF) results indicate that the scenarios involving alternative legume sourcing locations (Scenarios 1–9) have only a marginal influence on the overall sustainability performance, as their OSF values remain very close to the baseline (approximately 0.98–1.00). This suggests that, although local sourcing may provide benefits in individual sustainability dimensions, the combined environmental, economic, and social improvements are not sufficiently pronounced to substantially alter the overall sustainability score. In contrast, the scenarios incorporating alternative packaging materials (Scenarios 10–12) exhibit considerably lower OSF values (approximately 0.78–0.81), demonstrating a significant improvement in overall sustainability. These results indicate that packaging selection has a greater influence on the combined sustainability performance than the geographical origin of the legume ingredient, as more sustainable packaging (Bio-PE, PE and PLA) simultaneously contributes to lower environmental impacts, reduced overall costs, and improved social performance.

The Optimum Scenario achieved the lowest OSF value, representing the best overall sustainability performance among all evaluated scenarios. This scenario combines local sourcing of the ingredient with the highest proportion in the formulation, namely pea flour, with the use of an alternative packaging material (Bio-PE), highlighting that the greatest sustainability benefits are obtained when optimising both raw material sourcing and packaging simultaneously. Overall, these findings demonstrate that while changes in ingredient sourcing alone provide only modest improvements, the incorporation of sustainable packaging solutions, particularly when combined with strategic local sourcing, can substantially enhance the sustainability performance of the conventional production system.

## 3.2. European Cultivated Peanuts Exploitation

### 3.2.1. Goal & Scope

The main goal of the sustainability assessements on advancing the exploitation of european cultivated peanuts was to evaluate the environmental, economic, and social sustainability of European cultivated and produced peanut products, which are currently underdeveloped in Europe.Thus, three different product systems were studied, with each one focusing on the production of a different product (peanut milk, peanut butter, and peanut oil), with data regarding the cultivation of peanuts in Portugal and their subequent processing being provided by project partner, BEOTANICS Ltd.

#### *3.2.1.1. Product System*

The product system consists of the cultivation, deshelling, and subsequent processing of the peanuts to produce these different products. Specifically, the product systems refer to the production of peanut milk (Figure 7), peanut butter (Figure 8), and peanut oil (Figure 9), with the cultivation and deshelling processes being the same in all studied systems.

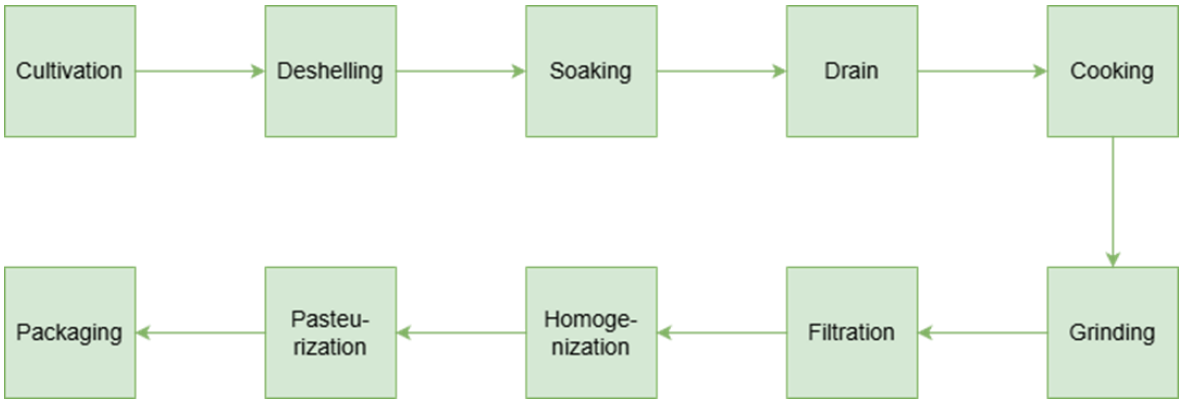



*Figure 7: Flowchart of peanut milk production*

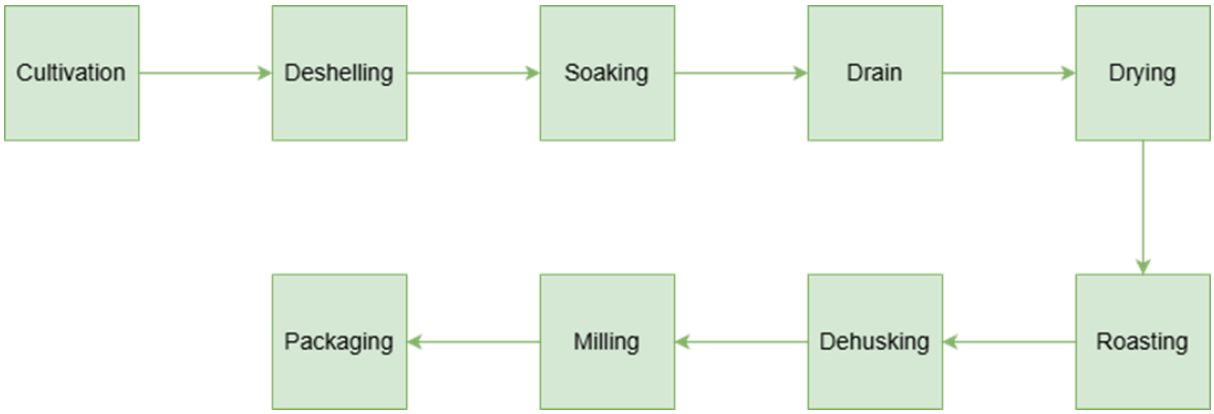



*Figure 8: Flowchart of peanut butter production*

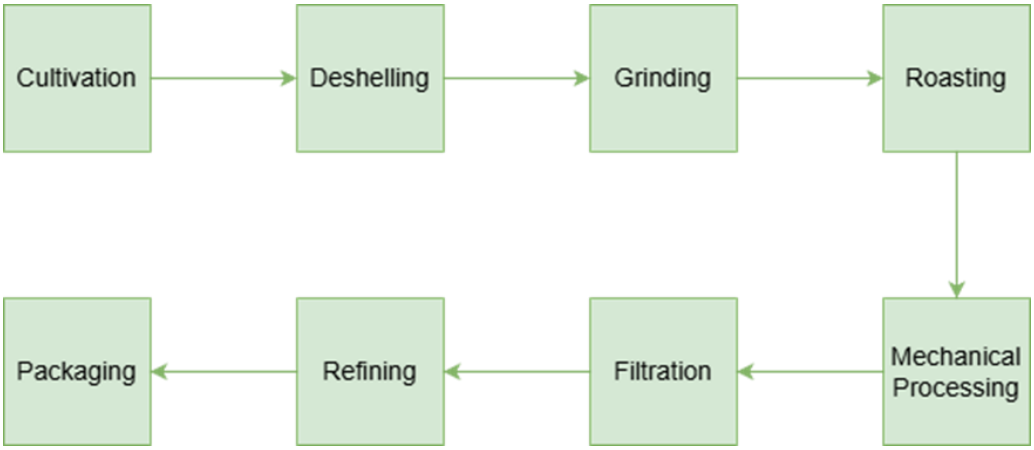



*Figure 9: Flowchart of peanut oil production*

#### *3.2.1.2. Functional Unit, System Boundaries, Data Requirements, Assumptions and Limitations*

To ensure direct comparison, the functional unit was defined as 1 kg of final product for each system. A cradle-to-gate system boundary was adopted, covering peanut cultivation and deshelling, followed by the processing stages required to produce each final product up to the factory gate.

Primary data on peanut cultivation, deshelling, and processing were obtained through communication with BEOTANICS Ltd., while data for auxiliary materials and background processes were sourced from Ecoinvent and LCA for Experts. The consistent use of data sources and assumptions across all systems ensured comparability and minimized variability in the results.

For the deshelling stage, the purchase of a KMBK-4000 Peanut Shelling and Cleaning Machine (400 kg/h) was assumed, with a total equipment cost of €5,900. For the LCC analysis, a discount rate of 5% and a depreciation period of 7 years were considered. Due to the limited utilization of the equipment, maintenance costs were assumed to be negligible and were therefore set to zero.

### 3.2.2. Life Cycle Inventory (LCI)

The LCI data for every process involved in the production of the different peanut products is presented in the Supplementary Materials (Tables 20-23).

### 3.2.3. LCA Results

The results of selected indicators for the different peanut products studied within the VALPRO Path project are depicted in Figure 10.

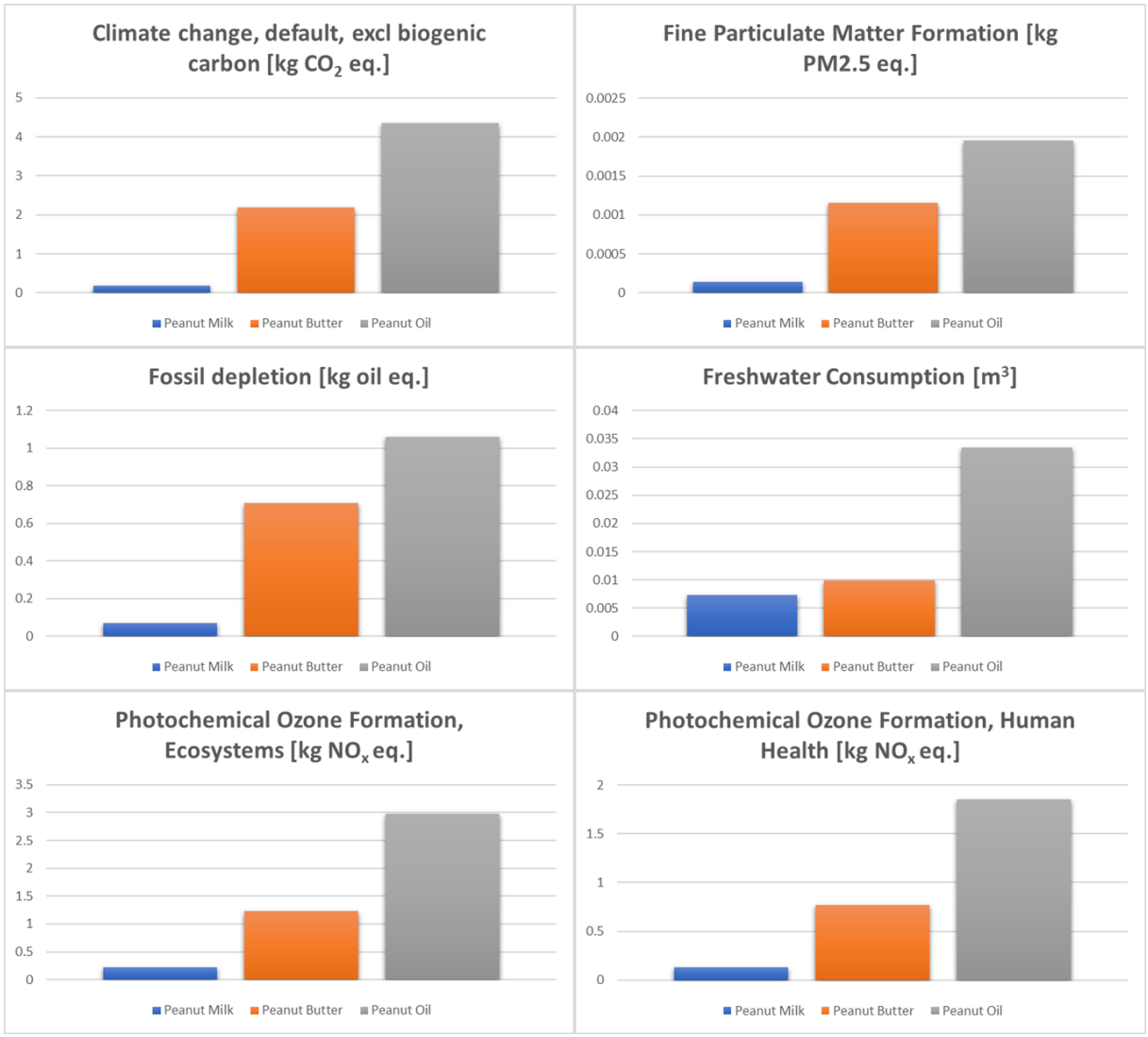



*Figure 10: Comparison of the different peanut products in selected midpoint categories*

The environmental assessment of peanut-based products demonstrates substantial differences in impact intensity among peanut milk, peanut butter, and peanut oil, with impacts generally increasing alongside processing complexity and energy demand.

Among the evaluated products, peanut milk exhibits the lowest environmental burdens. Its climate change impact is estimated at 0.183 kg $CO_2$ eq. per kg of product, mainly driven by packaging production, peanut cultivation, cooking, deshelling, and pasteurization. Packaging contributes significantly due to the production of packaging materials, while cultivation impacts are associated with diesel consumption and fertilizer application. Cooking and pasteurization further increase emissions because of electricity and natural gas use. Fine particulate matter formation reaches $1.38 \times 10^{-4}$ kg PM2.5 eq., primarily linked to cultivation and packaging, whereas fossil depletion amounts to 0.070 kg oil eq. per kg, dominated by packaging and thermal energy use during pasteurization. Freshwater consumption reaches $7.38 \times 10^{-3}$ $m^3$ per kg and is mainly associated with pasteurization and grinding. Photochemical ozone formation impacts amount to 0.215 kg $NO_x$ eq. for ecosystems and 0.134 kg $NO_x$ eq. for human health, mainly due to packaging production and electricity consumption during cooking.

Peanut butter production exhibits considerably higher impacts across all categories, largely due to energy-intensive thermal processing stages. Climate change impact reaches 2.196 kg $CO_2$ eq. per kg of product, more than ten times higher than peanut milk, with roasting and drying identified as the dominant contributors because of their substantial thermal energy requirements. Nevertheless, these values remain lower than those reported in previous studies, indicating relatively improved process efficiency (Kekes et al., 2026). Fine particulate matter formation amounts to $1.16 \times 10^{-3}$ kg PM2.5 eq., mainly resulting from diesel use during cultivation. Fossil depletion reaches 0.710 kg oil eq. per kg and follows a similar pattern to climate change impacts, being strongly influenced by roasting and drying. Freshwater consumption is estimated at $9.87 \times 10^{-3}$ $m^3$ per kg, primarily associated with soaking operations. Photochemical ozone formation reaches 1.236 kg $NO_x$ eq. for ecosystems and 0.768 kg $NO_x$ eq. for human health, driven mainly by roasting, milling, and drying through combined thermal energy and electricity consumption.

Peanut oil production demonstrates the highest environmental impacts among the studied products due to extensive thermal and mechanical processing requirements. Climate change impact reaches 4.358 kg $CO_2$ eq. per kg of refined oil, with roasting and mechanical processing representing the largest contributors because of high electricity demand and the generation of peanut cake as solid waste. However, peanut cake may be valorized as a byproduct for animal feed or protein applications, potentially improving overall system efficiency. Fine particulate matter formation amounts to $1.95 \times 10^{-3}$ kg PM2.5 eq., mainly associated with diesel consumption during cultivation. Fossil depletion reaches 1.059 kg oil eq. per kg, dominated by roasting and energy-intensive operations. Freshwater consumption is particularly high at $3.34 \times 10^{-2}$ $m^3$ per kg, mainly driven by mechanical processing and grinding. Photochemical ozone formation impacts reach 2.981 kg $NO_x$ eq. for ecosystems and 1.852 kg $NO_x$ eq. for human health, resulting primarily from energy consumption during roasting and grinding, as well as waste generation during mechanical processing. Overall, the results highlight the strong influence of energy-intensive processing stages on the environmental performance of peanut-derived products. Detailed explanations and analyses of all studied peanut products have been published under the umbrella of the VALPRO Path project (Kekes et al., 2026).

Further details on LCA results are contained in the Supplementary Materials, Table 24.

### 3.2.4. LCC Results

In order to assess the economic sustainability of exploiting European cultivated peanuts it is necessary to take into account the expenses associated with the cultivation and deshelling. To this aim a technoeconomic assessment focusing only the cultivation and on-farm deshelling is presented below based on the following assumptions:

- Equipment CaPex: 5900 €
- Discount rate = 5 %
- Payback period = 7 yr
- Average selling price of deshelled peanuts = 8 €/kg

The results regarding the technoeconomic assessment of peanuts cultivation and deshelling are presented in the following Table and Figure.

| Year | Cash Flow (€) | Present Value (€) | Net Present Value (€) | Payback Period (yr) | Internal Return Rate (%) |
|---|---|---|---|---|---|
| 0 | -5900 | -5900 | | | |
| 1 | 1334.385 | 1270.843 | 1821.251 | 4.42 | 13.01 |
| 2 | 1334.385 | 1210.327 | | | |

| | | |
|---|---|---|
| 3 | 1334.385 | 1152.692 |
| 4 | 1334.385 | 1097.802 |
| 5 | 1334.385 | 1045.526 |
| 6 | 1334.385 | 995.7388 |
| 7 | 1334.385 | 948.323 |

*Table 8: Results of the economic performance of peanuts cultivation and deshelling*

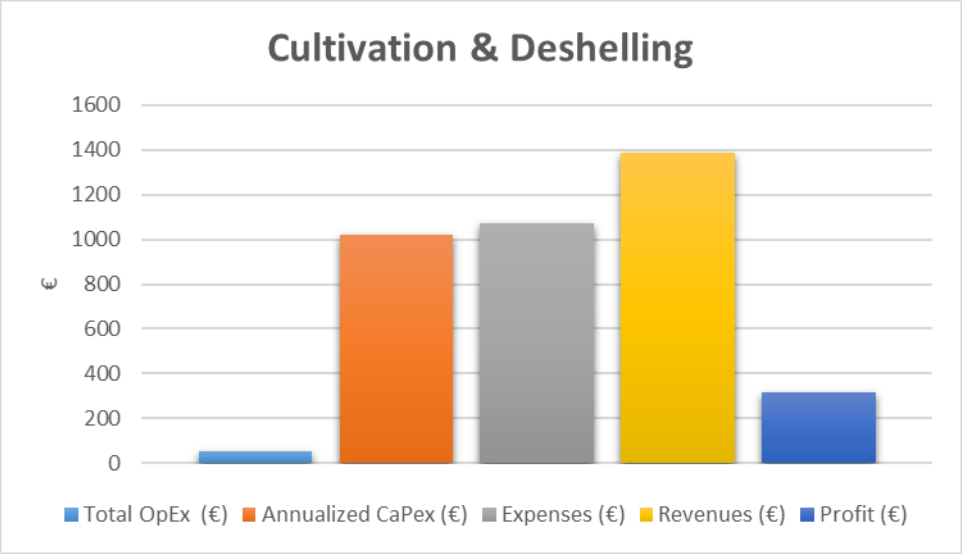



*Figure 11: Results of the economic performance of peanuts cultivation and deshelling*

Based on the LCC analyses, the total OpEx for cultivating and deshelling peanuts amounts to 52.81 €/yr of the product system (204 kg of harvested peanuts), with the total expense when taking into account the annualized CaPex rising to 1072.45 €/yr. On the other hand, with an average selling price of 8 € per kg of deshelled peanuts, the total revenues equal 1387.20 €/yr, resulting in a profit of 314.75 €/yr. These findings, coupled with the positive Techno-Economic Assessment (TEA) indicators, namely the net present value, the payback period, and the internal return rate, suggest that the cultivation and deshelling of European cultivated peanuts is economically feasible and an increase in the production volume will result in increased revenues (Further details in supplementary materials, Table 25).

A comparative assessment of the LCC analysis for the three different peanut products is depicted in Figure 12.

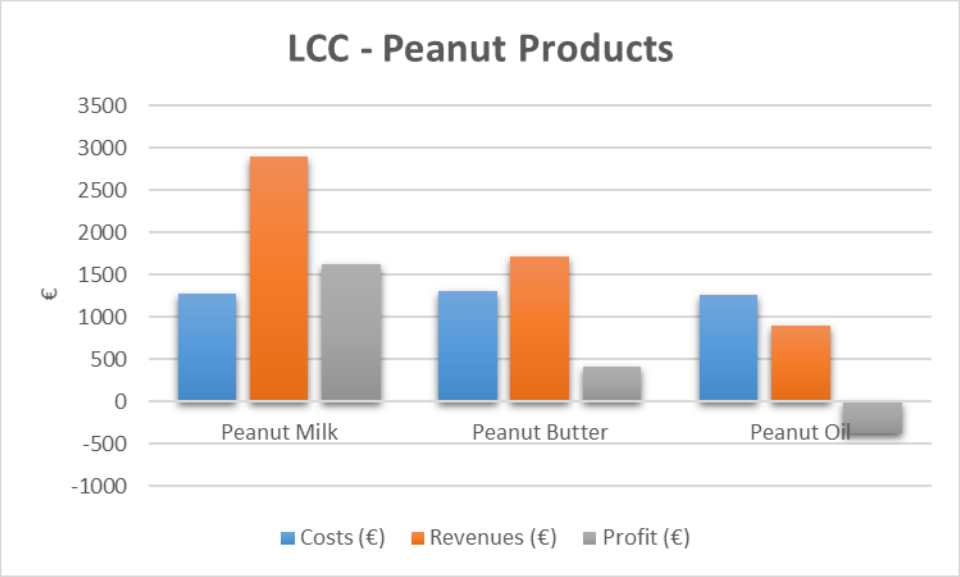



*Figure 12: LCC analysis of the different studied peanut products*

The economic assessment of the different studied peanut products, indicates that milk and butter can be characterized as profitable, with peanut milk being the one with the highest profit. On the other hand, the total costs associated with the production of the peanut oil produces a negative revenue, thus peanut oil under the studied conditions is not economically viable. However, it is worth mentioning that the quantity of the cultivated and harvested peanuts in this business case is limited (204 kg of harvested peanuts), thus the quantity of the final products (145.2 kg, 143.1 kg, and 75 kg for peanut milk, butter, and oil, respectively) is also limited (Further details in supplementary materials, Tables 26-29).

If the total quantity of cultivated peanuts were increased, the production of the final products would also increase without a corresponding rise in annual CAPEX, since the capacity of the equipment can handle an increase in the volume of the harvested peanuts. As a result, revenues would increase significantly, making all three products profitable. Specifically, a tenfold increase in the volume of harvested peanuts results in all peanut products being profitable, as depicted in the Supplementary Materials (Figure 43). Based on the results of the economic analysis, it can be concluded that the valorization of European-produced peanuts and their derived products has the potential to be economically profitable.

## 3.2.5. s-LCA Results

### *3.2.5.1. Goal and Scope*

The goal and scope of this social analysis was to evaluate the social impacts associated with the entire peanut use case, as well as to conduct separate social evaluations for individual peanut-derived products: peanut milk, peanut butter, and peanut oil. The system boundaries follow a cradle-to-gate approach, including peanut cultivation, product processing, and packaging. The functional unit for this analysis is the annual production and use of cultivated peanuts, with the entire system located in Portugal. The annual production of peanuts is equally divided and processed into milk, butter, and oil. The analysis is performed using OpenLCA 2.3 software and utilizing the latest SOCA v3 database, which integrates Ecoinvent v3.10 and PSILCA v3.1.1. To assess the social impacts, the Social Impacts Weighting Method is applied which provides insights into the effects on main stakeholder groups: workers, society, the local community, and value chain actors.

### *3.2.5.2. Social Risks Results*

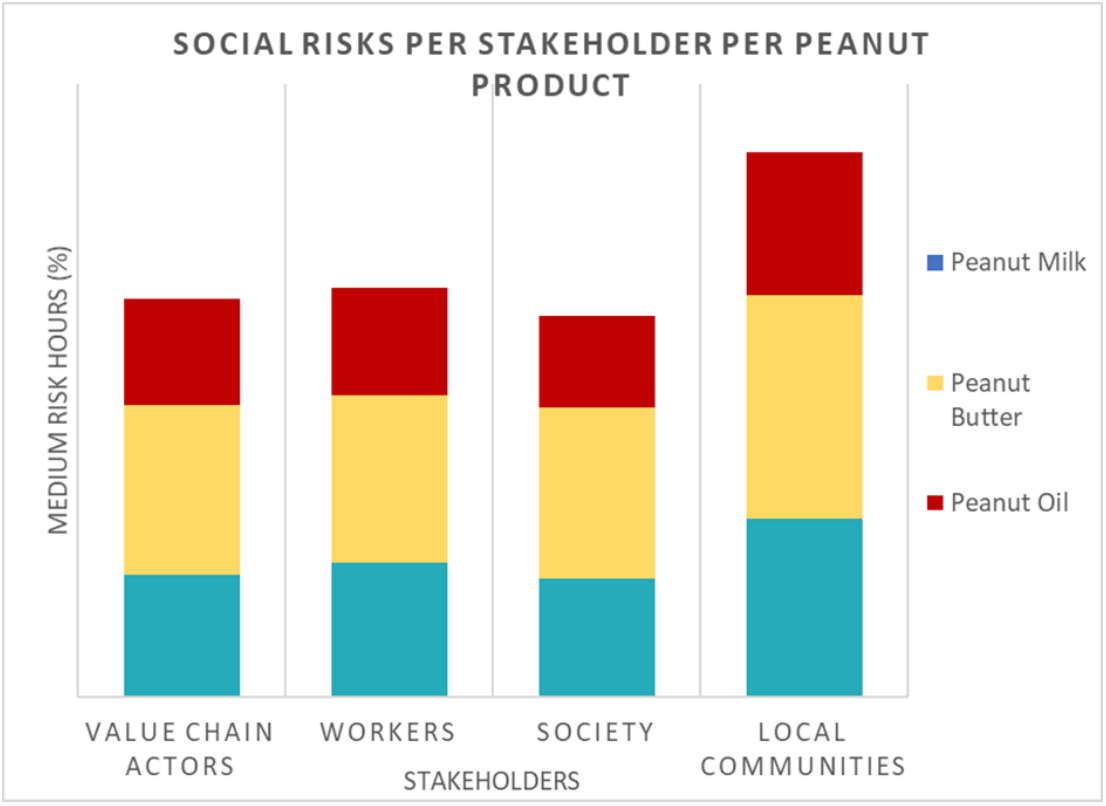



*Figure 13: Social LCA Results of the peanut use case: Mean Social Risks per stakeholder per peanut product*

As presented in Figure 13, out of the three peanut products the highest social impact is noticed on the peanut butter production for the same peanut input per processing product. More precisely, peanut butter production impacts by 42.8% the value chain actors, by 41.1% the workers, by 44.9% the society and by 40.9% the local communities. In comparison, peanut oil production impacts stakeholders at approximately 25–27%, while peanut milk production affects them around 30–33%.

Peanut butter production has the highest social impacts compared to peanut milk and peanut oil production due to its greater complexity and resource demands. For value chain actors, the peanut butter process involves multiple steps such as roasting, grinding, and mixing, which require more inputs and increase risks related to governance, traceability, and informal supply chains. At the societal level, the process's complexity demands greater interaction with national infrastructure, such as energy, regulation, and food safety and has a higher potential for informal economic activity, exposing the system to risks. Finally, local communities are more affected due to the longer processing times and higher consumption of resources, which lead to increased emissions, noise, and environmental impacts that reduce quality of life. Additionally, the greater waste output places more pressure on local waste management and disposal systems. Together, these factors explain the fact that peanut butter production has more pronounced social impacts than peanut oil and peanut milk production. It should be emphasised that the results presented in this section represent a comparative assessment of the three peanut-derived products investigated, namely peanut milk, peanut butter, and peanut oil. Therefore, the finding that peanut butter production exhibits the highest social impacts should be interpreted only in relative terms within the assessed peanut product systems and should not be considered an indication that peanut butter production is inherently socially unsustainable or unsuitable for further development.

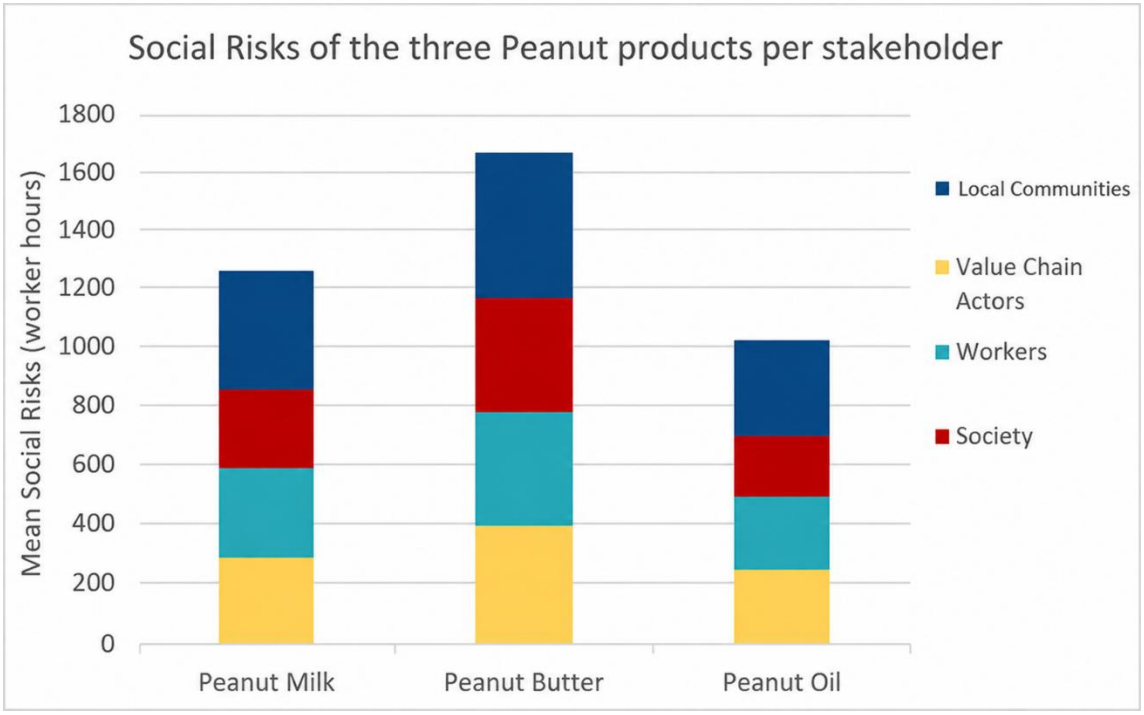



*Figure 14: Social LCA Results of the peanut use case: Mean Social Risks of the three Peanut products per stakeholder*

The analysis shows that local communities experience the highest social impact across all peanut based products. This is largely due to the environmental and resource related pressures associated with on-farm processing. In peanut milk production, the impact on local communities is especially significant due to high water usage and the strain it places on local water resources and rural infrastructure. Similarly, peanut butter and peanut oil production involve extended processing times and greater energy consumption, which contribute to emissions, noise, and increased waste output, which directly affect the quality of life in surrounding communities. These processes also set added pressure on local waste management systems. In contrast, while value chain actors and workers do face notable risks, particularly in the more complex or industrialized processes of peanut butter and oil, these are comparatively lower than the broader and more sustained impacts felt at the community level.

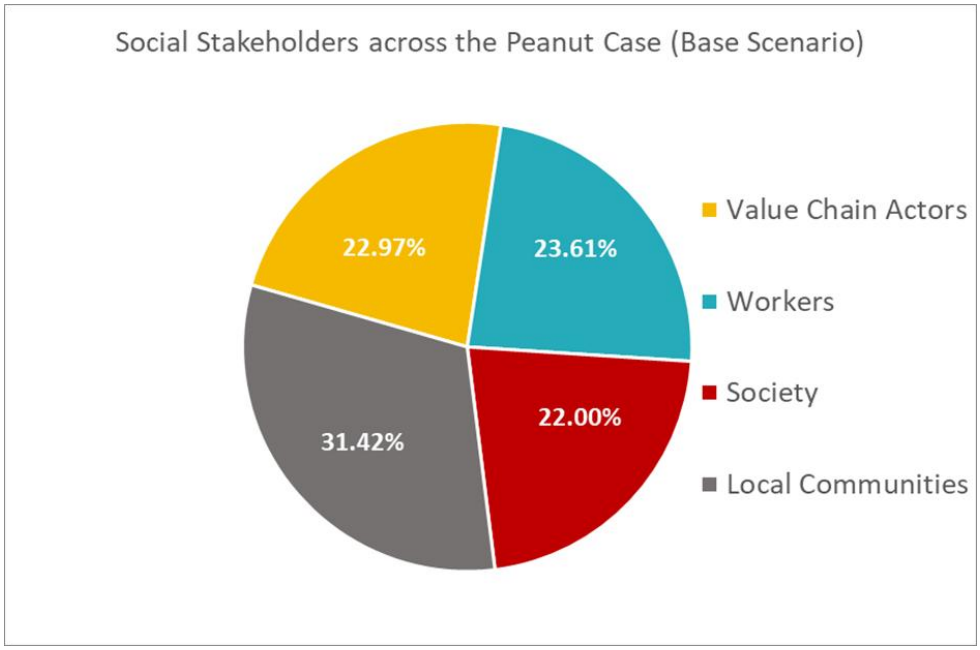



*Figure 15: Social LCA Results of the peanut use case: Base scenario mean social impacts composition per stakeholder*

The associated challenges reflect the broader social, economic, and ethical issues within the system. Value chain actors face significant risks due to their reliance on upstream inputs such as electricity, equipment, and raw materials. These inputs are part of global supply chains that often lack transparency and are linked to concerns about labor rights and negative environmental impacts. Labor-related risks are high in the agricultural sector because the seasonal nature of the work often necessitates the employment of temporary and migrant workers, who themselves are vulnerable to low wages, job insecurity, and limited access to social protections. As a result, these conditions reinforce long-term vulnerability and social inequality. Peanut cultivation and on-farm processing in Portugal impact society by changing land use and limiting crop diversity, which can affect local food availability. Economic benefits are often unequally shared, increasing social inequality. Seasonal and migrant workers face low wages and poor social protections, contributing to social vulnerability in rural communities. Local communities are particularly affected by competition for natural resources like land and water and are often not involved in important decision-making processes.

## 3.3. Intercropping of Peas and Faba Beans

### 3.3.1. Goal & Scope

The main goal of the intercropping business case was to evaluate the environmental, economic, and social sustainability of intercropping two legumes, field peas and faba beans, in Ireland and the subsequent milling of the intercrop to produce a flour for inclusion in confectionary. This alternative confectionery product can be characterized as an alternative option to conventional cakes and provide the foundations for exploiting legume intercrops as a centerpiece in humans diet. To further evaluate the performance of the novel cake, results were compared to a conventional cake following the same recipe and using wheat flour as the main ingredient.

#### *3.3.1.1. Product System*

The product system consists of three main components: intercropping of peas and faba beans, production of the intercrop flour, and cake production. The processes involved in the three production components were thoroughly investigated, and data were collected for each process separately following communication with project partner, TEAGASC, who was responsible for the intercropping trials and the formulation of the final product.

#### *3.3.1.2. Functional Unit, System Boundaries, Data Requirements, Assumptions and Limitations*

The selected functional unit was defined as 1 unit of baked cake, corresponding to approximately 74.9 g. A cradle-to-gate approach was adopted to assess the environmental, economic, and social performance of the novel cake produced using the intercrop flour.

Primary data were obtained through communication with the various research departmenst at TEAGASC responsible for the intercropping trials and cake formulation. Additional data were generated through pilot trials, first-principles calculations, and expert consultation, while Ecoinvent and LCA for Experts were used for background processes and auxiliary materials, with data adapted to the Irish context. Cost data for faba bean cultivation were obtained from a 2024 Teagasc report (Collins & Phelan, 2024)(Collins & Phelan, 2024)(Collins & Phelan, 2024)(Collins & Phelan, 2024)(Collins & Phelan, 2024)(Collins & Phelan, 2024). Additionally, the analysis was based on individual test cakes produced under research-trial conditions rather than at an industrial production scale. Therefore, the results should be interpreted with consideration of the experimental scale of the investigated process.

### 3.3.2. Life Cycle Inventory (LCI)

The LCI data for every process involved in the production of the cake using peas and faba beans intercrop flour are presented in the Supplementary Materials, Table 30-32.

### 3.3.3. LCA Results

The results regarding the environmental performance of the cake using peas and faba beans intercrop flour in selected indicators are depicted in Figure 16, while the complete results are contained in the Supplementary Materials, Table 33.

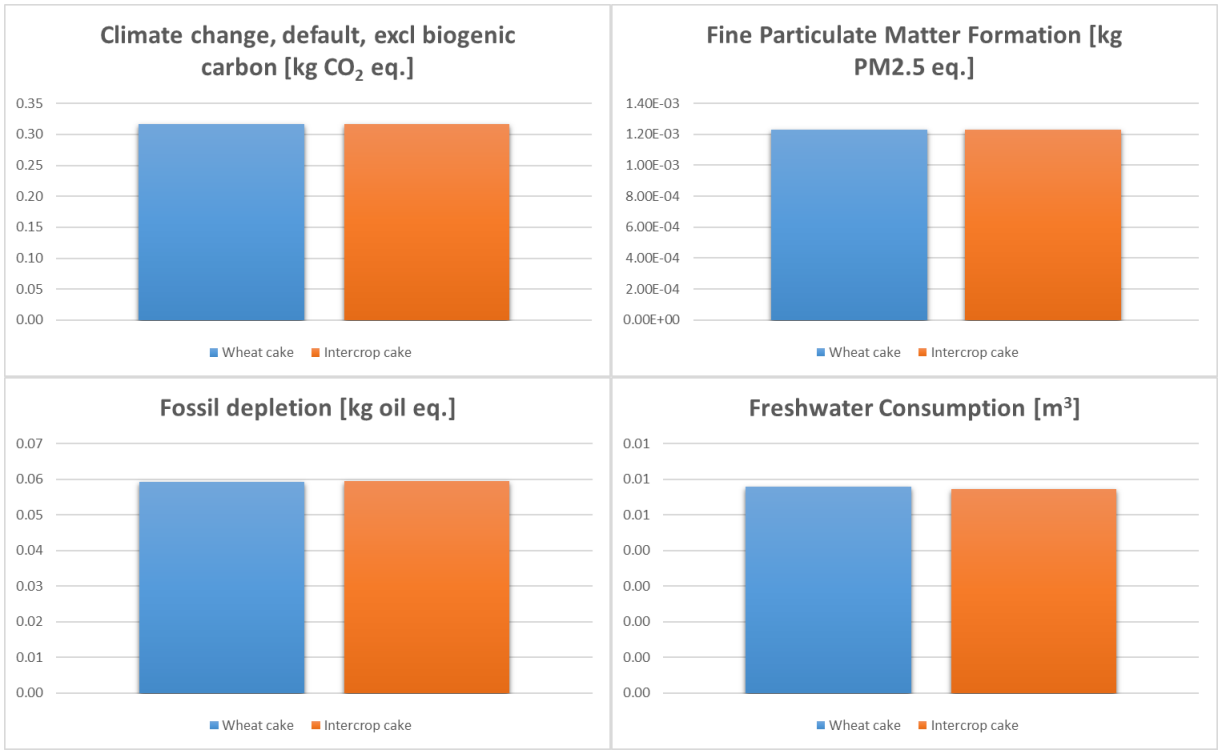



*Figure 16: Comparison of the wheat and intercrop cakes in selected environmental midpoints*

The LCA results indicate that the environmental performance of the cakes produced with intercrop flour is highly comparable to that of the conventional wheat-based cakes across all midpoint and endpoint impact categories. The differences between the two formulations are generally small, with most impact categories varying by less than 3%. Conversely, the intercrop cake exhibits marginally lower impacts in categories such as freshwater consumption, metal depletion, marine eutrophication, and stratospheric ozone depletion. Overall, the endpoint indicators for damage to human health, ecosystems, and resource availability remain nearly identical between the two products.

The similarity in environmental performance is primarily explained by the composition of the cake formulation, where the environmental burdens are dominated by ingredients other than the flour. In particular, the use of animal-based fat represents the largest contributor to several impact categories, including climate change, fossil resource use, and human health impacts, thereby reducing the relative influence of substituting wheat flour with intercrop flour. As a result, the environmental differences associated with the flour ingredient alone are comparatively small within the overall product system.

Despite the limited differences observed, the intercrop cake demonstrates that flour derived from intercrop systems can be used as an environmentally sustainable alternative to conventional wheat flour without compromising the overall environmental performance of the final product. Beyond the LCA results presented here, intercropping systems offer additional agronomic and ecosystem benefits, including improved biodiversity, enhanced soil health, more efficient nutrient utilisation, and reduced reliance on synthetic fertilisers and pesticides. These benefits are not always fully captured by conventional life cycle impact assessment methods but contribute to the broader sustainability of agricultural production.

### 3.3.4. LCC Results

An overview of the costs associated for the intercropping of peas and faba beans, the production of the intercrop flour, and the cake production are presented in Figure 17, while more information are contained in the Supplementary Materials, Tables 34-36

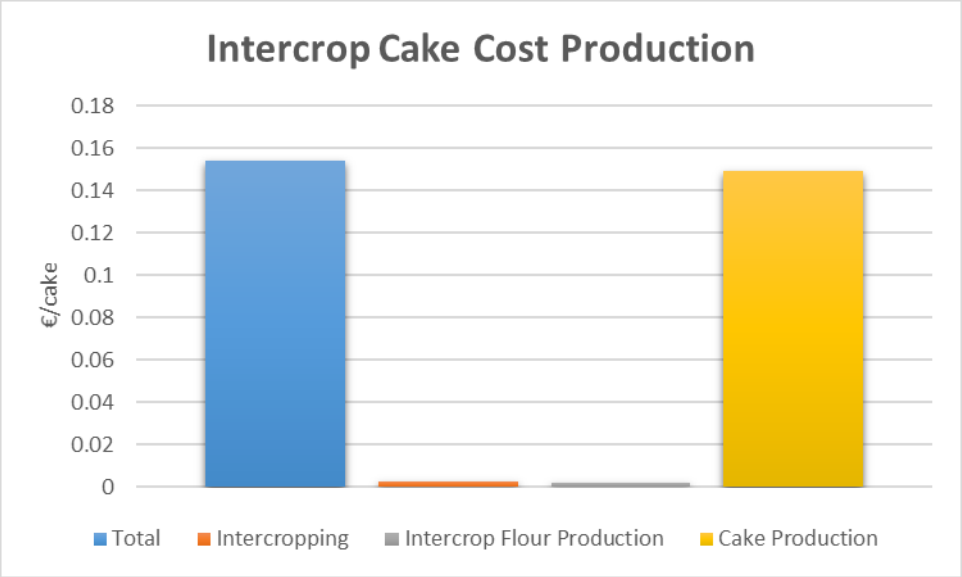



*Figure 17: Total cost and cost per production component for producing 1 cake using peas and faba beans intercrops*

The total production cost was €0.1539 per cake for the intercropped cake and €0.1538 per cake for the conventional wheat cake, representing a negligible difference of €0.0001 per cake (approximately 0.06%). The similarity in costs indicates that substituting intercropped wheat flour does not significantly affect the overall production cost of the cake. In both formulations, the recipe ingredients were the dominant contributors to the total production cost, while the cost associated with flour production or the intercropping system represented only a very small proportion of the overall cost. The results suggest that ingredient costs, particularly high-value ingredients such as butter and eggs, dominate the economics of cake production. Consequently, any cost differences associated with producing intercropped wheat flour are largely diluted when incorporated into the final product. This indicates that adopting intercropped wheat as a flour source is unlikely to increase manufacturing costs for cake production, while still offering potential environmental benefits identified in the life cycle assessment.

### 3.3.5. s-LCA Results

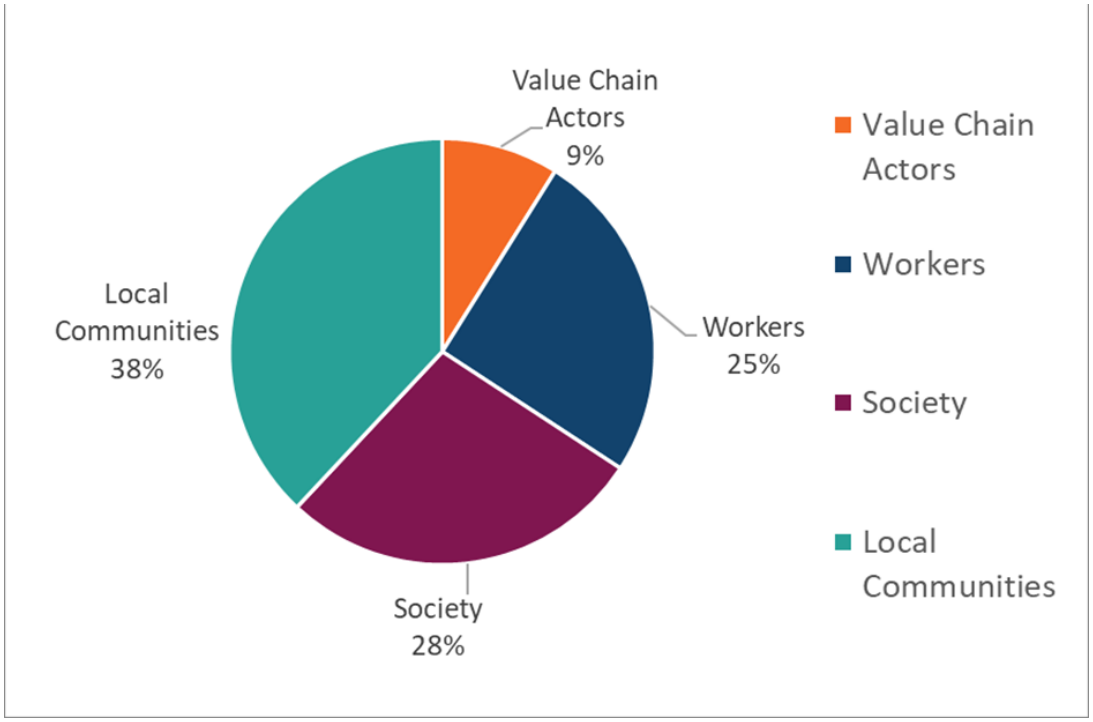



*Figure 18: Distribution of total social impacts across stakeholder groups (Value Chain Actors, Workers, Society, and Local Communities), expressed as percentage contribution to total medium risk hours for 1 cake produced with intercropped of pea and fava share*

The social impacts of the cake production across stakeholder groups are presented in Figure 26. The total social impact results across stakeholder categories show that local communities account for the largest share (38%), followed by society (28%), workers (25%), and value chain actors (9%). This distribution highlights the broad scope of social considerations captured in the assessment, extending beyond direct manufacturing to include upstream processes and wider socio-economic contexts. The contribution from local communities reflects the close interaction between production systems and regional resource use, particularly in agricultural stages. The society category represents systemic aspects such as governance and economic structures, emphasizing the relevance of contextual conditions. The substantial contribution from workers underlines the importance of labor conditions across both agricultural and processing stages, indicating opportunities to enhance social performance within manufacturing. Meanwhile, the lower contribution from value chain actors suggests relatively lower risk intensity in supply chain interactions. Overall, the results provide a comprehensive view of social impacts across the supply chain and highlight key areas for targeted improvements.

The social impact assessment indicates that wheat cultivation and processing are the main contributors across all stakeholder categories, including local communities, society, workers, and value chain actors. Wheat cultivation accounts for approximately 39–48% of the total social impacts, reflecting both its dominant share in the cake formulation and its relatively higher impact intensity associated with conventional agricultural practices, labor conditions, and resource use. Processing contributes 27–41%, particularly affecting workers due to energy-intensive and labor-demanding operations such as mixing, scaling, and baking, while also contributing to broader societal and value-chain risks. In contrast, intercropped pea and faba bean cultivation contributes a smaller but consistent share (13–19%), suggesting a comparatively more favorable social performance, while flour production remains the least significant contributor (4–6%). Overall, the results highlight agricultural production and processing as the key stages for improving the social sustainability of the cake

production system, while the lower contribution of intercropped cultivation indicates its potential to reduce social risks across the value chain.

Further details on social LCA results are contained in the Supplementary Materials, Figures 44-48.

### 3.3.6. Results from Intercropping Questionnaire

In order to further understand the social effects of intercropping on farmers, a comprehensive questionnaire was created and distributed to farmers via partners and stakeholders across the European Union. Its scope was to identify and assess the expected social impacts of intercropping, including positive impacts, risks, motivators, and constraints. It aimed to understand farmers' experiences with intercropping, their willingness to adopt such practices, the important benefits for those already practicing it, and the challenges or barriers faced. The questionnaire also explored broader social outcomes, such as community cooperation, knowledge sharing, food security and contributions to sustainable agriculture, while noting potential concerns like increased labor demands, resource competition, and pest or disease risks.

Out of all the participants, one-third had practiced intercropping on their farms, with no significant influence from country, gender, or age. A significant percentage (85%) believe that intercropping contributes to better household income and livelihoods, which may result from increased crop diversity and higher overall yields. A notable 56% of respondents, both intercropping and non-intercropping farmers, perceive intercropping as having the potential to promote cooperation and knowledge sharing.

The top reported benefits of intercropping are efficient use of resources, improved soil health and increased crop yield per unit area. Preservation of cultural and traditional practices was considered largely unimportant by most participants.

Socially, intercropping is perceived to enhance community cooperation, knowledge sharing and food security. The main challenges identified are knowledge and skill gaps regarding intercropping techniques. Additional concerns include resistance within communities and cultural reluctance to adopt new agricultural methods.

A large majority (85%) believe that intercropping improves household income and livelihoods, likely due to crop diversification and better yields. More than half (56%) also see it as a driver for cooperation and knowledge sharing.

In terms of broader impacts, intercropping is seen to contribute to sustainable agriculture for future generations, nutritional diversity and resilience to drought. Only a minority mentioned concerns such as increased labor intensity, resource competition, and pest or disease transfer between crops.

### 3.3.7. LCSA of European Intercropping Peas and Faba Beans Business Case

The results regarding the overall sustainability of the Intercropping Business Case are presented in the following Figure.

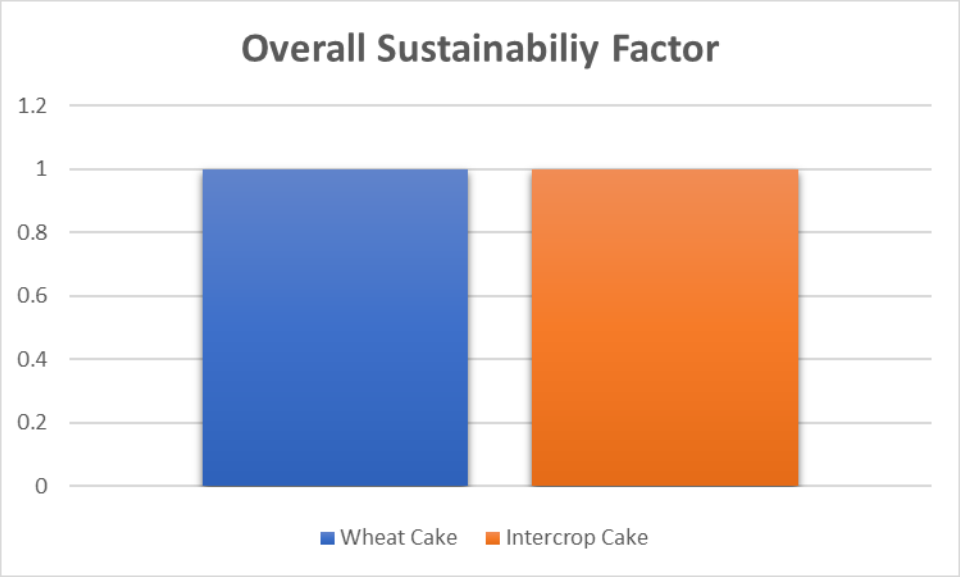



*Figure 19: Overall Sustainability of the Intercropping business case*

Based on the obtained results, the Overall Sustainability Factor (OSF) of the intercrop cake is identical to that of the conventional wheat cake, indicating that the substitution of wheat flour with intercrop-derived legume ingredients does not compromise the overall sustainability performance of the final product. Considering the equal weighting assigned to the environmental, economic, and social dimensions, the results demonstrate that the intercrop cake performs equivalently to the conventional formulation across the selected sustainability indicators. These findings suggest that the intercrop cake can be considered a sustainable alternative to the conventional wheat-based product, offering comparable overall sustainability while promoting the utilisation of legumes in value-added food applications. The incorporation of intercrop-derived legumes into bakery products provides an opportunity to diversify legume consumption beyond traditional applications, supporting the development of sustainable food systems and encouraging the wider adoption of legumes as ingredients in innovative food products without compromising their overall sustainability performance.

## 3.4. Plant-based Beverage Production

### 3.4.1. Goal & Scope

The main goal of the plant-based beverage production business case was to evaluate the environmental, economic, and social sustainability of a novel functional food that uses faba bean protein isolate as one of the main ingredients. This model nutritional beverage can be characterized as an alternative option to conventional energy drinks and beverages and provide the foundations for exploiting protein crops in different ways.

#### *3.4.1.1. Product System*

The product system consists of three main components: faba beans cultivation, faba bean protein isolate production, and beverage production. The processes involved in the three production components were thoroughly investigated, and data were collected for each process separately following communication with project partnert TEAGASC, which was responsible for the production of the model beverage.

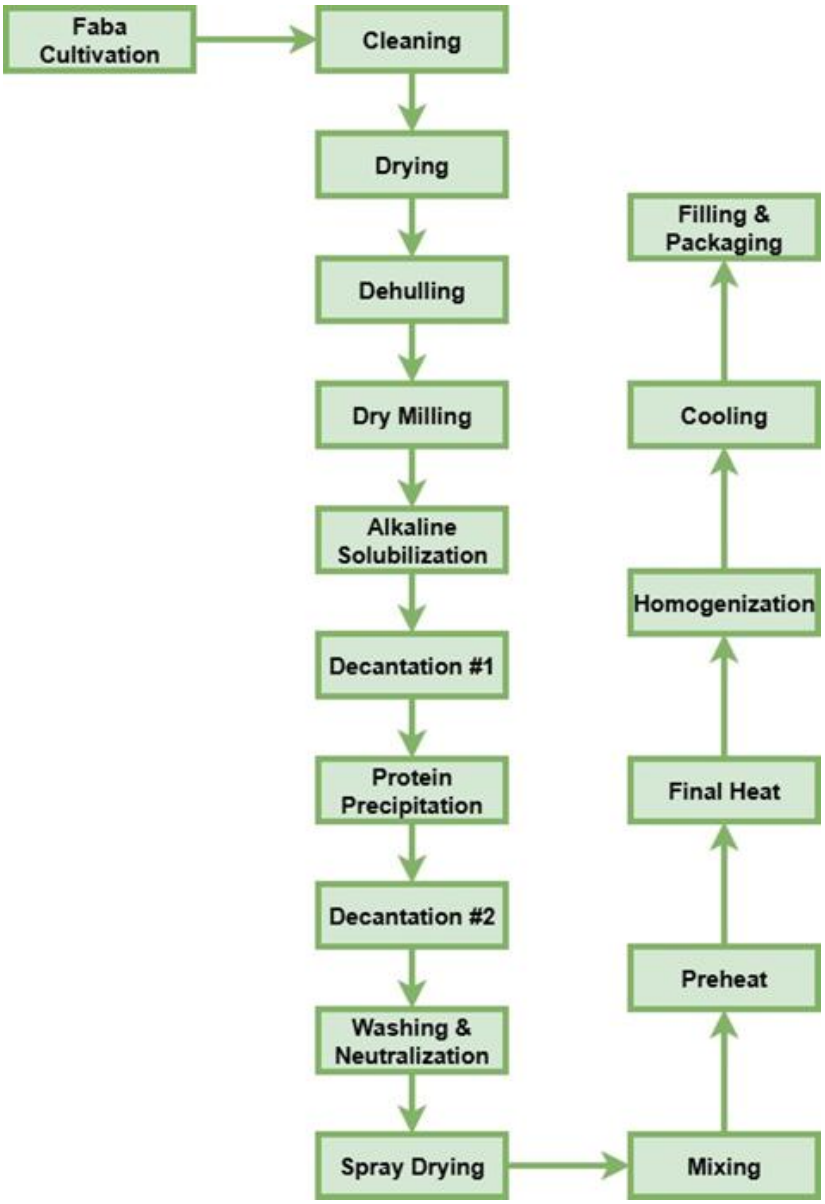


*Figure 20: Flowchart of plant-based beverage production*

#### *3.4.1.2. Functional Unit, System Boundaries, Data Requirements, Assumptions and Limitations*

The selected functional unit was defined as 1 unit of packaged beverage, corresponding to 330 mL. A cradle-to-gate approach was adopted to assess the environmental, economic, and social performance of the plant-based beverage produced using faba bean protein isolate. The system boundary included faba bean cultivation, production of the protein isolate, and subsequent beverage production up to the point at which the final product is ready to leave the factory for distribution.

Primary data were obtained through communication with stakeholders in Ireland involved in the different stages of the production chain. Data on faba bean cultivation were collected from Irish farmers, while data related to protein isolate and beverage production were obtained from relevant Irish industries. Additional data were generated through pilot trials, first-principles calculations, and expert consultation, while Ecoinvent and LCA for Experts were used for background processes, with data adapted to the Irish context. Cost data for faba bean cultivation were obtained from a 2024 Teagasc report.

For the LCC analysis, capital expenditures were considered negligible, as the production of the protein isolate and beverage involves well-established processes within the food and beverage sector. Maintenance and other costs were additionally considered, each corresponding to 5% of the total production costs. Maintenance costs accounted for equipment and machinery maintenance, while other costs included taxation and similar cost flows.

### 3.4.2. Life Cycle Inventory (LCI)

The LCI data for every process involved in the production of the beverage are contained in the Supplementary Materia; Tables 37-39.

### 3.4.3. LCA Results

The results regarding the environmental performance of the plant-based beverage in selected indicators are depicted Figures 21 and 22, with full results being in the Supplementary Material, Table 40 and Figure 49.

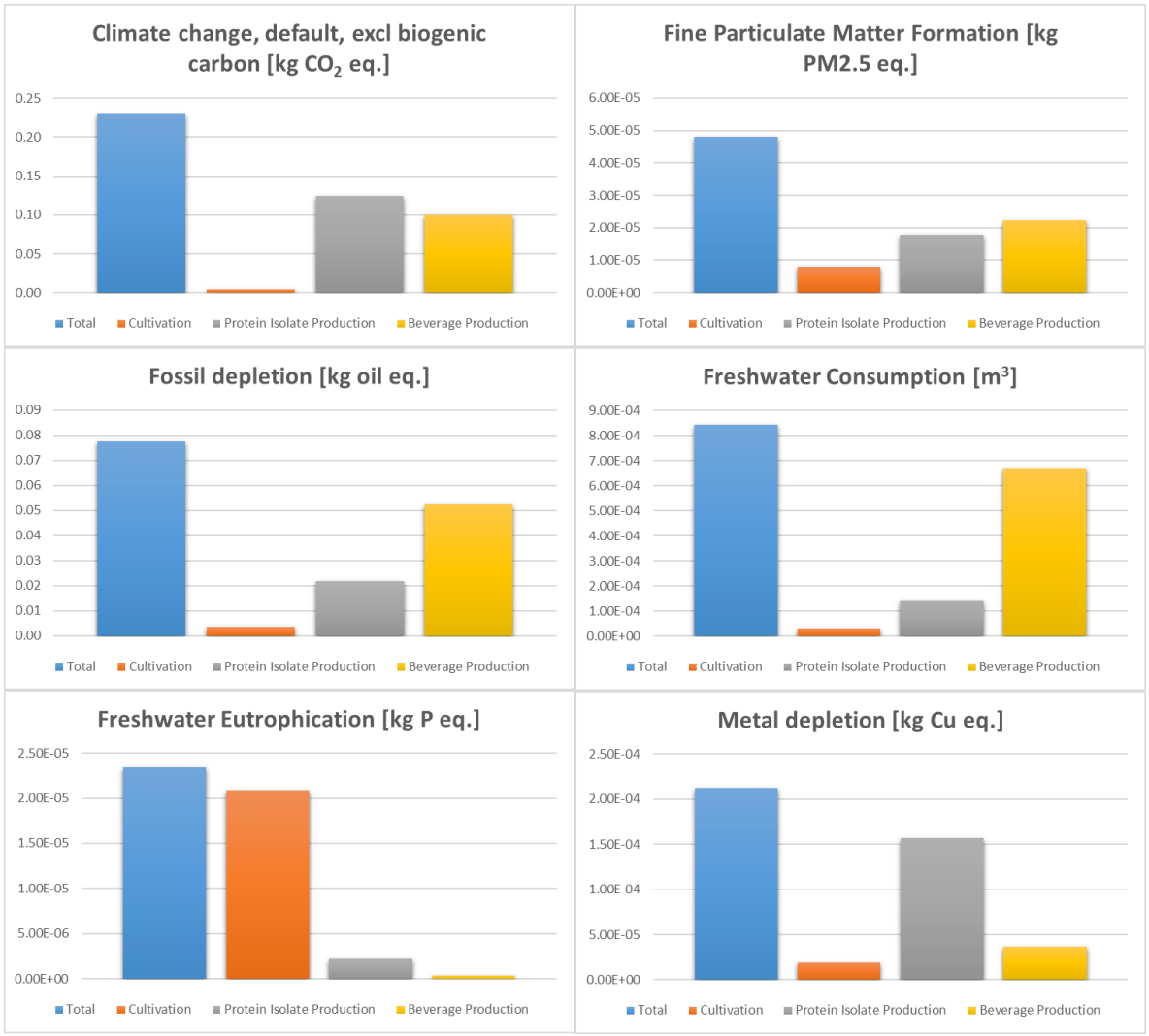



*Figure 21: LCA results of plant-based beverage production in selected midpoint indicators*

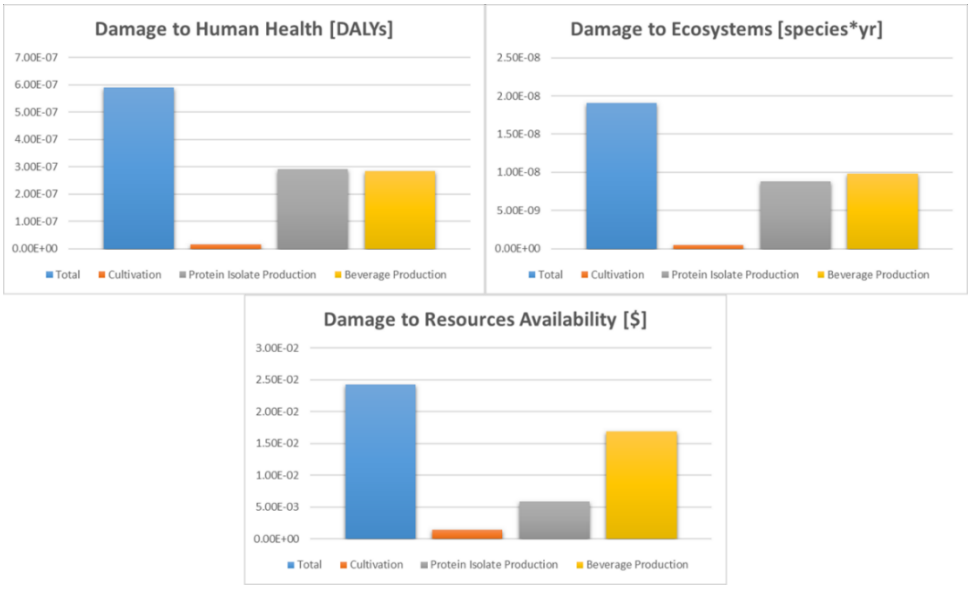



*Figure 22: ReCiPe endpoints of the beverage production*

The LCA results indicate that the main environmental impacts of faba bean-based beverages originate from energy-intensive stages during protein isolate manufacture and beverage production. The filling and packaging, decantation, and spray-drying processes are the largest contributors to climate change, fossil depletion, and fine particulate matter formation due to high energy demand, packaging materials, and the use of sodium hydroxide during alkaline solubilization. Freshwater consumption remains relatively low because faba beans are not irrigated, although fertiliser use during cultivation may contribute to eutrophication risk if nutrient runoff is not properly managed. Electricity consumption during dehulling and decantation also contributes to metal depletion. Compared with other plant-based beverages, faba bean beverages show a higher carbon footprint (0.229 kg $CO_2$ eq. per 330 mL) than almond, soy, and oat drinks, mainly because the formulation relies on protein isolate rather than minimally processed crops. Nevertheless, the use of protein isolate improves nutritional and sensory quality by increasing protein concentration, reducing off-flavours, and minimising anti-nutritional factors. Despite the impacts associated with processing, the beverage can still be considered an environmentally sustainable product. Cultivation contributes minimally to freshwater consumption because faba beans are not irrigated, and overall impacts remain lower than those typically associated with animal-based dairy beverages. Furthermore, the product benefits from the agronomic advantages of legumes, including nitrogen fixation and reduced dependence on synthetic fertilisers. The findings suggest that further improvements in energy efficiency during protein isolate manufacture and beverage production, together with effective nutrient management practices, could further reduce the environmental footprint and enhance the sustainability performance of faba bean-based beverages. Detailed explanations and analyses for the environmental performance of the plant-based beverage have been published under the umbrella of the VALPRO Path project (Drosou et al., 2026).

### 3.4.4. LCC Results

An overview of the costs associated for the cultivation of faba beans, the production of the protein isolate, and the beverage production can be found in Figure 23.

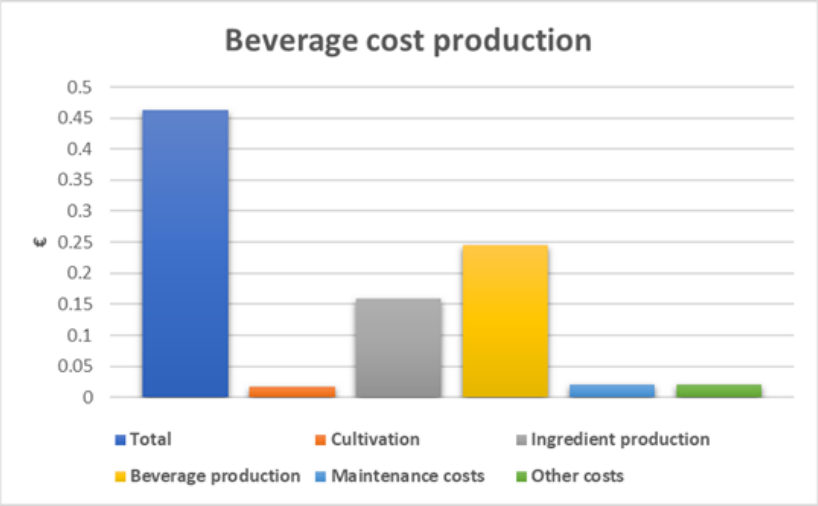



*Figure 23: Total cost and cost per production component for producing 330 mL of beverage*

The economic assessment of the novel faba bean-based beverage, expressed per 330 mL of product, demonstrates that a total of 0.46 € is required for production, including all operating expenditures across cultivation, ingredient production, and beverage production. Beverage production represents the largest contributor to the total cost (0.24 €), mainly due to the energy requirements of heating processes and the use of conventional packaging materials during filling and packaging. Protein isolate

production is the second largest contributor (0.16 €), reflecting the energy, labour, and material demands associated with isolate manufacture. Maintenance and other operational costs contribute 0.021 € each, accounting for equipment upkeep, repairs, taxation, and related overheads. In contrast, cultivation contributes the least to the total cost (0.018 €), indicating the efficiency of low-input, non-irrigated faba bean cultivation systems. The detailed cost breakdown further highlights the importance of utilities, labour, and auxiliary materials in both ingredient and beverage production. In ingredient production, water-related costs account for the largest share (32%), followed by utilities (24%), auxiliary materials (20%), and labour (18%). For beverage production, auxiliary materials, labour, and utilities contribute 35%, 34%, and 31% of total costs, respectively, while water-related costs are negligible. Overall, despite the relatively high costs associated with energy-intensive processing and packaging, the beverage can still be considered economically promising and environmentally sustainable. The low cultivation costs, combined with the sustainability advantages of faba beans as a non-irrigated legume crop, support the feasibility of the product. Furthermore, targeted improvements in energy efficiency, process optimization, and sustainable packaging solutions could further reduce production costs and enhance the overall sustainability and market competitiveness of the beverage. Detailed explanations and analyses for the economic performance of the plant-based beverage have been published under the umbrella of the VALPRO Path project (Drosou et al., 2026). Further deails regarding the LCC can be found on Supplementary Materials, Tables 41-43.

### 3.4.1. s-LCA Results

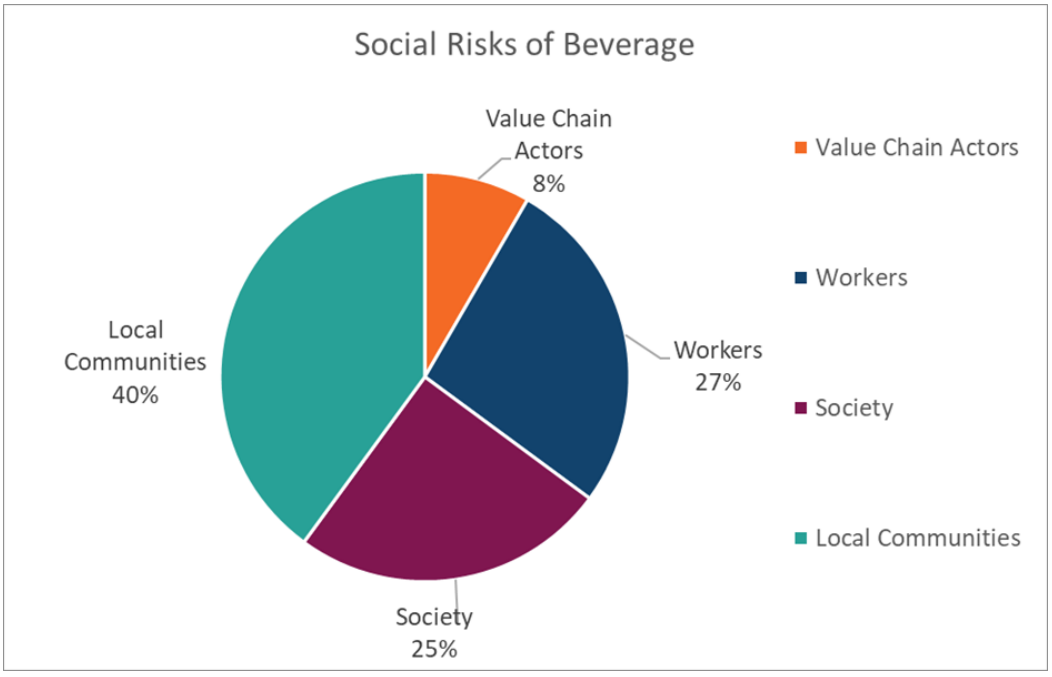



*Figure 24: Distribution of total social impacts across stakeholder groups (Value Chain Actors, Workers, Society, and Local Communities), expressed as percentage contribution to total medium risk hours for 1 kg of fava bean–based protein beverage*

The social impacts of a plant-based protein beverage made from fava beans reflect the dynamics of its production and supply chain, while also highlighting opportunities for positive interventions. Local communities show the highest impact (40%), largely due to the reliance on raw materials and energy inputs that can influence land use, resource management, and local environmental conditions. Workers experience a 26% impact, mainly associated with labor conditions, fair wages, and occupational health in production and processing phases, particularly during protein precipitate

extraction. Society at large has a 23% impact, reflecting broader considerations such as sustainable food production, energy sourcing, and environmental health. Value chain actors are affected the least (11%), as structured production processes and regulatory frameworks in Europe help mitigate social risks. Overall, while certain social risks exist, they are moderate and manageable, and with targeted actions such as sustainable sourcing, energy efficiency, and fair labor practices, the fava bean protein value chain can enhance positive social outcomes across communities, workers, and society.

The social life cycle assessment indicates that the overall social risk profile of the fava bean–based protein beverage is moderate, with local communities accounting for the largest share of the total impact, followed by workers and society, while value chain actors represent the smallest contribution (8%). Across the life cycle, beverage processing is the main contributor to social risks, followed by protein precipitate production, whereas fava bean cultivation and flour production contribute comparatively less. The higher contribution of the processing stages is primarily associated with their greater resource and energy requirements and the associated upstream supply chains, while the contribution of agricultural stages reflects the social risks embedded in raw material production. The concentration of impacts in these stages identifies clear opportunities for improvement through measures such as process optimization, improved energy efficiency, responsible sourcing, and enhanced supply-chain transparency. A detailed stakeholder-specific analysis of the contribution of individual life cycle stages is provided in the Supplementary Materials (Figures 50-54).

## 3.5. Energy Bar Production

### 3.5.1. Goal & Scope

The main goal of the energy bar production business case was to evaluate the environmental, economic, and social sustainability of a novel functional food that uses faba bean protein isolate as one of the main ingredients. This model energy bar can be characterized as an alternative option to conventional protein snacks and provide the foundations for exploiting protein crops in different ways.

#### *3.5.1.1. Product System*

The product system consists of three main components: faba beans cultivation, faba bean protein isolate production, and beverage production. The processes involved in the three production components were thoroughly investigated, and data were collected for each process separately following communication with project partner TEAGASC, which was responsible for the production of the model beverage.

#### *3.5.1.2. Functional Unit, System Boundaries, Data Requirements, Assumptions and Limitations*

The selected functional unit was defined as 1 piece of energy bar, corresponding to 50 g. A cradle-to-gate approach was adopted to assess the environmental, economic, and social performance of the model energy bar produced using faba bean protein isolate. The system boundary included faba bean cultivation, production of the protein isolate, and subsequent energy bar production up to the point at which the final product is ready to leave the factory for distribution.

Primary data were obtained through communication with stakeholders in Ireland involved in the different stages of the production chain. Data on faba bean cultivation were collected from Irish farmers, while data related to protein isolate and energy bar production were obtained from relevant Irish industries. Additional data were generated through pilot trials, first-principles calculations, and expert consultation, while Ecoinvent and LCA for Experts were used for background processes, with data adapted to the Irish context. Cost data for faba bean cultivation were obtained from a 2024 Teagasc report.

For the LCC analysis, capital expenditures were considered negligible, as the production of the protein isolate and energy bar involves well-established processes within the food and beverage sector. Maintenance and other costs were additionally considered, each corresponding to 5% of the total production costs. Maintenance costs accounted for equipment and machinery maintenance, while other costs included taxation and similar cost flows.

### 3.5.2. Life Cycle Inventory (LCI)

The inventory for the data related to the cultivation of faba beans and the production of the faba protein isolate for the energy bar production is the same as the beverage business case, while the inventory for the final step of the enrgy bar formulation and production is contained in the Supplementary Materials; Table 44.

### 3.5.3. LCA Results

The results regarding the environmental performance of the plant-based beverage in selected midpoint indiactors and in the endpoint indicators are depicted in Figures 25 and 26.

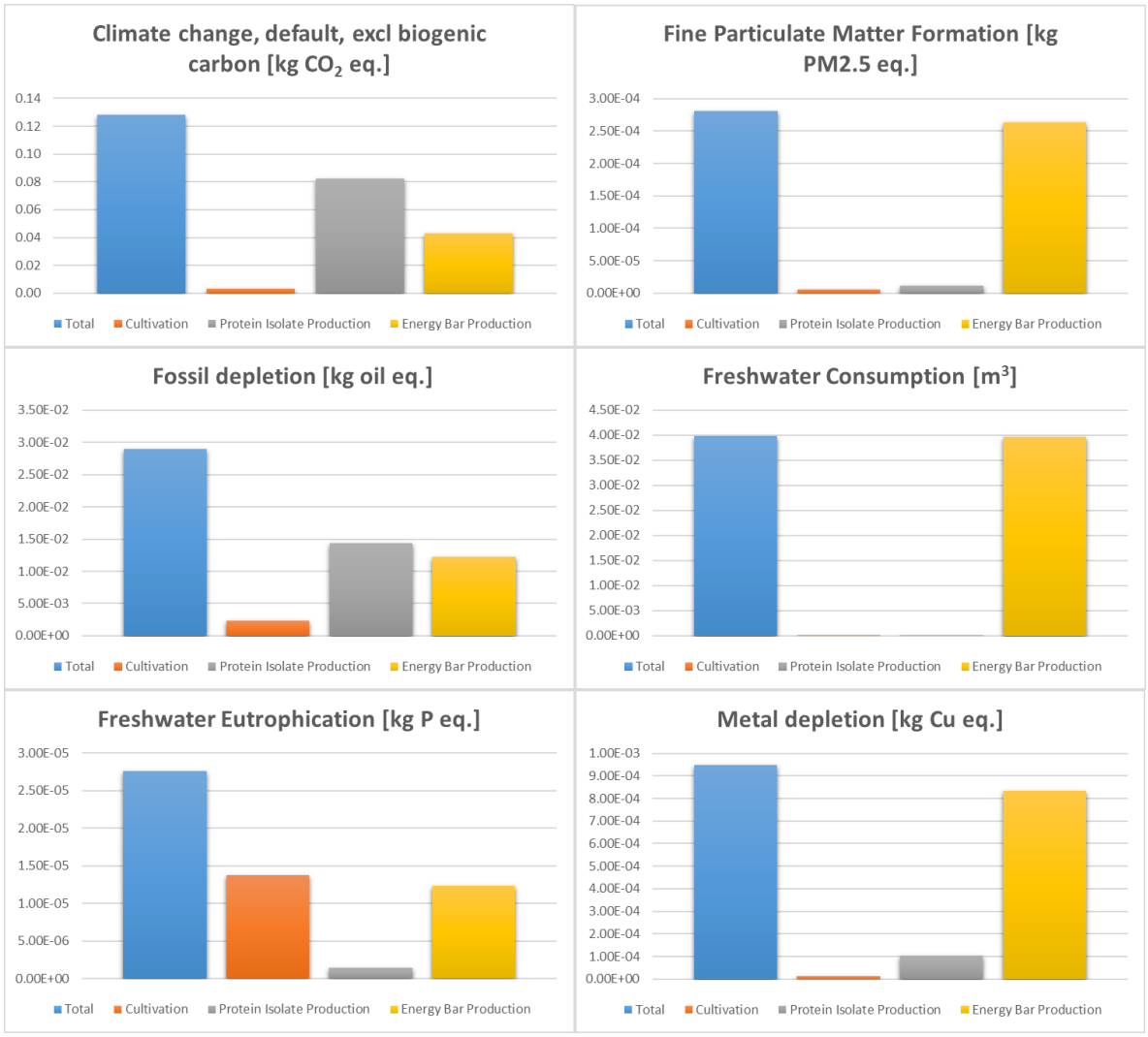



*Figure 25: LCA results of plant-based energy bar production in selected midpoint indicators*

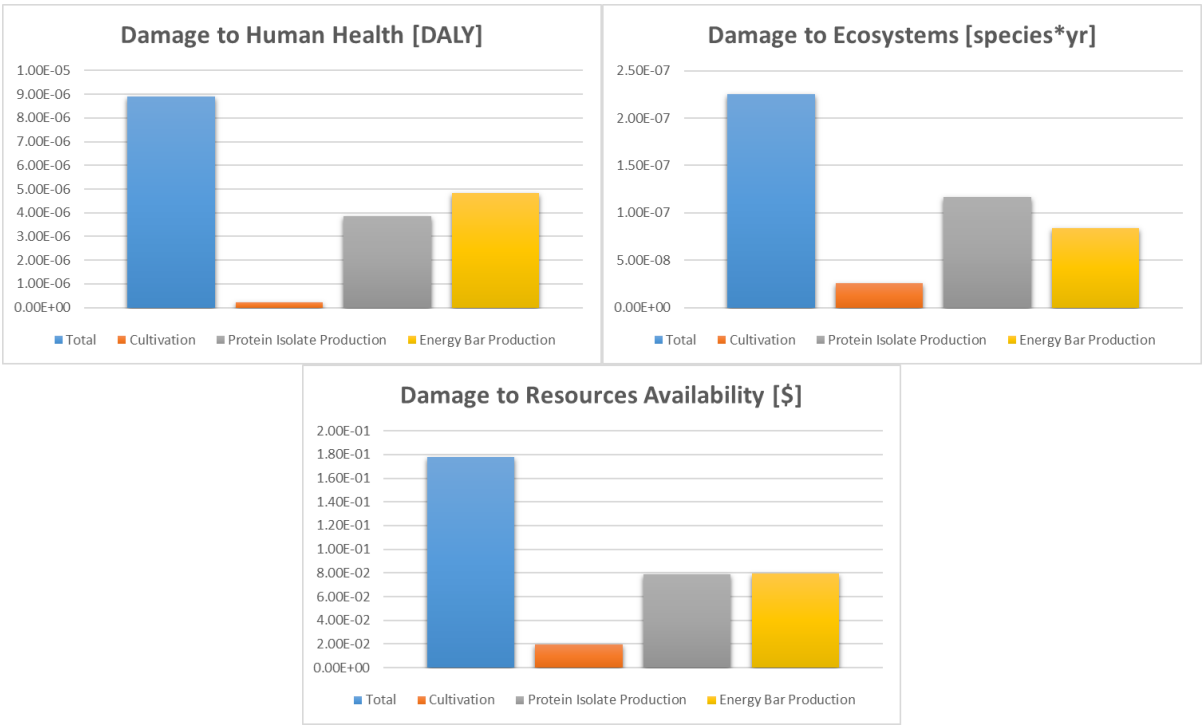



*Figure 26: ReCiPe endpoints of the energy bar production*

The LCA results indicate that the environmental impacts of the protein-based energy bar are primarily associated with the protein isolate production and energy bar production stages, while the cultivation stage contributes comparatively little to most impact categories. Protein isolate production is the dominant contributor to climate change, accounting for approximately 64% of the total greenhouse gas emissions (0.0823 kg $CO_2$ eq. of the total 0.128 kg $CO_2$ eq.), reflecting the energy-intensive nature of protein extraction and purification processes. This stage also contributes substantially to fossil depletion, photochemical ozone formation, and damage to ecosystems and resource availability, largely due to electricity consumption and industrial processing operations.

The energy bar production stage is the largest contributor to several impact categories, including fine particulate matter formation, freshwater consumption, freshwater ecotoxicity, metal depletion, terrestrial acidification, human toxicity (non-cancer), and damage to human health. These impacts are primarily driven by energy use during mixing, baking, and packaging operations, together with the production of packaging materials and other ingredients incorporated during formulation. Freshwater consumption is almost entirely associated with the manufacturing stage (0.0396 $m^3$ of the total 0.0398 $m^3$), indicating that water use during processing dominates over agricultural water demand.

Cultivation contributes most significantly to land use, accounting for approximately half of the total land occupation (0.110 Annual crop eq.·y of the total 0.213 Annual crop eq.·y), reflecting the agricultural area required for crop production. Cultivation also represents the largest contributor to freshwater eutrophication, mainly due to phosphorus emissions associated with fertiliser application and nutrient runoff. However, its contribution to most other impact categories, including climate change and fossil depletion, remains relatively small compared with downstream processing.

At the endpoint level, damage to human health is shared between protein isolate production and energy bar production, while damage to ecosystems is mainly associated with protein isolate manufacture and agricultural production. Resource availability impacts are almost equally distributed

between protein isolate production and energy bar manufacturing, highlighting the importance of reducing energy and material consumption throughout processing.

Overall, the results demonstrate that the environmental performance of the energy bar is driven predominantly by processing rather than cultivation. Consequently, improvements in energy efficiency, the use of renewable electricity, optimisation of protein isolation technologies, and more sustainable packaging materials could substantially reduce the overall environmental footprint. Although protein isolate manufacture is associated with relatively high processing impacts, it enhances the nutritional quality of the energy bar by providing a concentrated, high-protein ingredient. Therefore, optimising industrial processing while maintaining nutritional functionality represents the greatest opportunity for improving the sustainability of the product. Full results of the LCA analysis are in Table 45 of the Supplementary Materials

### 3.5.4. LCC Results

The overview of the costs associated for the cultivation of faba beans and the production of the protein isolate are identical to the beverage production business case, while the figure below presents an overview of the costs associated with the energy bar production.

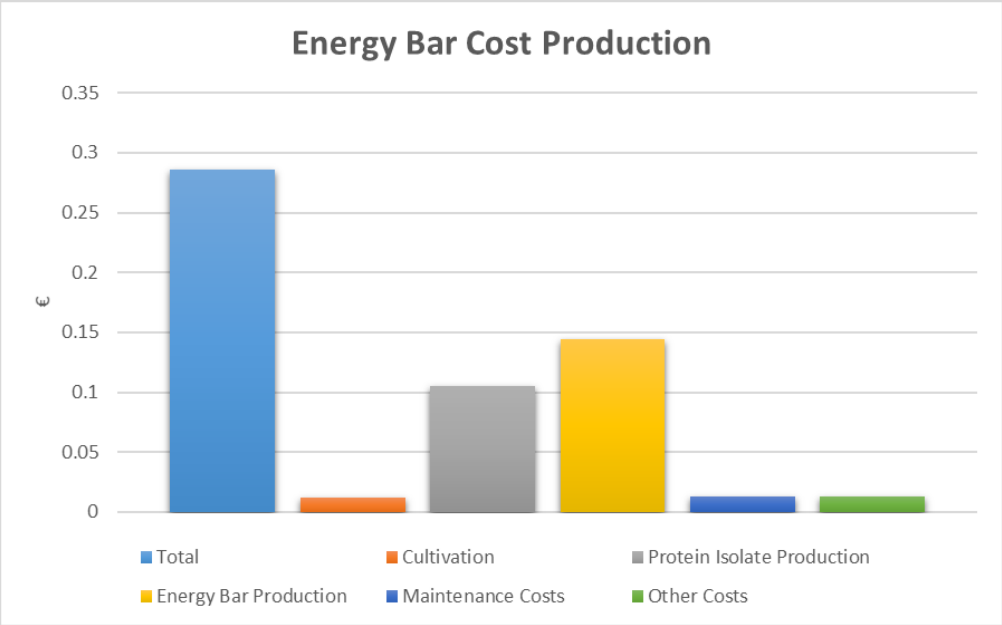



*Figure 27: Total cost and cost per production component for producing 330 mL of beverage*

The economic assessment of the protein-based energy bar, expressed per unit of product, demonstrates that a total production cost of €0.2862 is required, including all operating expenditures associated with cultivation, protein isolate production, energy bar manufacturing, maintenance, and other operational costs. Energy bar production represents the largest contributor to the total cost (€0.1439), accounting for approximately 50% of the overall production cost. This is primarily attributed to the cost of ingredients used in the recipe, together with labour, utilities, packaging materials, and energy requirements during mixing, baking, and packaging operations.

Protein isolate production is the second largest contributor (€0.1048), representing approximately 37% of the total production cost. The relatively high cost of this stage reflects the energy, labour, water, and material requirements associated with protein extraction, purification, and drying. In contrast, cultivation contributes only €0.0116 (approximately 4% of the total cost), indicating that

agricultural production represents a relatively small proportion of the overall manufacturing cost. Maintenance and other operational costs each contribute €0.0130, accounting for equipment maintenance, repairs, administration, and other indirect production expenses.

The cost distribution clearly demonstrates that the ingredients incorporated into the recipe are the principal economic drivers of energy bar production, with protein isolate representing the single most expensive ingredient due to its processing requirements. Consequently, the downstream manufacturing stages dominate the overall production cost, whereas primary agricultural production contributes only marginally.

Overall, despite the relatively high costs associated with protein isolate manufacture and ingredient formulation, the energy bar can be considered economically feasible, due to its overall limited cos of production and a considerable margin for profit. The findings suggest that future reductions in production costs could be achieved through improvements in protein isolation efficiency, optimisation of manufacturing operations, increased use of renewable energy, and procurement of lower-cost ingredients and sustainable packaging materials. Such measures would further enhance both the economic performance and sustainability of the product while maintaining its nutritional quality. Full details of the LCC analysis are presented in Supplementary Materials, Table 46.

### 3.5.5. s-LCA Results

The social impacts of the protein-based energy bar are distributed unevenly across the four stakeholder categories considered in the assessment. Local communities carry the largest share of the total social risk (34%), followed by society (29%), workers (22%) and value chain actors (15%). This distribution reflects the resource- and energy-intensive nature of the downstream processing stages, which weigh more heavily on local communities and broader societal conditions than on the immediate labour force or upstream business relationships.




*Figure 28: Total social risks of energy bar production per stakeholder [medium risk hours*

Local communities are the most affected stakeholder group as a result of the cumulative resource demand of the manufacturing chain, in particular the electricity consumed throughout processing and the sourcing of processed ingredients such as cocoa fibre and cocoa powder, both of which are linked to environmental pressures and supply-chain conditions in the regions where these inputs originate.

Society bears the second largest share of the impact, largely driven by reliance on grid electricity and by ingredients sourced through international supply chains, whose social performance depends on the governance, transparency and regulatory context of the countries of origin, a consideration that is particularly relevant for cocoa, which is frequently associated with elevated social risk in producing regions. Workers are affected mainly through occupational conditions during the more labour- and energy-intensive processing steps, while value chain actors, similarly to the beverage business case, are comparatively less exposed, reflecting the more structured and regulated nature of the European segments of the supply chain.

In order to interpret these results further, the contribution of each life cycle stage, namely faba beans cultivation, protein isolate production and energy bar production, to the social impacts on each stakeholder group was examined.

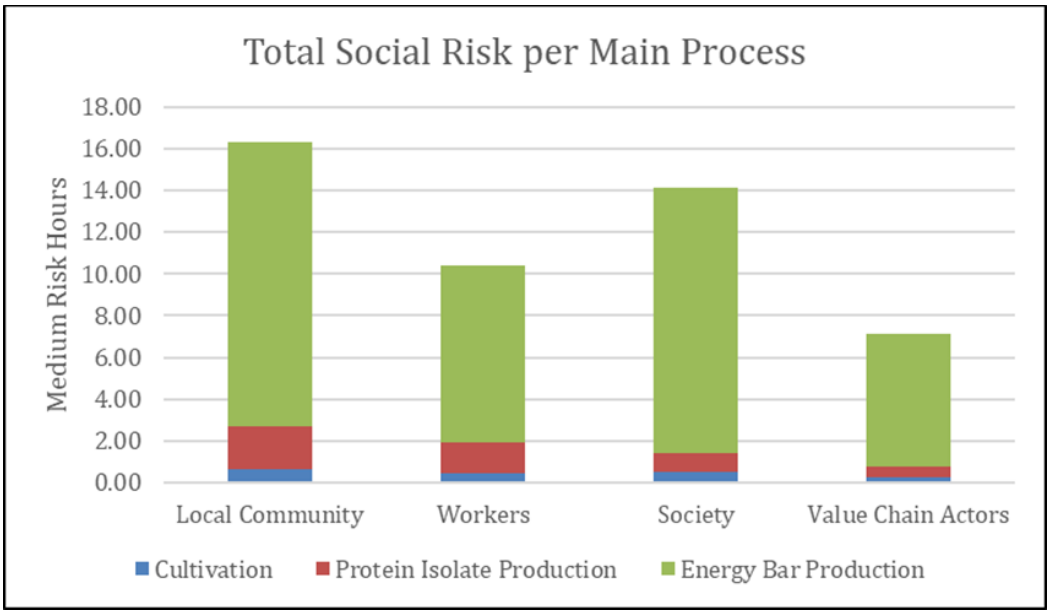



*Figure 29: Total social risks of energy bar production per stakeholder [med risk hours]*

Across all four stakeholder groups, the energy bar production stage is by far the dominant contributor to social risk, accounting for approximately 84% of the impact on local communities, 82% on workers, 90% on society and 89% on value chain actors. Protein isolate production is the second largest contributor, ranging from approximately 6% (society) to 14% (workers). As in the beverage business case, this stage's contribution is mainly associated with its energy-intensive nature, in particular the electricity used during decantation, precipitation and spray drying, which drives a comparatively higher exposure for workers relative to other stakeholder groups. Faba bean cultivation, in turn, contributes only marginally to the overall social footprint, remaining below 5% for every stakeholder group; consistent with the beverage business case, its limited impact is primarily linked to land use and resource availability at the local level, rather than to labour- or governance-related risks.

This concentration of impact within the energy bar production stage is primarily attributable to two factors. The first is the electricity demand of the formulation process itself: nearly every step involved in transforming the protein isolate into the finished bar, including blending, ingredient heating, mixing, pressing, refrigeration, cutting and packaging, draws on grid electricity, so that the cumulative energy input of this stage substantially exceeds that of cultivation and is comparable to, or higher than, that of protein isolate production. Because electricity generation and distribution carry their own upstream

social risk profile, this reliance on electricity throughout the recipe translates directly into elevated medium risk hours for all four stakeholder groups.

The second factor is the inclusion of cocoa-derived ingredients, namely cocoa fibre and cocoa powder, in the dry ingredient blend. Cocoa is a crop with a well-documented and comparatively high social risk profile internationally, associated with issues such as smallholder farmer poverty, child labour and limited access to social protections in several of the main producing regions. Although cocoa fibre and cocoa powder represent a small proportion of the total mass of the recipe, their inclusion introduces a disproportionately high social burden relative to their weight, which is reflected in the elevated risk hours attributed to the energy bar production stage, particularly for local communities and society.

Taken together, these findings indicate that the social performance of the energy bar is shaped less by the cultivation of the base crop and more by decisions made during formulation and processing, specifically the intensity of electricity use and the choice of auxiliary ingredients. This offers clear leverage points for improvement: increasing the share of renewable electricity used during processing, improving energy efficiency across the mixing, heating and packaging steps, and sourcing cocoa fibre and cocoa powder from certified, socially responsible supply chains would be expected to yield the most significant reductions in the overall social footprint of the product.

The social life cycle assessment of the protein-based energy bar indicates that the overall social impacts are concentrated almost entirely in the energy bar production stage, which accounts for the large majority of the medium risk hours across all stakeholder groups, while faba bean cultivation contributes only marginally. Among stakeholders, local communities and society experience the highest share of impacts, followed by workers, while value chain actors are comparatively less affected.

Within the energy bar production stage, the two main drivers of social risk are the electricity consumed across the successive processing steps and the use of cocoa fibre and cocoa powder as ingredients, the latter reflecting the elevated social risk generally associated with cocoa production internationally.

The concentration of impacts within a single stage and around a small number of specific inputs provides clear and actionable leverage points for improvement. Reducing electricity intensity through process optimisation and the use of renewable energy sources, together with sourcing cocoa ingredients from certified, socially responsible suppliers, can substantially reduce the social risk profile of the product without requiring changes to the underlying cultivation system.

Overall, the results demonstrate that, similarly to the plant-based beverage business case, the energy bar's social performance is driven predominantly by downstream processing choices rather than agricultural production, highlighting the importance of responsible sourcing and energy management as the primary pathways toward a more socially sustainable product.

## 3.6. Legume-based Pasta Production

### 3.6.1. Goal & Scope

The main goal of the legume-based pasta production business case was to evaluate the environmental, economic, and social sustainability of a novel pasta recipe that utilizes legumes as the main ingredients and compare its performance to conventional pasta products that have semolina flour as the main ingredient.

#### *3.6.1.1. Product System*

The product system consists of the cultivation of the legume ingredients and their subsequent processing to produce the corresponding flours, along with all the processes involved in the production and packaging of the pasta.

#### *3.6.1.2. Functional Unit, System Boundaries, Data Requirements, Assumptions and Limitations*

The selected functional unit was defined as 1 kg of protein content in the final product, reflecting the main objective of developing a legume-based pasta with higher protein content compared to conventional counterparts. A cradle-to-gate approach was adopted to assess the environmental, economic, and social performance of the legume-based pasta, covering legume cultivation, flour production, and subsequent pasta production up to the point at which the final product is ready to leave the factory for distribution.

Primary data on legume flour production were obtained through communication with project partner Molino Peila SPA, while data on pasta production were provided by project partner Antignano Prodotto Tipico. Data related to the cultivation of the different legumes were obtained from LCA for Experts and Ecoinvent. The consistent use of the same data sources and assumptions across the production chain ensured comparability and minimized potential variability in the results.

For the LCC analysis, capital expenditures were considered negligible, as flour and pasta production involve well-established processes within the food sector

### 3.6.2. Life Cycle Inventory (LCI)

The LCI data for the production of the legume-based pasta and the conventional pasta are in the Supplementary Materials; Tables 47 and 48.

### 3.6.3. LCA Results

A direct comparison of the results of the legume-based pasta and the conventional wheat pasta per kg of protein content in selected impact categories are depicted in the following Figures 30 and 31.

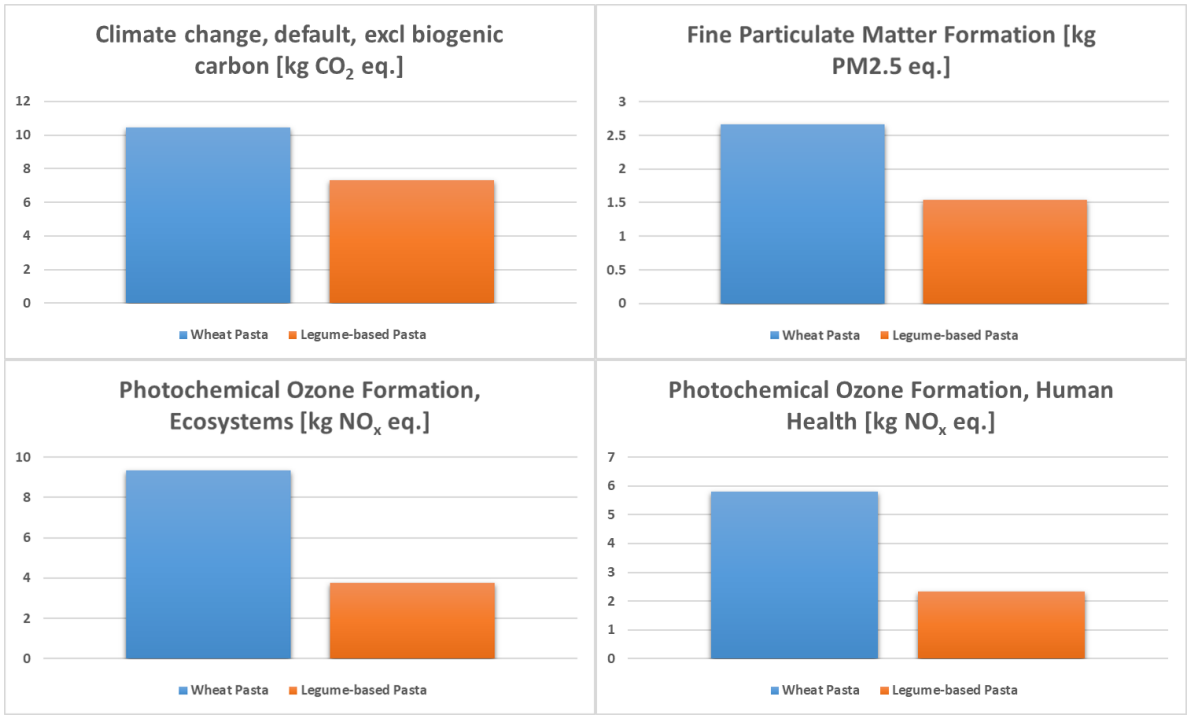



*Figure 30: LCA results of pasta production in selected midpoint indicators*

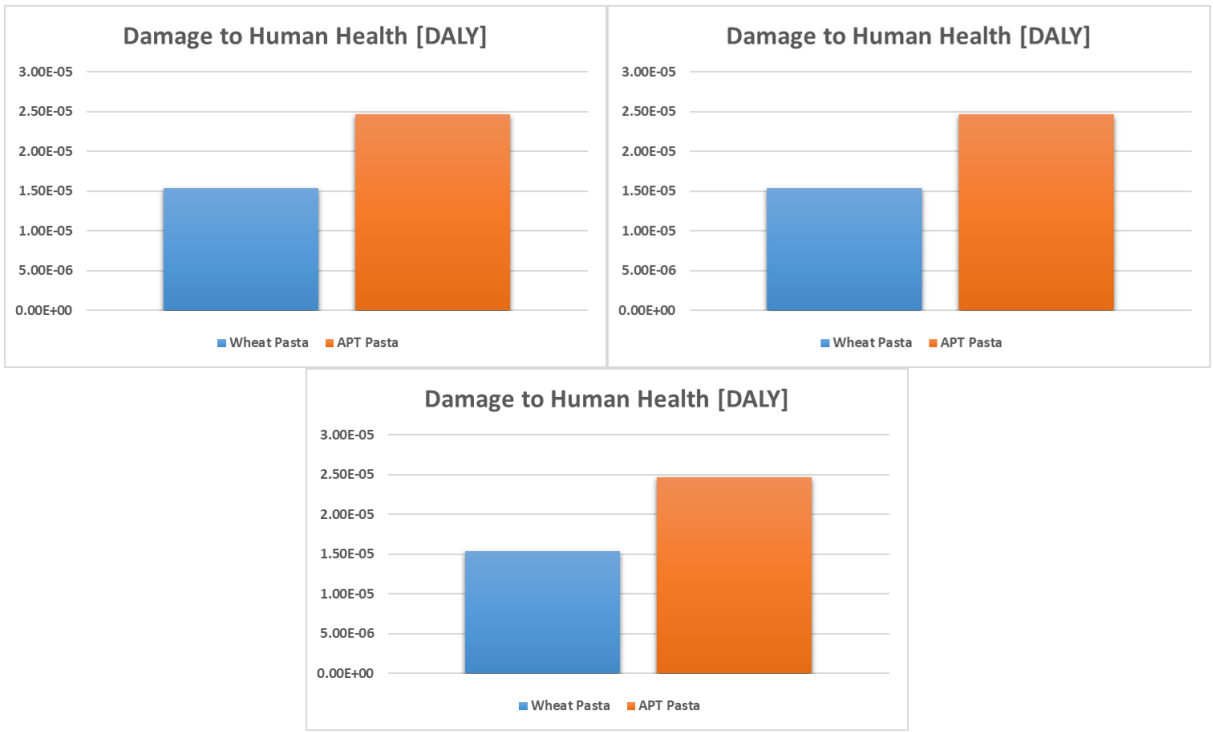



*Figure 31: ReCiPe endpoints of the pasta production*

The comparative life cycle assessment between the legume-based pasta and conventional pasta demonstrates that the legume-based product exhibits strong environmental performance across several key impact categories, highlighting its potential as a more sustainable alternative to traditional pasta products. Compared with conventional pasta, the legume-based pasta reduced greenhouse gas emissions (excluding biogenic carbon) from 10.5 to 7.3 kg $CO_2$ eq., representing approximately a 30% reduction in climate change impacts. It also achieved substantial improvements in fossil resource use,

with fossil depletion decreasing from 2.67 to 1.54 kg oil eq. (approximately 42%), while photochemical ozone formation was reduced by nearly 60% for both ecosystem and human health indicators. Additional environmental benefits were observed for marine eutrophication, marine ecotoxicity, terrestrial ecotoxicity, metal depletion, human toxicity (both cancer and non-cancer), and stratospheric ozone depletion. The ReCiPe endpoint assessment further confirmed these advantages, showing a reduction in damage to resource availability from 0.786 to 0.486 $, indicating more efficient use of finite resources throughout the product life cycle.

Although the legume-based pasta exhibited higher impacts in some categories, such as freshwater consumption, freshwater eutrophication, terrestrial acidification, and ecosystem damage, mainly liked with the agricultural production of the legume ingredients, particularly due to irrigation requirements and nutrient-related emissions from cultivation, its overall environmental profile demonstrates clear advantages in several of the most critical sustainability indicators associated with food production, particularly climate change mitigation and fossil resource conservation. In addition to its environmental benefits, legume-based pasta offers important nutritional advantages, including higher protein and dietary fibre content, making it an attractive option for consumers seeking healthier and more sustainable diets. Full results of the LCA can be found in Table 49 of the Supplementary Materials.

### 3.6.4. LCC Results

An overview of the costs associated for the production of the legume-based and conventional wheat pasta are presented in the Supplementary Materials (Tables 50 and 51).

Table 9 presents the total costs associated for the production of 1 kg of pasta products. Additionally, since the main objective of the business case was to produce a novel product with high protein content, the economic performance is also presented per kg of protein content in the final product.

| Cost (€) | Per kg of pasta | | Per kg of Protein Content | |
|---|---|---|---|---|
| | Legume-based Pasta | Wheat Pasta | Legume-based Pasta | Wheat Pasta |
| | 1.20 | 0.91 | 6.01 | 7.10 |

*Table 9: Total cost for producing the legume-based and wheat pasta per 1 kg of pasta and 1 kg of protein content*

The economic assessment indicates that the legume-based pasta has a higher production cost than conventional wheat pasta, with manufacturing costs of €1.20/kg and €0.91/kg, respectively. This corresponds to an increase of approximately 32% in the production cost per kilogram of product, primarily reflecting the higher cost of legume raw materials. However, when the cost is evaluated based on the nutritional value provided, the difference becomes considerably smaller. The cost per kilogram of protein was €6.01 for the legume-based pasta compared with €7.10 for conventional wheat pasta, representing an approximately 15% lower cost per unit of protein for the legume-based product. These findings demonstrate that although legume-based pasta is more expensive on a mass basis, it provides protein more cost-effectively than conventional pasta. Consequently, from a nutritional-economic perspective, the legume-based formulation offers improved value by delivering higher protein content at a lower cost per unit of protein, supporting its potential as a competitive and sustainable alternative in the growing market for functional and plant-based foods.

### 3.6.5. s-LCA Results

The social impacts associated with 1 kg of protein delivered by wheat pasta and legume-based pasta differ substantially across all four stakeholder categories considered in this assessment. Wheat pasta

generates approximately 4900 medium risk hours per kg of protein, compared with approximately 1350 medium risk hours for the legume-based pasta. This difference reflects two combined effects: the higher social risk intensity of wheat cultivation itself, and the larger raw material mass required by wheat pasta to deliver 1 kg of protein compared with the legume-based blend.

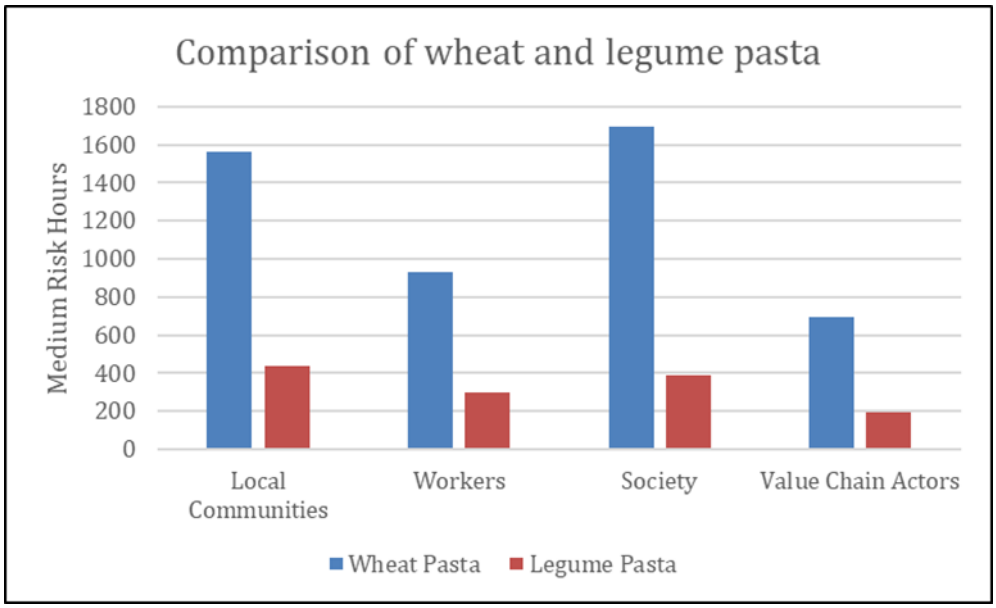



*Figure 32: Total risk hours for wheat and legume pasta per stakeholder*

The distribution of impacts among stakeholder groups follows a broadly similar pattern for both products, with society and local communities together accounting for roughly two-thirds of the total risk burden, followed by workers and, to a lesser extent, value chain actors. For wheat pasta, society represents approximately 35% of total risk hours and local communities approximately 32%, with workers at 19% and value chain actors at 14%. The legume-based pasta shows a comparable profile, with local communities at approximately 33%, society at 30%, workers at 22% and value chain actors at 15%. The similarity in relative distribution indicates that, although the legume-based product performs considerably better in absolute terms, the underlying drivers of social risk act on the same stakeholder groups in both systems.

To understand the origin of these impacts, the contribution of each life cycle stage to the total social risk was examined separately for the two products.

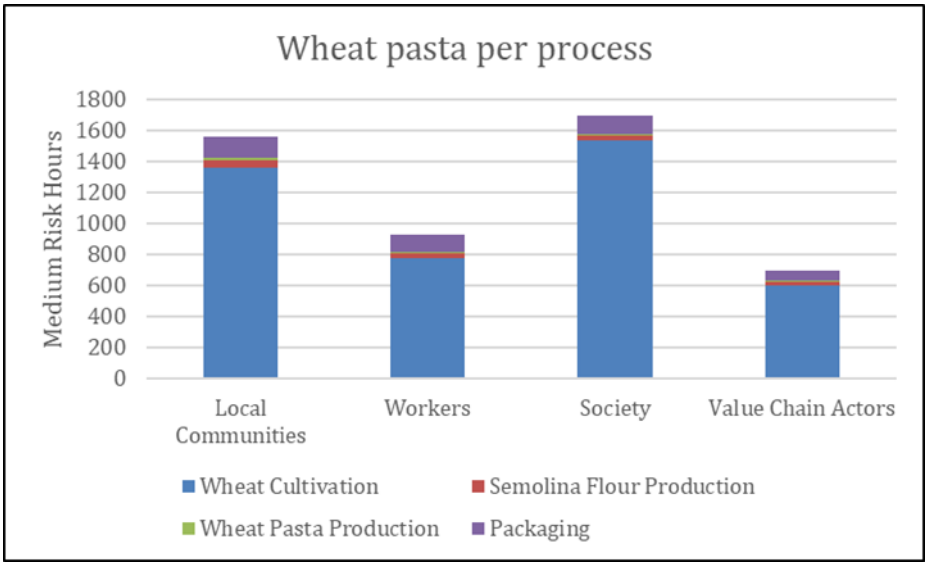



*Figure 33: Total risk hours for wheat pasta per process*

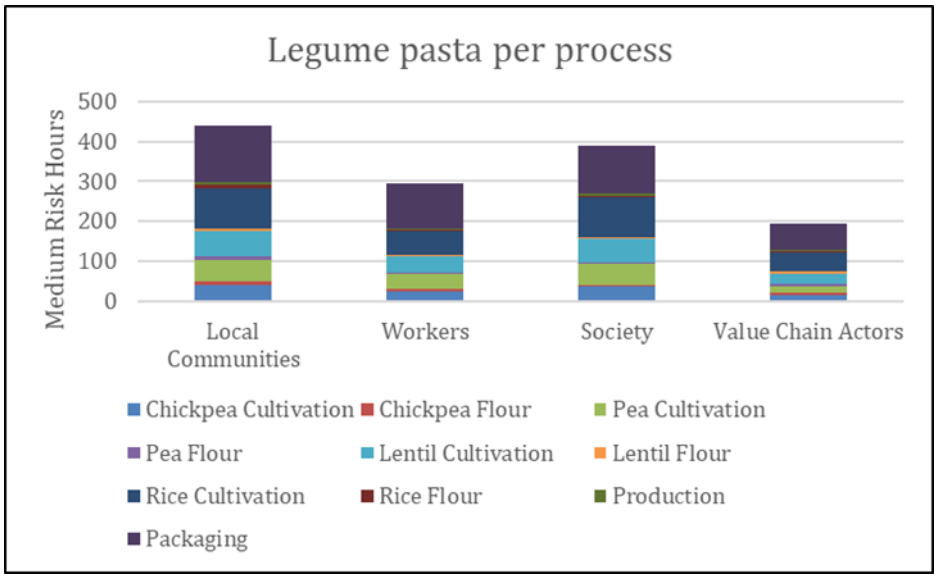



*Figure 34: Total risk hours for legume pasta per proces*

In wheat pasta production, the cultivation stage is overwhelmingly dominant, accounting for approximately 87% of the total social risk, with packaging contributing a further 9% and semolina flour and pasta production together responsible for less than 4%. This concentration means that the social performance of conventional pasta is, in practice, determined almost entirely by farming-related conditions rather than by downstream processing choices.

The legume-based pasta shows a more evenly distributed risk profile across its four raw material streams. Rice cultivation is the single largest contributor, accounting for approximately 27% of total social risk, reflecting comparatively higher risk hours across indicators such as sanitation coverage, health expenditure, illiteracy and trade unionism, in line with the social conditions typically associated with rice-producing regions. Lentil follows at approximately 18%, pea at approximately 16%, while chickpea consistently shows the lowest risk profile among the four legumes, at approximately 12%, performing best across nearly all social indicators considered. Packaging accounts for a comparatively high share of the legume-based pasta's footprint, approximately 26%, while the pasta production step itself contributes only around 2%.

The comparative social life cycle assessment indicates that, per kg of protein delivered, legume-based pasta is associated with substantially lower social risk than conventional wheat pasta, with a reduction on the order of 79% across the combined stakeholder categories. This advantage stems from the fact that legume-based pasta requires less raw material mass to deliver the same amount of protein, combined with the considerably lower aggregate social risk profile of the four legumes used in the blend, chickpea, pea, lentil and rice, relative to wheat cultivation, which alone accounts for the large majority of the social footprint of conventional pasta.

Within the legume blend itself, the choice of ingredient matters: chickpea consistently shows the lowest social risk of the four crops, while rice is the largest single contributor, reflecting the social conditions associated with its regions of cultivation. This suggests that further reductions in social risk could be achieved by adjusting the blend ratio in favour of chickpea, pea and lentil, or by sourcing rice from lower-risk producing regions. Packaging also represents a comparatively larger share of the legume-based pasta's social footprint than of the wheat pasta's, indicating that packaging material selection is a further lever for improvement.

Overall, the results support legume-based pasta as a socially preferable alternative to conventional wheat pasta on a protein-equivalent basis, while identifying cultivation-stage sourcing decisions, particularly for rice, and packaging material choices as the primary areas where further improvements could be pursued.

### 3.6.6. Results from Consumer Acceptance Questionnaire

This questionnaire was created in order to identify the consumer perception towards plant-based protein products in general and assess their perception also towards VALPRO Path's products. Moreover, it contributes to mapping the consumer behavioral change after being informed of the VALPRO Path's products. The participant sample group was 126.

In order to understand the answers of the participants it was crucial to know their dietary preferences. The majority of the sample are omnivores (81%), while a smaller percentage are vegetarians (13%) and vegans (2%).

The respondents to the questionnaire appear to consume plant-based protein products quite frequently, with half consuming them more than once a week. This frequency is not influenced by gender, age, or income, suggesting that these products are accessible to everyone. Only a small percentage (11%) are somewhat or not at all satisfied with the taste and texture. Younger individuals tend to dislike plant-based protein products due to taste and texture, while older individuals appear to hold a different opinion.

When comparing plant-based protein products with conventional ones, 39% of respondents felt the taste was the same, 29% preferred the plant-based options, while 32% considered their taste inferior. The sample is divided on the issue of price: half of the respondents reported no concern about the cost of plant-based protein products, while the other half expressed indifference. This division does not appear to be associated with gender, age, or income.

The questionnaire was administered to consumers along with an introduction to the VALPRO Project, highlighting its significant environmental and social impacts. This allowed the influence of that information on consumer behavior and perception regarding VALPRO Path products and the broader goal of the project to be examined.

Before the briefing, 32% of respondents expressed dissatisfaction with plant-based protein products compared to conventional options. This proportion decreased to just 14% afterward. Many

participants reported a positive shift in their opinions, with only 12% indicating a negative change. These results suggest substantial potential for increased consumption of plant-based protein products

### 3.6.7. LCSA of Legume-based Pasta Production Business Case

The results regarding the overall sustainability of the Legume-based Pasta Business Case per kg of product and per kg of protein are presented in the following Figures.

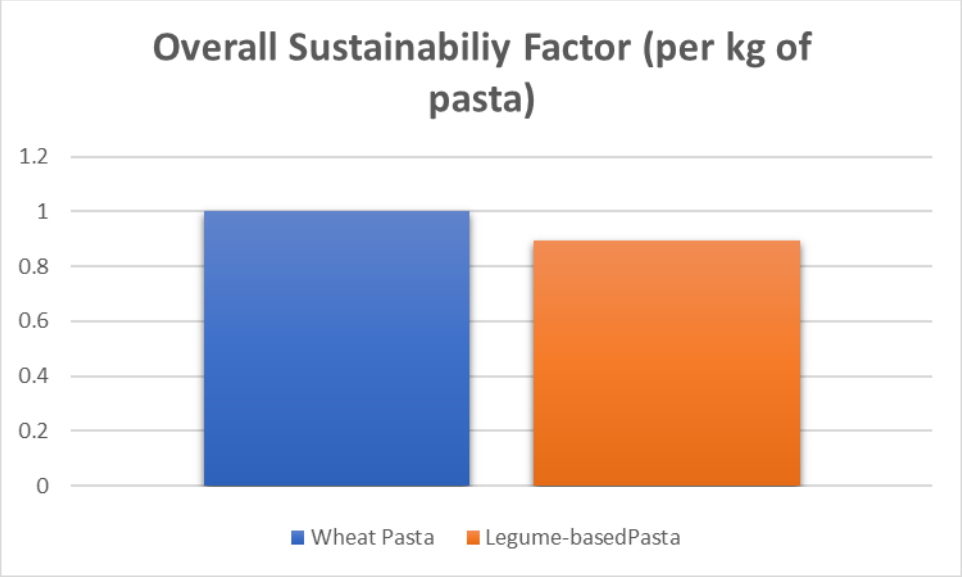



*Figure 35: Overall Sustainability of the Legume-based Pasta business case per kg of pasta*

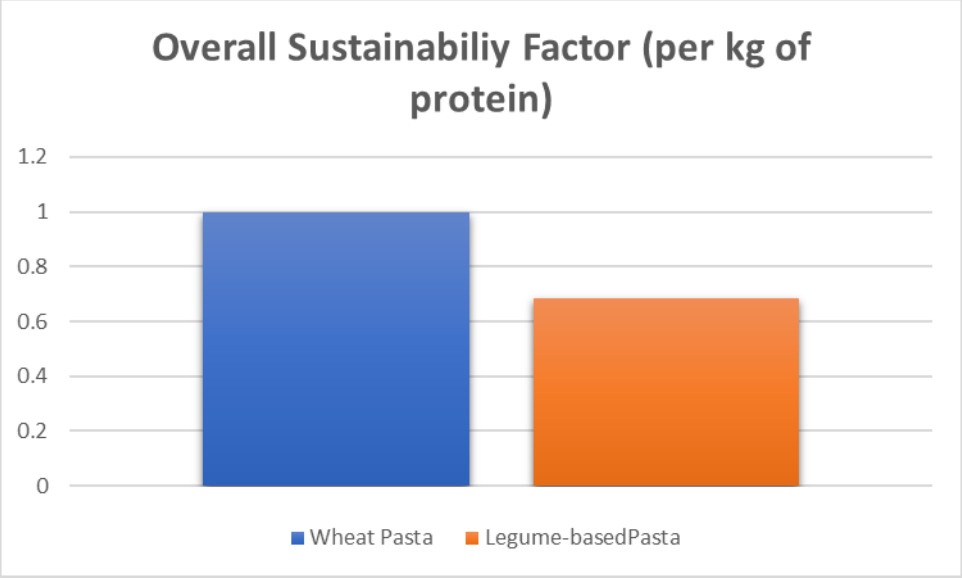



*Figure 36: Overall Sustainability of the Legume-based Pasta business case per kg of protein*

The OSF results demonstrate that the legume-based pasta outperforms the conventional wheat pasta under both functional units considered. On a per kilogram of pasta basis, the legume-based product achieves an OSF of approximately 0.90, corresponding to an overall sustainability improvement of around 10% compared with the conventional wheat pasta. This indicates that the legume-based formulation provides a more favourable balance between environmental performance, production costs, and social risks. The sustainability advantage becomes even more evident when the products are compared on a per kilogram of protein basis. Under this functional unit, the legume-based pasta

exhibits an OSF of approximately 0.68, representing an improvement of about 32% relative to conventional wheat pasta. This result highlights the importance of considering the nutritional function of the product, as the higher protein content of the legume-based pasta allows its sustainability benefits to be more accurately captured. Overall, these findings indicate that replacing conventional wheat pasta with legume-based pasta enhances overall sustainability regardless of the selected functional unit, while the protein-based comparison further emphasises the benefits associated with producing nutrient-dense foods. The results support the potential of legume-based pasta as a sustainable alternative capable of reducing environmental impacts, maintaining economic competitiveness, and lowering social risks while simultaneously increasing the nutritional value of the final product.

# 4. References

Bachmann, T. M., van der Kamp, J., Bianchi, M., Pihkola, H., & Saavedra del Oso, M. (2024). Life cycle costing as part of a life cycle sustainability assessment of products: methodology and case studies. *The International Journal of Life Cycle Assessment*, *29*(10), 1863–1879. https://doi.org/10.1007/s11367-024-02347-1

Collins, C., & Phelan, S. (2024). *CROPS COSTS AND RETURNS*.

Drosou, F., Kekes, T., Uribe-Alvarez, R., Murphy, E., Fenelon, M. A., Lynch, R., & Krokida, M. (2026). Sustainable and Cost-Effective: The Environmental and Economic Advantages of a Model Plant-Based Beverage. *Sustainable Food Technol.* https://doi.org/10.1039/D6FB00068A

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H.-J. (2006). The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment*, *11*(2), 80–85. https://doi.org/10.1065/lca2006.02.002

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, *22*(2), 138–147. https://doi.org/10.1007/s11367-016-1246-y

International Organization for Standardization [ISO]. (2006). *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*.

Kekes, T., Drosou, F., FitzGerald, P., FitzGerald, R., O'Brien, M., Fenelon, M., & Krokida, M. (2026). Life cycle assessment of European cultivated peanuts: evaluating sustainability across different peanut products. *The International Journal of Life Cycle Assessment*, *31*(9), 159. https://doi.org/10.1007/s11367-026-02728-8

Kekes, T., Drosou, F., Nair, N. R., Corredig, M., Boukouvalas, C., di Stefano, M. B., Ruggiero, V., & Krokida, M. (2025). Ecodesign of a Legume-Based Vegan Burger: A Holistic Case Study Focusing on Ingredient Sourcing and Packaging Material. *Sustainability*, *17*(12). https://doi.org/10.3390/su17125243

LIFE CYCLE INITIATIVE. (2020). *LIFE CYCLE INITIATIVE PROGRESS REPORT 2020*.

# 5. Supplementary Material

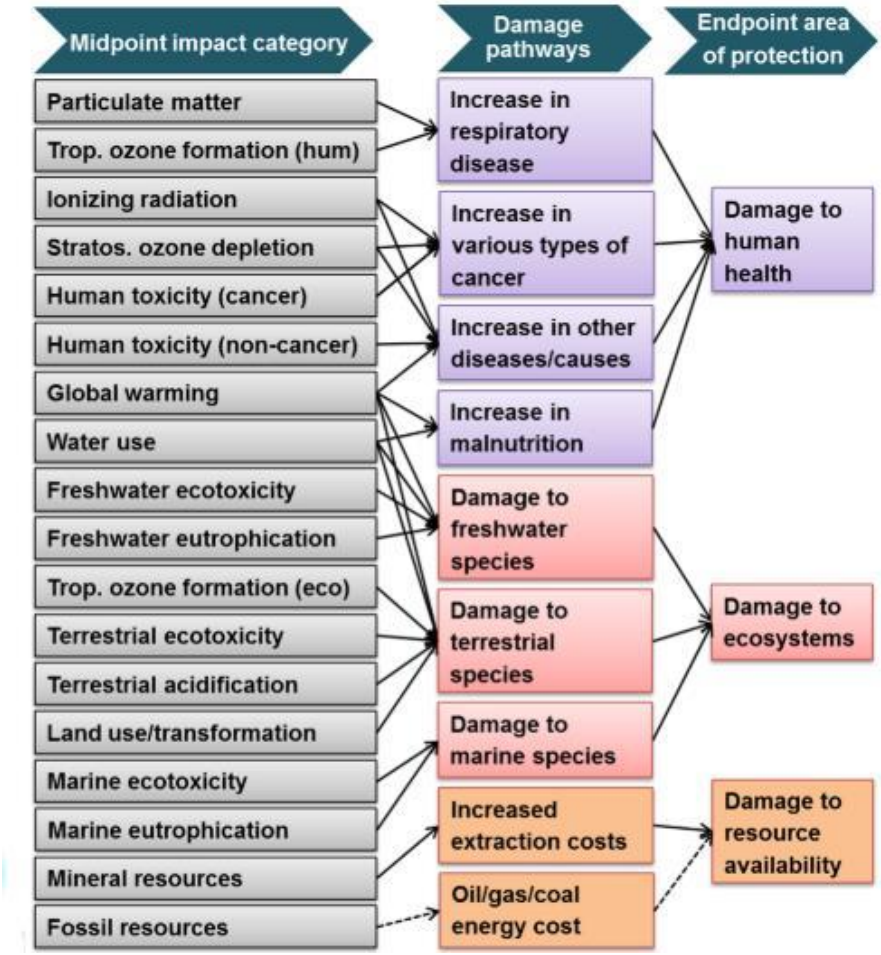



*Figure 37: ReCiPe 2016 – overview of impact caegories*

## 5.1. Vegan Burger Production

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Burger Production | Alcoholic vinegar | In | 0.012 | kg |
| | Lentil flour (cooked) | In | 0.0132 | kg |
| | Pea flour | In | 0.0317 | kg |
| | Pea protein (texturized) | In | 0.0132 | kg |
| | Salt | In | 0.00232 | kg |
| | Sunflower flour | In | 0.0132 | kg |
| | Sunflower oil | In | 0.00368 | kg |
| | Water | In | 0.104 | kg |
| | Electricity | In | 1.69 | MJ |
| | 2 pieces of vegan burger | Out | 2 | pieces |
| | Solid wastes | Out | 0.002 | kg |
| Burger packaging | 2 pieces of vegan burger | In | 2 | pieces |
| | Electricity | In | 0.072 | MJ |
| | Cardboad | In | 0.3 | kg |
| | PET | In | 0.023 | kg |
| | PE | In | 0.001 | kg |
| | 2 pieces of packaged vegan burger | Out | 2 | pieces |
| Products' end of life | Expired vegan burger | In | 0.00667 | kg |
| | Solid wastes (landfill) | Out | 0.00667 | kg |

*Table 10: Life Cycle Inventory of the base case scenario*

| Component | Distance (km) |
|---|---|
| Sunflower flour | 1009 |
| Pea protein (texturized) | 604 |
| Lentil flour (cooked) | 426 |
| Water | 0 |
| Salt | 0 |
| Pea flour | 678 |
| Sunflower oil | 631 |
| Alcoholic vinegar | 171 |
| 2 pieces of packaged vegan burger | 113 |
| Expired vegan burger | 113 |

*Table 11: Life Cycle Inventory of the base case scenario*

| | Impact Category | Value |
|---|---|---|
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 1.30E+00 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 1.46E+00 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 3.14E-04 |
| | Fossil depletion [kg oil eq.] | 2.37E-01 |
| | Freshwater Consumption [$m^3$] | -9.07E-05 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 3.80E-04 |
| | Freshwater Eutrophication [kg P eq.] | 4.86E-05 |

| | | |
|---|---|---|
| | Human toxicity, cancer [kg 1,4-DB eq.] | 1.49E-03 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 2.10E-01 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 4.70E-03 |
| | Land use [Annual crop eq.*y] | 7.77E-02 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 6.69E-04 |
| | Marine Eutrophication [kg N eq.] | 1.00E-04 |
| | Metal depletion [kg Cu eq.] | 3.72E-03 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 8.65E-01 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 5.37E-01 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 3.82E-07 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 9.74E-04 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 3.06E-01 |
| Endpoint | Damage to Human Health [DALY] | 3.30E-06 |
| | Damage to Ecosystems [species*yr] | 1.20E-07 |
| | Damage to Resources Availability [$] | 7.16E-02 |

*Table 12: LCA results of the base case scenario*

| | Impact Category | Base Case | Scenario 1 (300 km) | Scenario 2 (150 km) | Scenario 3 (10 km) |
|---|---|---|---|---|---|
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 1.30E+00 | 1.30E+00 | 1.30E+00 | 1.30E+00 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 1.46E+00 | 1.46E+00 | 1.46E+00 | 1.46E+00 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 3.14E-04 | 3.14E-04 | 3.14E-04 | 3.14E-04 |
| | Fossil depletion [kg oil eq.] | 2.37E-01 | 2.37E-01 | 2.37E-01 | 2.37E-01 |
| | Freshwater Consumption [$m^3$] | -9.07E-05 | -9.09E-05 | -9.09E-05 | -9.10E-05 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| | Freshwater Eutrophication [kg P eq.] | 4.86E-05 | 4.86E-05 | 4.86E-05 | 4.86E-05 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 1.49E-03 | 1.49E-03 | 1.49E-03 | 1.49E-03 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 2.10E-01 | 2.10E-01 | 2.10E-01 | 2.10E-01 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 4.70E-03 | 4.70E-03 | 4.70E-03 | 4.70E-03 |
| | Land use [Annual crop eq.*y] | 7.77E-02 | 7.77E-02 | 7.77E-02 | 7.77E-02 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 6.69E-04 | 6.69E-04 | 6.69E-04 | 6.69E-04 |
| | Marine Eutrophication [kg N eq.] | 1.00E-04 | 1.00E-04 | 1.00E-04 | 1.00E-04 |
| | Metal depletion [kg Cu eq.] | 3.72E-03 | 3.72E-03 | 3.72E-03 | 3.72E-03 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 8.65E-01 | 8.65E-01 | 8.65E-01 | 8.65E-01 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 5.37E-01 | 5.37E-01 | 5.37E-01 | 5.37E-01 |

| | | | | | |
|---|---|---|---|---|---|
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 3.82E-07 | 3.82E-07 | 3.82E-07 | 3.82E-07 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 9.74E-04 | 9.74E-04 | 9.74E-04 | 9.73E-04 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 3.06E-01 | 3.06E-01 | 3.06E-01 | 3.06E-01 |
| Endpoint | Damage to Human Health [DALY] | 3.30E-06 | 3.30E-06 | 3.30E-06 | 3.30E-06 |
| | Damage to Ecosystems [species*yr] | 1.20E-07 | 1.20E-07 | 1.20E-07 | 1.20E-07 |
| | Damage to Resources Availability [$] | 7.16E-02 | 7.16E-02 | 7.16E-02 | 7.16E-02 |

*Table 13: LCA results of the different studied scenarios regarding the transportation of lentils flour*

| | Impact Category | Base Case | Scenario 4 (400 km) | Scenario 5 (200 km) | Scenario 6 (10 km) |
|---|---|---|---|---|---|
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 1.30E+00 | 1.30E+00 | 1.30E+00 | 1.30E+00 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 1.46E+00 | 1.46E+00 | 1.46E+00 | 1.46E+00 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 3.14E-04 | 3.14E-04 | 3.14E-04 | 3.14E-04 |
| | Fossil depletion [kg oil eq.] | 2.37E-01 | 2.37E-01 | 2.37E-01 | 2.37E-01 |
| | Freshwater Consumption [$m^3$] | -9.07E-05 | -9.08E-05 | -9.10E-05 | -9.11E-05 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.79E-04 |
| | Freshwater Eutrophication [kg P eq.] | 4.86E-05 | 4.86E-05 | 4.86E-05 | 4.86E-05 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 1.49E-03 | 1.49E-03 | 1.49E-03 | 1.49E-03 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 2.10E-01 | 2.10E-01 | 2.10E-01 | 2.10E-01 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 4.70E-03 | 4.70E-03 | 4.70E-03 | 4.70E-03 |
| | Land use [Annual crop eq.*y] | 7.77E-02 | 7.77E-02 | 7.77E-02 | 7.77E-02 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 6.69E-04 | 6.69E-04 | 6.69E-04 | 6.69E-04 |
| | Marine Eutrophication [kg N eq.] | 1.00E-04 | 1.00E-04 | 1.00E-04 | 1.00E-04 |
| | Metal depletion [kg Cu eq.] | 3.72E-03 | 3.72E-03 | 3.72E-03 | 3.72E-03 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 8.65E-01 | 8.65E-01 | 8.65E-01 | 8.65E-01 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 5.37E-01 | 5.37E-01 | 5.37E-01 | 5.37E-01 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 3.82E-07 | 3.82E-07 | 3.82E-07 | 3.82E-07 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 9.74E-04 | 9.74E-04 | 9.73E-04 | 9.73E-04 |

| | | | | | |
|---|---|---|---|---|---|
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 3.06E-01 | 3.06E-01 | 3.06E-01 | 3.06E-01 |
| Endpoint | Damage to Human Health [DALY] | 3.30E-06 | 3.30E-06 | 3.30E-06 | 3.30E-06 |
| | Damage to Ecosystems [species*yr] | 1.20E-07 | 1.20E-07 | 1.20E-07 | 1.20E-07 |
| | Damage to Resources Availability [$] | 7.16E-02 | 7.16E-02 | 7.16E-02 | 7.16E-02 |

*Table 14: LCA results of the different studied scenarios regarding the transportation of pea protein*

| | Impact Category | Base Case | Scenario 7 (400 km) | Scenario 8 (200 km) | Scenario 9 (10 km) |
|---|---|---|---|---|---|
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 1.30E+00 | 1.28E+00 | 1.26E+00 | 1.25E+00 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 1.46E+00 | 1.44E+00 | 1.42E+00 | 1.41E+00 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 3.14E-04 | 2.94E-04 | 2.80E-04 | 2.67E-04 |
| | Fossil depletion [kg oil eq.] | 2.37E-01 | 2.30E-01 | 2.25E-01 | 2.21E-01 |
| | Freshwater Consumption [$m^3$] | -9.07E-05 | -1.19E-04 | -1.40E-04 | -1.59E-04 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 3.80E-04 | 3.75E-04 | 3.72E-04 | 3.69E-04 |
| | Freshwater Eutrophication [kg P eq.] | 4.86E-05 | 4.85E-05 | 4.84E-05 | 4.84E-05 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 1.49E-03 | 1.49E-03 | 1.48E-03 | 1.48E-03 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 2.10E-01 | 2.08E-01 | 2.07E-01 | 2.05E-01 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 4.70E-03 | 4.68E-03 | 4.67E-03 | 4.66E-03 |
| | Land use [Annual crop eq.*y] | 7.77E-02 | 7.61E-02 | 7.49E-02 | 7.39E-02 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 6.69E-04 | 6.57E-04 | 6.48E-04 | 6.40E-04 |
| | Marine Eutrophication [kg N eq.] | 1.00E-04 | 9.96E-05 | 9.92E-05 | 9.89E-05 |
| | Metal depletion [kg Cu eq.] | 3.72E-03 | 3.71E-03 | 3.70E-03 | 3.69E-03 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 8.65E-01 | 8.63E-01 | 8.62E-01 | 8.61E-01 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 5.37E-01 | 5.35E-01 | 5.35E-01 | 5.34E-01 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 3.82E-07 | 3.73E-07 | 3.67E-07 | 3.62E-07 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 9.74E-04 | 9.12E-04 | 8.67E-04 | 8.24E-04 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 3.06E-01 | 3.05E-01 | 3.05E-01 | 3.04E-01 |
| Endpoint | Damage to Human Health [DALY] | 3.30E-06 | 3.25E-06 | 3.21E-06 | 3.17E-06 |

| | | | | | |
|---|---|---|---|---|---|
| | Damage to Ecosystems [species*yr] | 1.20E-07 | 1.20E-07 | 1.19E-07 | 1.19E-07 |
| | Damage to Resources Availability [$] | 7.16E-02 | 6.86E-02 | 6.64E-02 | 6.42E-02 |

*Table 15: LCA results of the different studied scenarios regarding the transportation of pea flour*

| | Impact Category | Base Case | Scenario 10 (Bio-PE) | Scenario 11 (PLA) | Scenario 12 (PE) |
|---|---|---|---|---|---|
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 1.30E+00 | 5.13E-01 | 5.56E-01 | 5.43E-01 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 1.46E+00 | 5.64E-01 | 5.90E-01 | 6.16E-01 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 3.14E-04 | 2.03E-04 | 1.99E-04 | 1.45E-04 |
| | Fossil depletion [kg oil eq.] | 2.37E-01 | 1.54E-01 | 1.59E-01 | 1.65E-01 |
| | Freshwater Consumption [$m^3$] | -9.07E-05 | 7.30E-03 | 5.48E-03 | 4.98E-03 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 3.80E-04 | 3.01E-04 | 2.85E-04 | 2.92E-04 |
| | Freshwater Eutrophication [kg P eq.] | 4.86E-05 | 3.98E-05 | 3.70E-05 | 3.66E-05 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 1.49E-03 | 1.13E-03 | 1.13E-03 | 1.14E-03 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 2.10E-01 | 1.96E-01 | 1.94E-01 | 1.97E-01 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 4.70E-03 | 3.91E-03 | 3.87E-03 | 3.50E-03 |
| | Land use [Annual crop eq.*y] | 7.77E-02 | 1.05E-01 | 6.69E-02 | 6.73E-02 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 6.69E-04 | 4.79E-04 | 4.63E-04 | 4.83E-04 |
| | Marine Eutrophication [kg N eq.] | 1.00E-04 | 9.37E-05 | 7.99E-05 | 7.70E-05 |
| | Metal depletion [kg Cu eq.] | 3.72E-03 | 1.42E-03 | 6.99E-04 | 6.60E-04 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 8.65E-01 | 6.89E-01 | 7.41E-01 | 7.25E-01 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 5.37E-01 | 4.28E-01 | 4.60E-01 | 4.50E-01 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 3.82E-07 | 3.92E-07 | 4.03E-07 | 3.15E-07 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 9.74E-04 | 6.34E-04 | 6.14E-04 | 4.41E-04 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 3.06E-01 | 1.22E-01 | 1.20E-01 | 1.18E-01 |
| Endpoint | Damage to Human Health [DALY] | 3.30E-06 | 1.57E-06 | 1.66E-06 | 1.63E-06 |
| | Damage to Ecosystems [species*yr] | 1.20E-07 | 9.30E-08 | 9.96E-08 | 9.75E-08 |
| | Damage to Resources Availability [$] | 7.16E-02 | 4.24E-02 | 4.34E-02 | 4.99E-02 |

*Table 16: LCA results of the different studied scenarios regarding the utilization of alternative packaging materials*

| | Impact Category | Base Case | Optimim Scenario (Distance of pea flour: 10 km nd Packaging material: Bio-PE) |
|---|---|---|---|
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 1.30E+00 | 5.13E-01 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 1.46E+00 | 5.64E-01 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 3.14E-04 | 2.03E-04 |
| | Fossil depletion [kg oil eq.] | 2.37E-01 | 1.54E-01 |
| | Freshwater Consumption [$m^3$] | -9.07E-05 | 7.30E-03 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 3.80E-04 | 3.01E-04 |
| | Freshwater Eutrophication [kg P eq.] | 4.86E-05 | 3.98E-05 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 1.49E-03 | 1.13E-03 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 2.10E-01 | 1.96E-01 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 4.70E-03 | 3.91E-03 |
| | Land use [Annual crop eq.*y] | 7.77E-02 | 1.05E-01 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 6.69E-04 | 4.79E-04 |
| | Marine Eutrophication [kg N eq.] | 1.00E-04 | 9.37E-05 |
| | Metal depletion [kg Cu eq.] | 3.72E-03 | 1.42E-03 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 8.65E-01 | 6.89E-01 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 5.37E-01 | 4.28E-01 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 3.82E-07 | 3.92E-07 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 9.74E-04 | 6.33E-04 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 3.06E-01 | 1.22E-01 |
| Endpoint | Damage to Human Health [DALY] | 3.30E-06 | 1.57E-06 |
| | Damage to Ecosystems [species*yr] | 1.20E-07 | 9.30E-08 |
| | Damage to Resources Availability [$] | 7.16E-02 | 4.23E-02 |

*Table 17: LCA results of the optimum scenario*




*Figure 38: Comparison of base case and optimum scenario in midpoint categories*

| Component | | Quantity | Unit | €/Unit | €/Packaged Product |
|---|---|---|---|---|---|
| Ingredients | Sunflower flour | 0.026 | kg | 3.2 | 0.084 |
| | Pea protein (texturized) | 0.026 | kg | 4.25 | 0.056 |
| | Lentil flour (cooked) | 0.026 | kg | 3.6 | 0.048 |
| | Water | 0.208 | kg | 0.002 | 0.0003 |
| | Salt | 0.004 | kg | 1.8 | 0.008 |
| | Pea flour | 0.064 | kg | 2.15 | 0.136 |
| | Sunflower oil | 0.008 | kg | 1.4 | 0.01 |
| | Alcoholic vinegar | 0.024 | kg | 14.56 | 0.349 |
| Transportation | Sunflower flour | 1009 | km | 0.01 | 0.135 |
| | Pea protein (texturized) | 604 | km | 0.01 | 0.08 |
| | Lentil flour (cooked) | 426 | km | 0.01 | 0.057 |
| | Water | 0 | km | 0.01 | 0 |
| | Salt | 0 | km | 0.01 | 0 |
| | Pea flour | 678 | km | 0.01 | 0.09 |
| | Sunflower oil | 631 | km | 0.01 | 0.084 |
| | Alcoholic vinegar | 171 | km | 0.01 | 0.023 |
| Burger production | Electricity | 1.69 | MJ | 0.04 | 0.068 |
| | Tap water | 0.02 | kg | 0.0016 | 0.000032 |
| | Wastewater | 0.02 | kg | 0.002 | 0.0004 |
| | Solid wastes (landfill) | 0.002 | kg | 0.075 | 0.00015 |
| Burger packaging | Electricity | 0.072 | MJ | 0.04 | 0.00288 |
| | Cardboard | 0.3 | kg | 0.163 | 0.04875 |
| | PET | 0.023 | kg | 0.428 | 0.009619 |
| | PE | 0.001 | kg | 0.3 | 0.000189 |
| Labor costs | Working hours | 0.0667 | hr | 15 | 1 |
| Distribution to retail centers | 2 pieces of vegan burger | 113 | km | 0.01 | 0.015 |
| Return of expired products | Expired vegan burgers | 113 | km | 0.01 | 0.015 |
| End-of-life costs | Solid wastes (landfill) | 0.00667 | kg | 0.075 | 0.0005 |

*Table 18: LCC data for the production of the vegan burger*

| Componenet (€/package) | Studied Scenarios | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Lenils flour distance | | | Pea protein distance | | | Pea flour distance | | | Packagine material | | | Optimum |
| | Base Case | 1 (300 km) | 2 (150 km) | 3 (1o km) | 4 (400 km) | 5 (200 km) | 6 (10 km) | 7 (400 km) | 8 (200 km) | 9 (10 km) | 10 (Bio-PE) | 11 (PLA) | 12 (PE) | Scenarios 9 + 10 |
| Ingredients | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 | 0.691 |
| Transportation of ingredients | 0.469 | 0.452 | 0.432 | 0.414 | 0.442 | 0.415 | 0.390 | 0.432 | 0.405 | 0.380 | 0.469 | 0.469 | 0.469 | 0.380 |
| Burger production | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 |
| Burger packaging | 0.058 | 0.058 | 0.058 | 0.058 | 0.058 | 0.058 | 0.058 | 0.058 | 0.058 | 0.061 | 0.085 | 0.097 | 0.056 | 0.085 |
| Retail distribution | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 |
| Return of expired products | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 |
| End of life costs | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| Labor Costs | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Maintenance costs | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 | 0.116 |
| Total | 2.434 | 2.417 | 2.397 | 2.379 | 2.407 | 2.380 | 2.356 | 2.397 | 2.370 | 2.345 | 2.461 | 2.473 | 2.432 | 2.372 |
| Didderence (%) | - | -0.70 | -1.52 | -2.26 | -1.11 | -2.22 | -3.20 | -1.52 | -2.63 | -3.66 | +1.11 | +1.60 | -0.08 | -2.55 |

*Table 19: Cost breakdown across all differet studied scenaios*

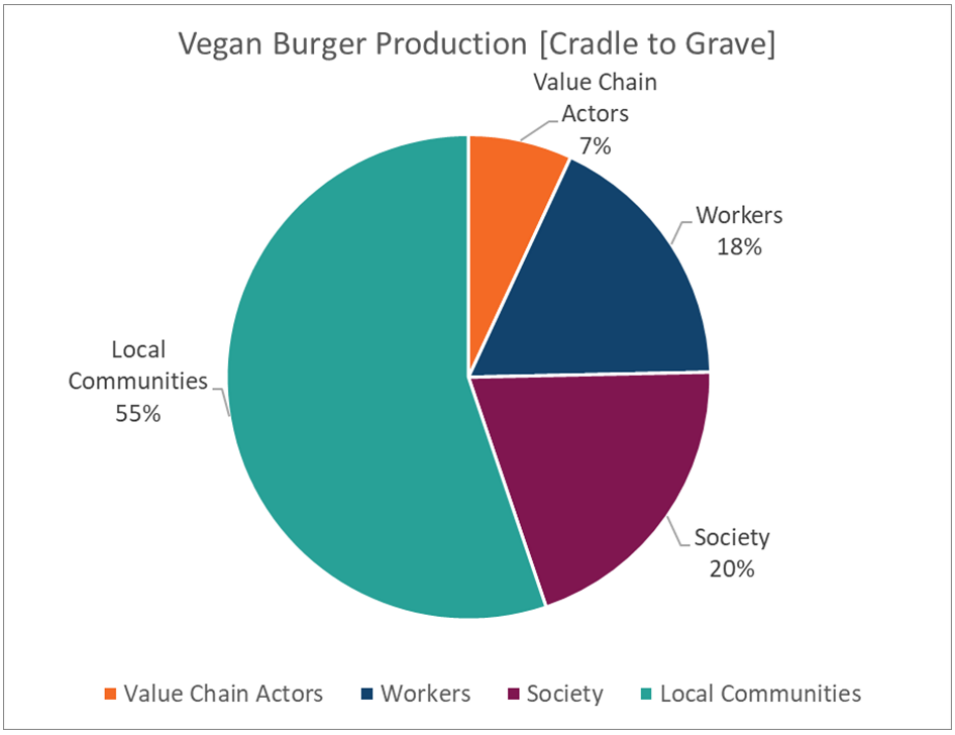



*Figure 39: Vegan Burger Production Base Case – Social Risks by Stakeholder Category*

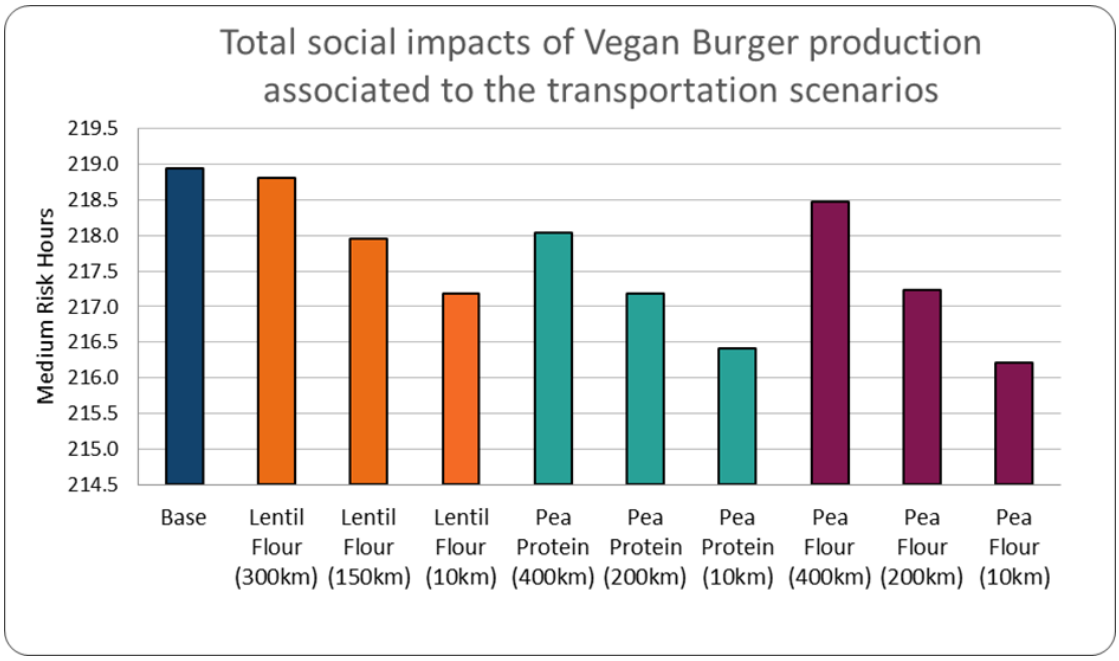



*Figure 40: Total Social Impacts of Vegan Burger Production Associated to the Transportation Scenarios*




*Figure 41: Social Risks by Stakeholder Category Across Packaging Scenarios*

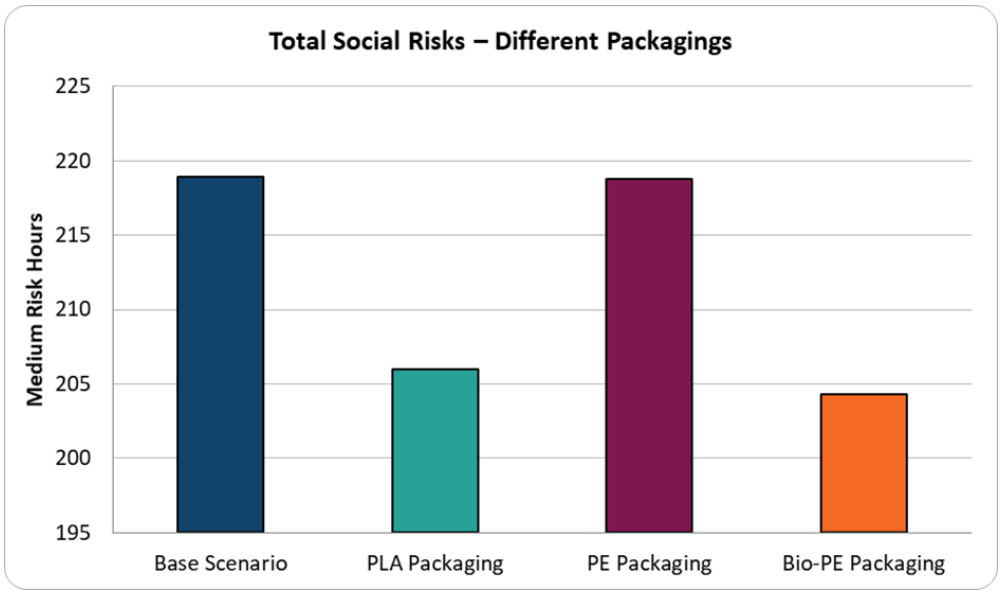



*Figure 42: Total Social Risks Across Packaging Scenarios*

## 5.2. European Cultivated Peanuts Exploitation

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Cultivation | Area Cultivated | In | ha | 0.17 |
| | Diesel | In | L | 1.31 |
| | Electricity | In | kWh | 3.67 |
| | N Fertilizer | In | kg | 11.9 |
| | P Fertilizer | In | kg | 5.95 |
| | K Fertilizer | In | kg | 14.45 |
| | Water | In | m3 | 2.35 |
| | Peanuts | Out | kg | 204 |
| Deshelling | Peanuts | In | kg | 204 |
| | Electricity | In | kWh | 2 |
| | Deshelled Peanuts | Out | kg | 173.4 |
| | Shells | Out | kg | 30.6 |

*Table 20: Life Cycle Inventory of peanuts cultivation and deshelling*

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Soaking | Deshelled Peanuts | In | kg | 173.4 |
| | $NaHCO_3$ (0.5%) | In | L | 427.5 |
| | Electricity | In | kWh | 6 |
| | Soaked Peanuts | Out | kg | 600.9 |
| Drain | Soaked Peanuts | In | kg | 600.9 |
| | Electricity | In | kWh | 1.5 |
| | Peanuts | Out | kg | 242.76 |
| | Wastewater | Out | kg | 358.14 |
| Cooking | Peanuts | In | kg | 242.76 |
| | Water | In | kg | 485.52 |
| | Electricity | In | kWh | 75 |
| | Peanuts | Out | kg | 242.76 |
| | Wastewater | Out | kg | 485.52 |
| Grinding | Peanuts | In | kg | 242.76 |
| | Electricity | In | kWh | 37.5 |
| | Water | In | kg | 1213.8 |
| | Peanuts | Out | kg | 1456.56 |
| Filtration | Peanuts | In | kg | 1456.56 |
| | Electricity | In | kWh | 4.5 |
| | Peanuts | Out | kg | 1452 |
| | Solid Wastes | Out | kg | 4.56 |
| Homogenization | Peanuts | In | kg | 1452 |
| | Electricity | In | kWh | 15 |
| | Peanut Milk | Out | kg | 1452 |
| Pasteurization | Peanut Milk | In | kg | 1452 |
| | Water | In | m3 | 5.79 |
| | Natural Gas | In | $Nm^3$ | 23.1 |
| | Peanut Milk | Out | kg | 1452 |
| Packaging | Peanut Milk | In | kg | 1452 |
| | Electricity | In | kWh | 87 |
| | Bottles | In | kg | 36.3 |
| | Peanut Milk | Out | kg | 1452 |

*Table 21: Life Cycle Inventory of peanut milk production*

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Soaking | Deshelled Peanuts | In | kg | 173.4 |
| | Brine (5%) | In | L | 520.2 |
| | Electricity | In | kWh | 6 |
| | Soaked Peanuts | Out | kg | 693.6 |
| Drain | Soaked Peanuts | In | kg | 693.6 |
| | Electricity | In | kWh | 1.5 |
| | Peanuts | Out | kg | 280.2 |
| | Wastewater | Out | kg | 413.4 |
| Drying | Peanuts | In | kg | 280.2 |
| | Thermal Energy | In | kWh | 336.3 |
| | Peanuts | Out | kg | 159.6 |
| Roasting | Peanuts | In | kg | 159.6 |
| | Thermal Energy | In | kWh | 359.1 |
| | Peanuts | Out | kg | 154.8 |
| | Solid Wastes | Out | kg | 4.8 |
| Dehusking | Peanuts | In | kg | 154.8 |
| | Electricity | In | kWh | 25.5 |
| | Peanuts | Out | kg | 143.1 |
| | Solid Wastes | Out | kg | 11.7 |
| Milling | Peanuts | In | kg | 143.1 |
| | Electricity | In | kWh | 57.6 |
| | Peanut Butter | Out | kg | 143.1 |
| Packaging | Peanut Butter | In | kg | 143.1 |
| | Electricity | In | kWh | 11.7 |
| | Glass Jars | In | kg | 7.5 |
| | Peanut Butter | Out | kg | 143.1 |

*Table 22: Life Cycle Inventory of peanut butter production*

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Grinding | Deshelled Peanuts | In | kg | 173.4 |
| | Electricity | In | kWh | 69.3 |
| | Soaked Peanuts | Out | kg | 173.4 |
| Roasting | Peanuts | In | kg | 173.4 |
| | Electricity | In | kWh | 360 |
| | Peanuts | Out | kg | 166.5 |
| | Solid Wastes | Out | kg | 6.9 |
| Mechanical Processing | Peanuts | In | kg | 166.5 |
| | Electricity | In | kWh | 99 |
| | Peanut Oil | Out | kg | 71.7 |
| | Peanut Cake | Out | kg | 94.8 |
| Filtration | Peanut Oil | In | kg | 71.7 |
| | Electricity | In | kWh | 6 |
| | Peanut Oil | Out | kg | 70.5 |
| | Solid Wastes | Out | kg | 1.2 |
| Refining | Peanut Oil | In | kg | 71.7 |
| | Sodium Hydroxide | In | kg | 1.41 |
| | Phosphoric Acid | In | kg | 0.072 |

| | | | | |
|---|---|---|---|---|
| | Bleaching Earth | In | kg | 1.41 |
| | Citric Acid | In | kg | 0.036 |
| | Water | In | kg | 5.64 |
| | Electricity | In | kWh | 27 |
| | Refined Peanut Oil | Out | kg | 75 |
| | Waste Oil | Out | kg | 3.96 |
| Packaging | Peanut Oil | In | kg | 75 |
| | Electricity | In | kWh | 6 |
| | Plastic Bottles | In | kg | 2.1 |
| | Peanut Oil | Out | kg | 75 |

*Table 23: Life Cycle Inventory of peanut oil production*

| | Impact Category | Peanut Product | | |
|---|---|---|---|---|
| | | Milk | Butter | Oil |
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 1.83E-01 | 2.20E+00 | 4.36E+00 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 1.60E-01 | 2.24E+00 | 4.52E+00 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 1.38E-04 | 1.16E-03 | 1.95E-03 |
| | Fossil depletion [kg oil eq.] | 7.01E-02 | 7.07E-01 | 1.06E+00 |
| | Freshwater Consumption [m3] | 7.35E-03 | 9.88E-03 | 3.34E-02 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 7.78E-05 | 6.31E-04 | 1.18E-03 |
| | Freshwater Eutrophication [kg P eq.] | 1.97E-06 | 6.63E-06 | 1.06E-05 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 9.40E-05 | 8.82E-04 | 1.10E-03 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 9.69E-03 | 5.02E-02 | 6.65E-02 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 1.37E-03 | 1.62E-03 | 3.21E-03 |
| | Land use [Annual crop eq.*y] | 8.37E-01 | 8.35E+00 | 1.60E+01 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 1.33E-04 | 8.90E-04 | 1.73E-03 |
| | Marine Eutrophication [kg N eq.] | 5.55E-06 | 1.89E-05 | 4.64E-05 |
| | Metal depletion [kg Cu eq.] | 5.51E-03 | 5.68E-02 | 1.11E-01 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 2.15E-01 | 1.24E+00 | 2.98E+00 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 1.34E-01 | 7.69E-01 | 1.85E+00 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 3.19E-07 | 3.27E-06 | 6.14E-06 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 4.57E-04 | 3.70E-03 | 6.50E-03 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 5.76E-02 | 9.02E-02 | 2.95E-01 |
| Endpoint | Damage to Human Health [DALY] | 3.30E-06 | 5.56E-06 | 1.12E-05 |
| | Damage to Ecosystems [species*yr] | 1.20E-07 | 2.47E-07 | 5.52E-07 |
| | Damage to Resources Availability [$] | 7.16E-02 | 2.02E-01 | 3.20E-01 |

*Table 24: LCA results of the different peanut products*

| Component | | Quantity | Unit | €/Unit | Total Cost (€) |
|---|---|---|---|---|---|
| Cultivation | N Fertilizer | 11.9 | kg | 0.50 | 5.95 |
| | P Fertilizer | 5.95 | kg | 3.65 | 21.7175 |
| | K Fertilizer | 14.45 | kg | 0.58 | 8.381 |
| | Diesel | 1.31 | L | 1.55 | 2.0305 |
| | Electricity | 3.67 | kWh | 0.24 | 0.8808 |

| | | | | | |
|---|---|---|---|---|---|
| Deshelling | Water | 2.35 | m3 | 1.7 | 3.995 |
| | Labor / Wokring hours | 0.84 | hr | 7 | 5.88 |
| | Peanuts | 204 | kg | - | - |
| | Peanuts | 204 | kg | - | - |
| | Electricity | 2 | kWh | 0.24 | 0.48 |
| | Deshelled Peanuts | 173.4 | kg | - | - |
| | Shells | 30.6 | kg | - | - |
| | Labor / Wokring hours | 0.5 | hr | 7 | 3.5 |

*Table 25: LCC data for the cultivation and deshelling of peanuts*

| Process | Flow | Unit | Value | €/Unit | Total Costs (€) |
|---|---|---|---|---|---|
| Soaking | Deshelled Peanuts | kg | 173.4 | - | - |
| | $NaHCO_3$ (0.5%) | L | 427.5 | 0.02 | 8.55 |
| | Electricity | kWh | 6 | 0.24 | 1.44 |
| | Soaked Peanuts | kg | 600.9 | - | - |
| Drain | Soaked Peanuts | kg | 600.9 | - | - |
| | Electricity | kWh | 1.5 | 0.24 | 0.36 |
| | Peanuts | kg | 242.76 | - | - |
| | Wastewater | kg | 358.14 | 0.0015 | 0.537 |
| Cooking | Peanuts | kg | 242.76 | - | - |
| | Water | kg | 485.52 | 0.001 | 0.486 |
| | Electricity | kWh | 75 | 0.24 | 18 |
| | Peanuts | kg | 242.76 | - | - |
| | Wastewater | kg | 485.52 | 0.0015 | 0.728 |
| Grinding | Peanuts | kg | 242.76 | - | - |
| | Electricity | kWh | 37.5 | 0.24 | 9 |
| | Water | kg | 1213.8 | 0.001 | 1.214 |
| | Peanuts | kg | 1456.56 | - | - |
| Filtration | Peanuts | kg | 1456.56 | - | - |
| | Electricity | kWh | 4.5 | 0.24 | 1.08 |
| | Peanuts | kg | 1452 | - | - |
| | Solid Wastes | kg | 4.56 | 0.1 | 0.456 |
| Homogenization | Peanuts | kg | 1452 | - | - |
| | Electricity | kWh | 15 | 0.24 | 3.6 |
| | Peanut Milk | kg | 1452 | - | - |
| Pasteurization | Peanut Milk | kg | 1452 | - | - |
| | Water | $m^3$ | 5.79 | 5.79 | 5.79 |
| | Natural Gas | $Nm^3$ | 23.1 | 1.35 | 31.185 |
| Packaging | Peanut Milk | kg | 1452 | - | - |
| | Peanut Milk | kg | 1452 | - | - |
| | Electricity | kWh | 87 | 24 | 20.88 |
| | Bottles | kg | 36.3 | 1.24 | 45.012 |
| | Peanut Milk | kg | 1452 | - | - |

*Table 26: LCC data for the production of peanut milk*

| Process | Flow | Unit | Value | €/Unit | Total Costs (€) |
|---|---|---|---|---|---|
| Soaking | Deshelled Peanuts | kg | 173.4 | - | - |
| | Brine (5%) | L | 520.2 | 0.15 | 78.03 |
| | Electricity | kWh | 6 | 0.24 | 1.44 |
| | Soaked Peanuts | kg | 693.6 | - | - |
| Drain | Soaked Peanuts | kg | 693.6 | - | - |
| | Electricity | kWh | 1.5 | 0.24 | 0.36 |
| | Peanuts | kg | 280.2 | - | - |
| | Wastewater | kg | 413.4 | 0.0015 | 0.62 |
| Drying | Peanuts | kg | 280.2 | - | - |
| | Thermal Energy | kWh | 336.3 | 0.09 | 30.267 |
| | Peanuts | kg | 159.6 | - | - |
| Roasting | Peanuts | kg | 159.6 | - | - |
| | Thermal Energy | kWh | 359.1 | 0.09 | 32.319 |
| | Peanuts | kg | 154.8 | - | - |
| | Solid Wastes | kg | 4.8 | 0.1 | 0.48 |
| Dehusking | Peanuts | kg | 154.8 | - | - |
| | Electricity | kWh | 25.5 | 0.24 | 6.12 |
| | Peanuts | kg | 143.1 | - | - |
| | Solid Wastes | kg | 11.7 | 0.1 | 1.17 |
| Milling | Peanuts | kg | 143.1 | - | - |
| | Electricity | kWh | 57.6 | 0.24 | 15 |
| | Peanut Butter | kg | 143.1 | - | - |
| Packaging | Peanut Butter | kg | 143.1 | - | - |
| | Electricity | kWh | 11.7 | 0.24 | 2.808 |
| | Glass Jar | kg | 7.5 | 1.2 | 9 |
| | Peanut Butter | kg | 143.1 | - | - |

*Table 27: LCC data for the production of peanut butter*

| Process | Flow | Unit | Value | €/Unit | Total Costs (€) |
|---|---|---|---|---|---|
| Grinding | Deshelled Peanuts | kg | 173.4 | - | - |
| | Electricity | kWh | 69.3 | 0.24 | 16.632 |
| | Peanuts | kg | 173.4 | - | - |
| Roasting | Peanuts | kg | 173.4 | - | - |
| | Electricity | kWh | 360 | 0.24 | 86.4 |
| | Peanuts | kg | 166.5 | - | - |
| | Solid Wates | kg | 6.9 | 0.1 | 0.69 |
| Mechanical Processing | Peanuts | kg | 166.5 | - | - |
| | Electricity | kWh | 336.3 | 0.09 | 30.267 |
| | Peanut Oil | kg | 71.7 | - | - |
| | Peanut Cake | kg | 94.8 | - | - |
| Filtration | Peanut Oil | kg | 71.7 | - | - |
| | Electricity | kWh | 6 | 0.24 | 1.44 |
| | Peanut Oil | kg | 70.5 | - | - |
| | Solid Wastes | kg | 1.2 | 0.1 | 0.12 |
| Refining | Peanut Oil | kg | 70.5 | - | - |
| | Sodium Hydroxide | kg | 1.41 | 0.5 | 0.705 |

| | | | | | |
|---|---|---|---|---|---|
| | Phosphoric Acid | kg | 0.072 | 1.2 | 0.086 |
| | Bleaching Earth | kg | 1.41 | 0.24 | 0.338 |
| | Citric Acid | kg | 0.036 | 1.8 | 0.065 |
| | Water | Kg | 5.64 | 0.0017 | 0.01 |
| | Electricity | kWh | 27 | 0.24 | 6.48 |
| | Refined Oil | kg | 75 | - | - |
| | Wate Oil | kg | 3.96 | - | - |
| Packaging | Peanut Oil | kg | 75 | - | - |
| | Electricity | kWh | 6 | 0.24 | 1.44 |
| | Plastic Bottles | kg | 2.1 | 0.32 | 0.672 |
| | Peanut Butter | kg | 75 | - | - |

*Table 28: LCC data for the production of peanut oil*

| Cash Flows | Peanut Milk | Peanut Butter | Peanut Oil |
|---|---|---|---|
| Costs associated with cltivation and deshelling (€) | | 1072.45 | |
| Processing Costs (€) | 148.32 | 176.44 | 138.84 |
| Total Costs (€) | 1276.77 | 1304.89 | 1267.29 |
| Quantity of Produced Final Product (kg) | 1452 | 143.1 | 75 |
| Average Selling Price (€/kg) | 2 | 12 | 12 |
| Total Revenues (€) | 2904 | 1717.2 | 900 |
| Total Profit (€) | 1627.23 | 412.31 | -367.29 |

*Table 29: LCC analysis of the different studied peanut products*

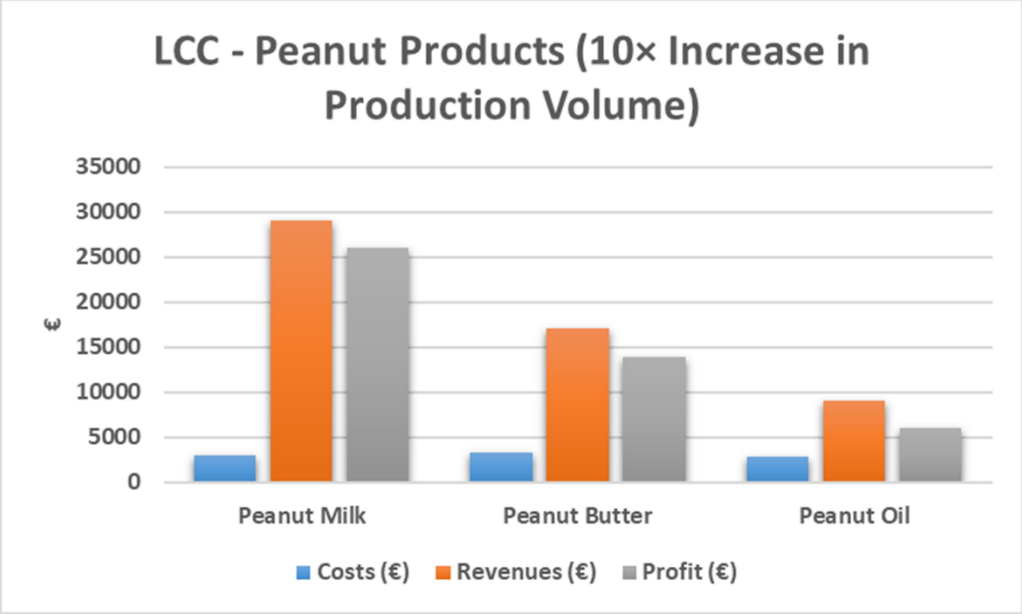



*Figure 43: LCC analysis of the different studied peanut products with a 10fold increase in the volume of harvesed peanuts*

## 5.3. Intercropping of Peas and Faba Beans

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Intercropping | Area Cultivated | In | ha | 1 |
| | Diesel | In | L | 78 |
| | Pea seeds | In | kg | 111.2 |
| | Faba Bean seeds | In | kg | 47.2 |
| | Fungicides | In | L | 3 |
| | Herbicides | In | L | 9 |
| | Insecticides | In | L | 0.05 |
| | P Fertilizer | In | kg | 40 |
| | K Fertilizer | In | kg | 60 |
| | Intercrop | Out | kg | 4832 |

*Table 30: Life Cycle Inventory of peas and faba beans intercropping*

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Dehulling | Intercrop | In | g | 1000 |
| | Electricity | In | kWh | 0.00842 |
| | Intercrop | Out | g | 999.2 |
| | Solid wastes | Out | g | 0.8 |
| Aspirating | Intercrop | In | g | 999.2 |
| | Electricity | In | kWH | 0.024 |
| | Intercrop | Out | g | 849 |
| | Hulls | Out | g | 145 |
| Grinding | Dehulledd Intercrop | In | g | 849 |
| | Electricity | In | kWh | 0.004 |
| | Intercrop | Out | g | 827 |
| | Solid Wastes | Out | g | 22 |
| Milling | Intercrop | In | g | 827 |
| | Electricity | In | MJ | 0.034 |
| | Intercrop Flour | Out | g | 743 |
| | Solid Wastes | Out | g | 84 |

*Table 31: Life Cycle Inventory of intercrop flour production*

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Ingrediet Weighting | Intercrop Flour | In | kg | 10.65 |
| | Wheat Flour | In | g | 24.85 |
| | Fat | In | g | 16 |
| | Eggs | In | g | 16 |
| | Baking Powder | In | g | 0.7 |
| | Water | In | g | 12.4 |
| | Sugar | In | g | 19.5 |
| | Cake Mixture | Out | g | 100 |
| Batter Mixing & Scaling | Cake Mixture | In | g | 100 |
| | Electricity | In | kWh | 0.00022 |
| | Cake Mixture | In | g | 96 |
| | Solid Wastes | Out | g | 4 |
| Baking | Cake Mixture | In | g | 96 |
| | Electricity | In | kWh | 0.05 |
| | Cake | In | Unit of cake | 1 |

*Table 32: Life Cycle Inventory of intercrop cake production*

| | Impact Category | Wheat Cake | Intercrop Cake | % Difference |
|---|---|---|---|---|
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 3.16E-01 | 3.17E-01 | +0.31 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 2.38E-01 | 2.54E-01 | +6.20 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 1.23E-03 | 1.23E-03 | +0.12 |
| | Fossil depletion [kg oil eq.] | 5.92E-02 | 5.94E-02 | +0.41 |
| | Freshwater Consumption [$m^3$] | 5.80E-03 | 5.73E-03 | -1.12 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 1.84E-04 | 1.82E-04 | -0.74 |
| | Freshwater Eutrophication [kg P eq.] | 3.06E-05 | 3.27E-05 | +6.47 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 5.07E-05 | 5.19E-05 | +2.32 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | -3.02E-02 | -3.01E-02 | -0.21 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 2.40E-03 | 2.39E-03 | -0.28 |
| | Land use [Annual crop eq.*y] | 2.06E-01 | 2.21E-01 | +6.62 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 2.56E-04 | 2.55E-04 | -0.48 |
| | Marine Eutrophication [kg N eq.] | 2.80E-04 | 2.76E-04 | -1.53 |
| | Metal depletion [kg Cu eq.] | 1.34E-03 | 1.30E-03 | -3.73 |
| | Photochemical Ozone Formation, Ecosystems [kg NOx eq.] | 2.94E-01 | 2.94E-01 | +0.29 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 1.83E-01 | 1.83E-01 | +0.08 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 1.47E-06 | 1.43E-06 | -2.67 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 2.53E-03 | 2.53E-03 | -0.20 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 3.19E-02 | 3.20E-02 | +0.17 |
| Endpoint | Damage to Human Health [DALY] | 1.45E-06 | 1.47E-06 | +1.17 |
| | Damage to Ecosystems [species*yr] | 4.19E-08 | 4.21E-08 | +0.50 |
| | Damage to Resources Availability [$] | 1.17E-02 | 1.17E-02 | +0.63 |

*Table 33: LCA results of intercrop cake production*

| Flow | | Unit | Value | €/Unit | Cost (€) |
|---|---|---|---|---|---|
| Utilities | Diesel | L | 78 | 1.63 | 127.14 |
| Chemical Agents | Fungicide | L | 3 | 13 | 39 |
| | Herbicide | L | 9 | 15 | 135 |
| | Insecticide | L | 0.05 | 12 | 0.6 |
| Seeds | Pea | Kg | 111.2 | 1.10 | 122.32 |
| | Faba Beans | kg | 47.2 | 1.05 | 49.56 |
| Fertilizers | P fertilizer | kg | 40 | 1.4 | 56 |
| | K Fertilizer | kg | 60 | 0.9 | 54 |
| Labor | Working Hours | hr | 21 | 15.86 | 333.06 |
| Output | Faba Beans | kg | 4832 | Total | 916.68 |

*Table 34: LCC inventory of peas and faba beans intercropping*

| Flow | | Unit | Value | €/Unit | Cost (€) |
|---|---|---|---|---|---|
| Utilities | Electricity | MJ | 253.51 | 0.04 | 10.14 |
| Labor | Working Hours | hr | 8 | 16.46 | 131.68 |
| Solid Wastes Management | Solid Wastes | kg | 251.8 | 0.105 | 26.44 |

| | | | | | |
|---|---|---|---|---|---|
| Output | Intercrop Flour | kg | 743 | Total | 168.26 |

*Table 35: LCC inventory of peas and faba beans intercrop flour production*

| Flow | | Unit | Value | €/Unit | Cost (€) |
|---|---|---|---|---|---|
| Utilities | Electricity | MJ | 502.22 | 0.04 | 20.09 |
| Water | Drinkig Water | kg | 124 | 0.0025 | 0.31 |
| Auxiliary Materials | Wheat Flour | kg | 248.5 | 0.58 | 144.13 |
| | Fat | kg | 160 | 7 | 1120 |
| | Eggs | kg | 160 | 2.5 | 400 |
| | Baking Powder | kg | 7 | 3.5 | 24.5 |
| | Sugar | kg | 195 | 0.75 | 146.25 |
| Solid Wastes Management | Solid Wastes | kg | 40 | 0.105 | 4.2 |
| Labor | Working Hours | hr | 8 | 16.46 | 131.68 |
| Output | Cake | kg | 1000 | Total | 1991.16 |

*Table 36: LCC inventory of intercrop cake production*

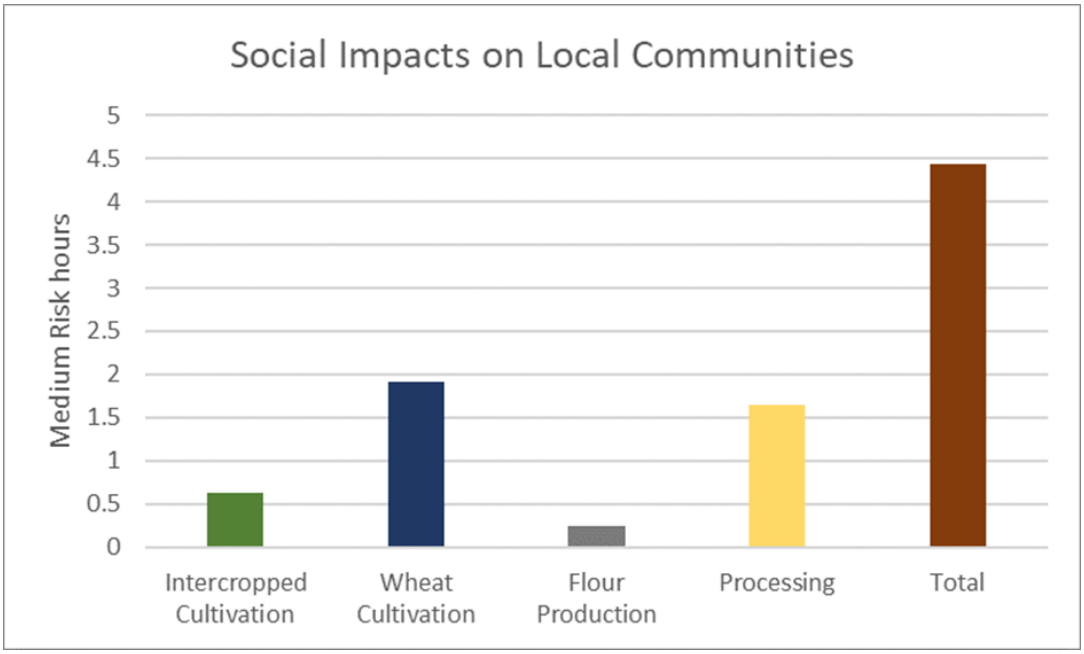



*Figure 44: Contribution of life cycle stages to total social impacts on Local Communities, expressed in medium risk hours*

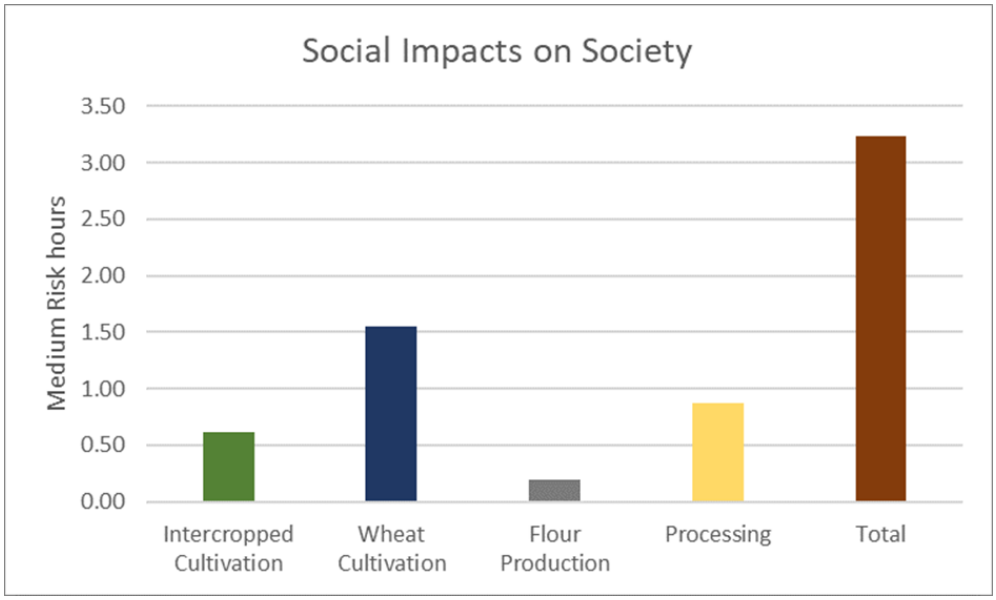



*Figure 45: Contribution of life cycle stages to total social impacts on Society, expressed in medium risk hours*

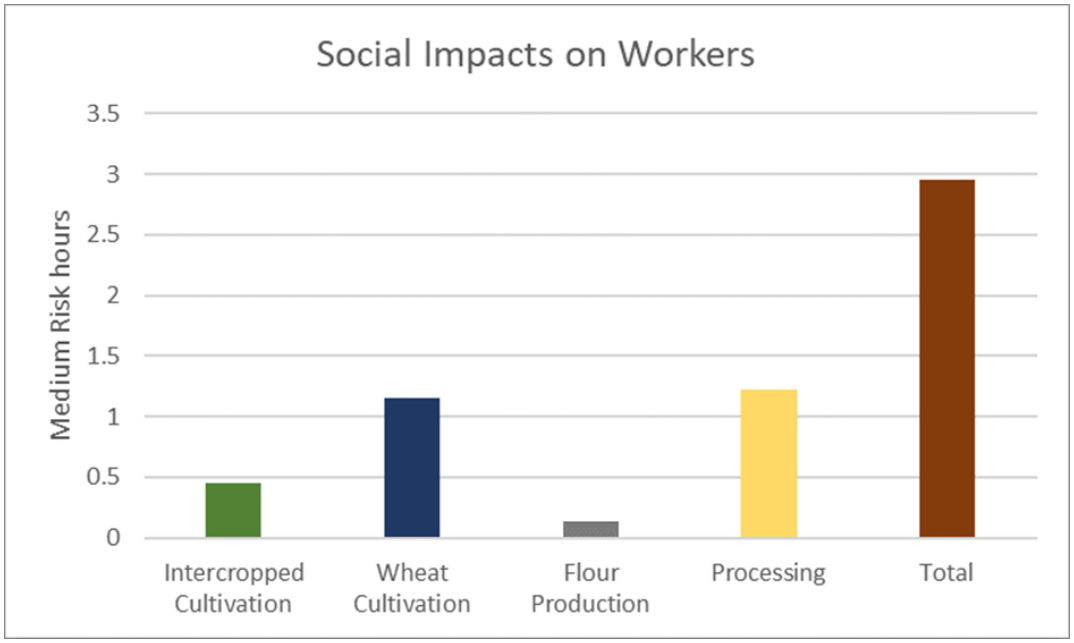



*Figure 46: Contribution of life cycle stages to total social impacts on Workers, expressed in medium risk hours*

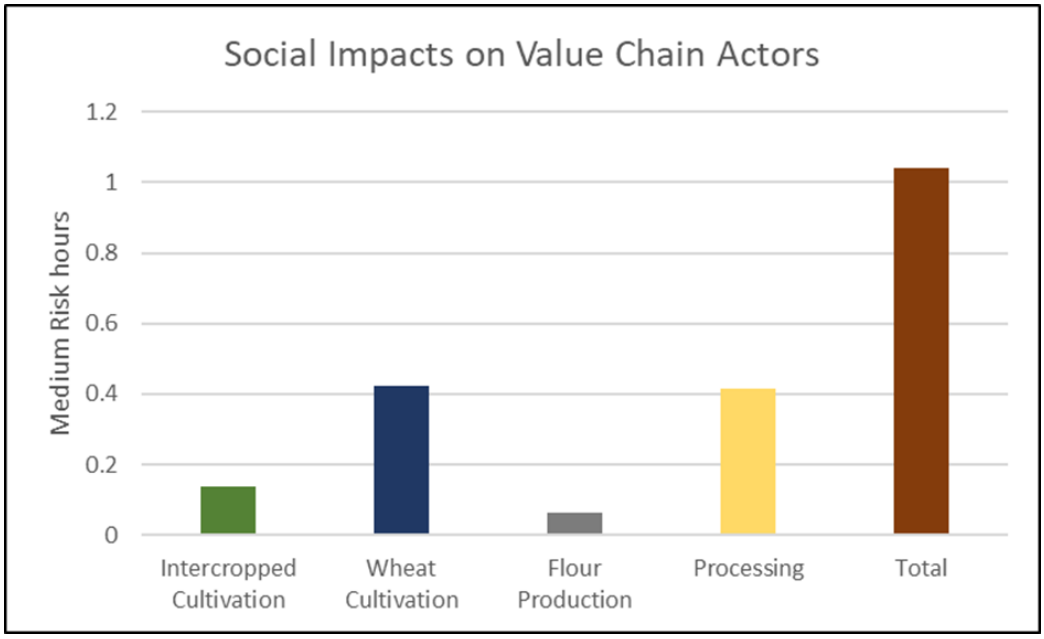



*Figure 47: Contribution of life cycle stages to total social impacts on Value Chain Actors, expressed in medium risk hours*

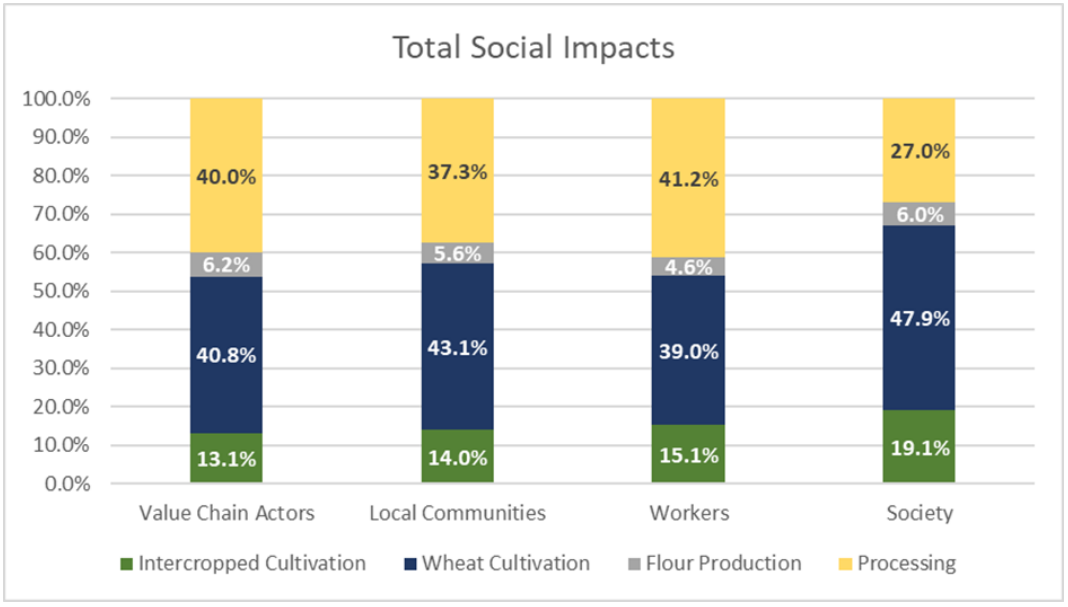



*Figure 48: Relative contribution of each life cycle stage to total social impacts across stakeholder groups, expressed as percentage of medium risk hours*

## 5.4. Plant-based Beverage Production

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Cultivation | Area Cultivated | In | ha | 1 |
| | Diesel | In | L | 78 |
| | Fungicides | In | L | 3 |
| | Herbicides | In | L | 9 |
| | Insecticides | In | L | 0.05 |
| | P Fertilizer | In | kg | 40 |
| | Faba Beans | Out | kg | 5500 |

*Table 37: Life Cycle Inventory of faba beans cultivation*

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Cleaning | Faba Beans (wet/dirty) | In | kg | 1181.25 |
| | Electricity | In | MJ | 3.6 |
| | Clean Faba Beans | Out | kg | 1125 |
| | Foreign Material | Out | kg | 56.25 |
| Drying | Clean Faba Beans | Out | kg | 1125 |
| | Electricity | In | MJ | 608 |
| | Faba Beans | Out | kg | 1000 |
| | Water Vapor | Out | kg | 125 |
| Dehulling | Faba Beans | In | kg | 1000 |
| | Electricity | In | MJ | 18.45 |
| | Dehulled Faba Beans | Out | kg | 800 |
| | Faba Bean Hulls | Out | kg | 200 |
| Dry Milling | Dehulled Faba Beans | In | kg | 800 |
| | Electricity | In | MJ | 46.7 |
| | Faba Flour | Out | kg | 800 |
| Alkaline Solubilization | Faba Flour | In | kg | 800 |
| | Sodium Hydroxide (10%) | In | kg | 43.2 |
| | Water | In | kg | 7200 |
| | Protein Solution | Out | kg | 8043.2 |
| Decantation #1 | Protein Solution | In | kg | 8043.2 |
| | Electricity | In | MJ | 198.5 |
| | Dried Cake | Out | kg | 396.27 |
| | Protein Solution | Out | kg | 7567.36 |
| Protein Precipitation | Protein Solution | In | kg | 7567.36 |
| | Hydrochloric Acid (10%) | In | kg | 105.98 |
| | Protein Solution | Out | kg | 7673.34 |
| Decantation #2 | Protein Solution | In | kg | 7673.34 |
| | Electricity | In | MJ | 275.4 |
| | Acidified Water | Out | kg | 6759.71 |
| | Protein Cake | Out | kg | 913.63 |
| Washing & Neutralization | Protein Cake | In | kg | 913.63 |
| | Sodium Hydroxide (10%) | In | Kg | 9.37 |
| | Deionized Water | In | Kg | 455.25 |
| | Protein Solution | Out | kg | 1378.25 |
| Spray Drying | Protein Solution | In | kg | 1378.25 |
| | Electricity | In | MJ | 167.2 |
| | Thermal Energy from Natural Gas | In | MJ | 4820.57 |
| | Faba Protein Isolate | Out | kg | 173.11 |
| | Water Vapor | Out | kg | 1205.14 |

*Table 38: Life Cycle Inventory of faba protein isolate production*

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Mixing | Faba Protein Isolate | In | kg | 60.4 |
| | Maltodextrin | In | kg | 50 |
| | Water | In | kg | 890 |
| | Electricity | In | MJ | 9.5 |
| | Beverage | Out | kg | 1000 |
| Preheat | Beverage | In | kg | 1000 |
| | Natural Gas | In | $Nm^3$ | 6 |
| | Steam | In | kg | 311.35 |
| | Beverage | Out | kg | 1000 |
| Final Heat | Beverage | In | kg | 1000 |
| | Natural Gas | In | $Nm^3$ | 10.1 |
| | Steam | In | kg | 134.56 |
| | Beverage | Out | kg | 1000 |
| Homogenization | Beverage | In | kg | 1000 |
| | Electricity | In | MJ | 43.2 |
| | Beverage | Out | kg | 1000 |
| Cooling | Beverage | In | kg | 1000 |
| | Electricity | In | MJ | 116 |
| | Beverage | Out | kg | 1000 |
| Packaging | Beverage | In | kg | 1000 |
| | Electricity | In | MJ | 19 |
| | PET Bottles | In | kg | 46.97 |
| | Bevrage | Out | kg | 1000 |

*Table 39: Life Cycle Inventory of beverage production*

| Impact Category | | Plant-based Beverage Production | | | |
|---|---|---|---|---|---|
| | | Total | Cultivation | Protein Isolate Production | Beverage Production |
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 2.29E-01 | 4.75E-03 | 1.24E-01 | 1.00E-01 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 2.88E-01 | 4.48E-03 | 1.39E-01 | 1.45E-01 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 4.81E-05 | 8.07E-06 | 1.77E-05 | 2.23E-05 |
| | Fossil depletion [kg oil eq.] | 7.77E-02 | 3.47E-03 | 2.17E-02 | 5.25E-02 |
| | Freshwater Consumption [$m^3$] | 8.45E-04 | 3.16E-05 | 1.42E-04 | 6.71E-04 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 3.13E-05 | 9.70E-06 | 1.03E-05 | 1.13E-05 |
| | Freshwater Eutrophication [kg P eq.] | 2.34E-05 | 2.09E-05 | 2.19E-06 | 3.43E-07 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 9.65E-05 | 1.33E-05 | 4.77E-05 | 3.55E-05 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 9.32E-03 | 3.29E-03 | 1.18E-03 | 4.85E-03 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 4.33E-04 | 1.68E-05 | 5.04E-05 | 3.66E-04 |
| | Land use [Annual crop eq.*y] | 1.66E-01 | 1.65E-01 | 1.90E-04 | 7.15E-04 |

| | | | | | |
|---|---|---|---|---|---|
| | Marine ecotoxicity [kg 1,4-DB eq.] | 8.59E-05 | 1.65E-05 | 2.07E-05 | 4.88E-05 |
| | Marine Eutrophication [kg N eq.] | 5.31E-06 | 2.53E-07 | 4.44E-06 | 6.11E-07 |
| | Metal depletion [kg Cu eq.] | 2.12E-04 | 1.89E-05 | 1.57E-04 | 3.63E-05 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 1.36E-01 | 3.11E-03 | 6.24E-02 | 7.09E-02 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 8.47E-02 | 1.93E-03 | 3.87E-02 | 4.40E-02 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 6.41E-08 | 8.70E-09 | 2.38E-08 | 3.16E-08 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 1.52E-04 | 2.72E-05 | 5.44E-05 | 7.03E-05 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 1.03E-01 | 2.35E-03 | 1.02E-02 | 9.08E-02 |
| Endpoint | Damage to Human Health [DALY] | 5.91E-07 | 1.62E-08 | 2.91E-07 | 2.84E-07 |
| | Damage to Ecosystems [species*yr] | 1.91E-08 | 4.47E-10 | 8.80E-09 | 9.86E-09 |
| | Damage to Resources Availability [$] | 2.43E-02 | 1.47E-03 | 5.93E-03 | 1.69E-02 |

*Table 40: LCA results of plant-based beverage production*

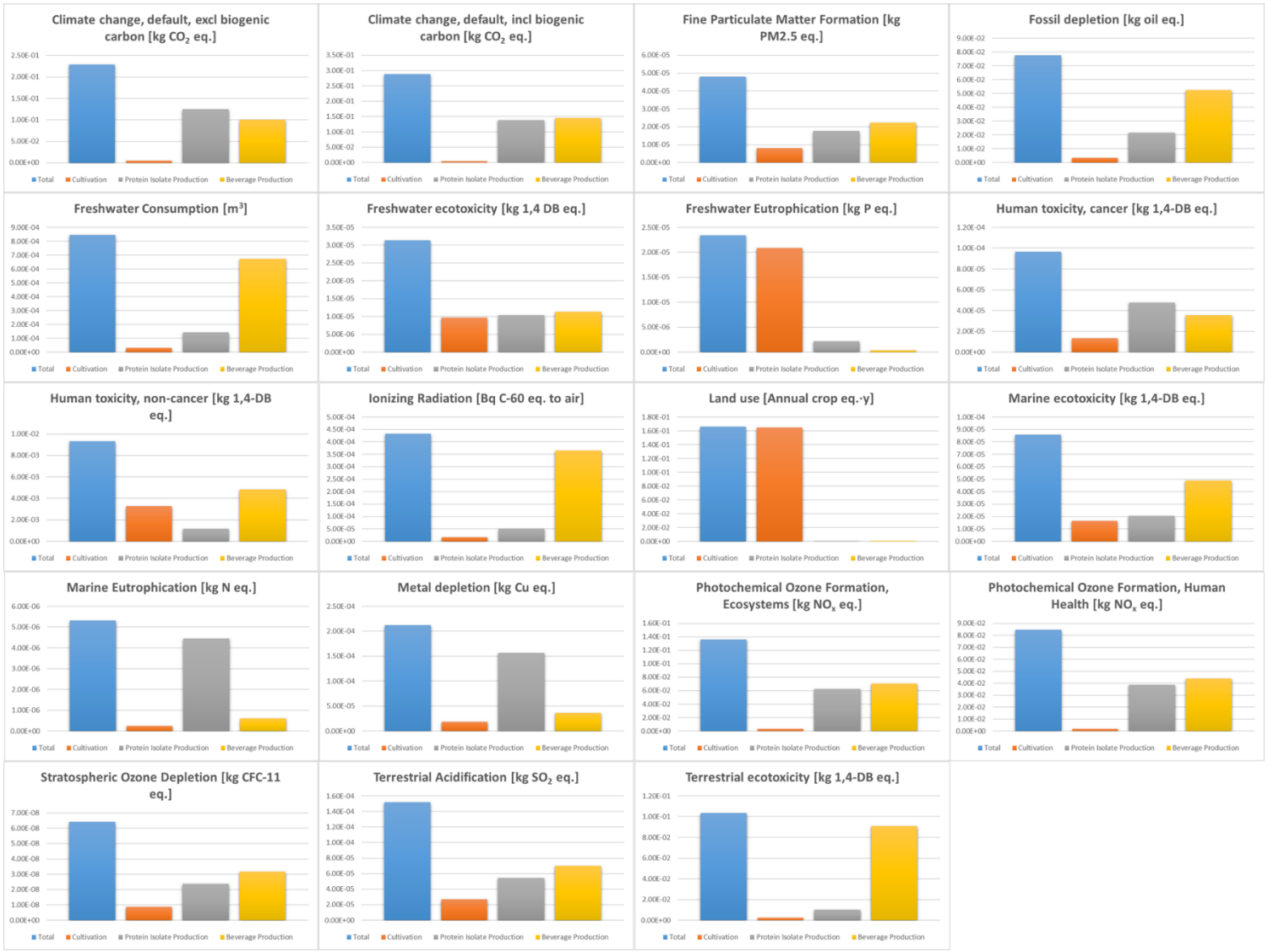



*Figure 49: LCA results of the plant-based beverage*

| Flow | | Unit | Value | €/Unit | Cost (€) |
|---|---|---|---|---|---|
| Utilities | Diesel | L | 78 | 1.63 | 127.14 |
| Chemical Agents | Fungicide | L | 3 | 13 | 39 |
| | Herbicide | L | 9 | 15 | 135 |
| | Insecticide | L | 0.05 | 12 | 0.6 |
| Fertilizers | P fertilizer | kg | 40 | 1.4 | 56 |
| | K Fertilizer | kg | 60 | 0.9 | 54 |
| Labor | Working Hours | hr | 21 | 15.86 | 333.06 |
| Output | Faba Beans | kg | 5500 | Total | 741.8 |

*Table 41: LCC inventory of faba beans cultivation*

| Flow | | Unit | Value | €/Unit | Cost (€) |
|---|---|---|---|---|---|
| Utilities | Natural Gas | MJ | 1317.85 | 0.1121 | 147.73 |
| | Electricity | MJ | 4820.57 | 0.04 | 192.82 |
| Water | Process Water | kg | 7200 | 0.00185 | 13.32 |
| | Deionized Water | kg | 455.25 | 1 | 455.25 |
| Auxiliary Materials | Sodium Hydroxide | kg | 52.57 | 0.4 | 21.03 |
| | Hydrochloric Acid | kg | 105.98 | 2.5 | 264.95 |
| Labor | Working Hours | hr | 16 | 16.46 | 263.36 |
| Wastewater | Acidified Water | kg | 6759.71 | 0.00182 | 12.3 |
| Solid Wastes | Hulls | kg | 200 | 0.105 | 21 |
| | Foreign Material | kg | 56.25 | 0.105 | 5.91 |
| | Dried Cake | kg | 396.27 | 0.105 | 41.61 |
| Output | Faba Beans Protein Isolate | kg | 173.11 | Total | 1439.28 |

*Table 42: LCC inventory of faba protein isolate production*

| Flow | | Unit | Value | €/Unit | Cost (€) |
|---|---|---|---|---|---|
| Utilities | Natural Gas | $Nm^3$ | 16.1 | 1.725 | 27.77 |
| | Electricity | MJ | 187.7 | 0.1121 | 21.04 |
| | Steam | kg | 445.91 | 0.42 | 187.28 |
| Water | Process Water | kg | 890 | 0.00185 | 1.65 |
| Auxiliary Materials | Maltodextrin | kg | 50 | 4.25 | 212.5 |
| | PET Bottles | kg | 46.97 | 1.19 | 55.89 |
| Labor | Working Hours | hr | 16 | 16.46 | 263.36 |
| Output | Beverage | kg | 1000 | Total | 769.49 |

*Table 43: LCC inventory of beverage production*

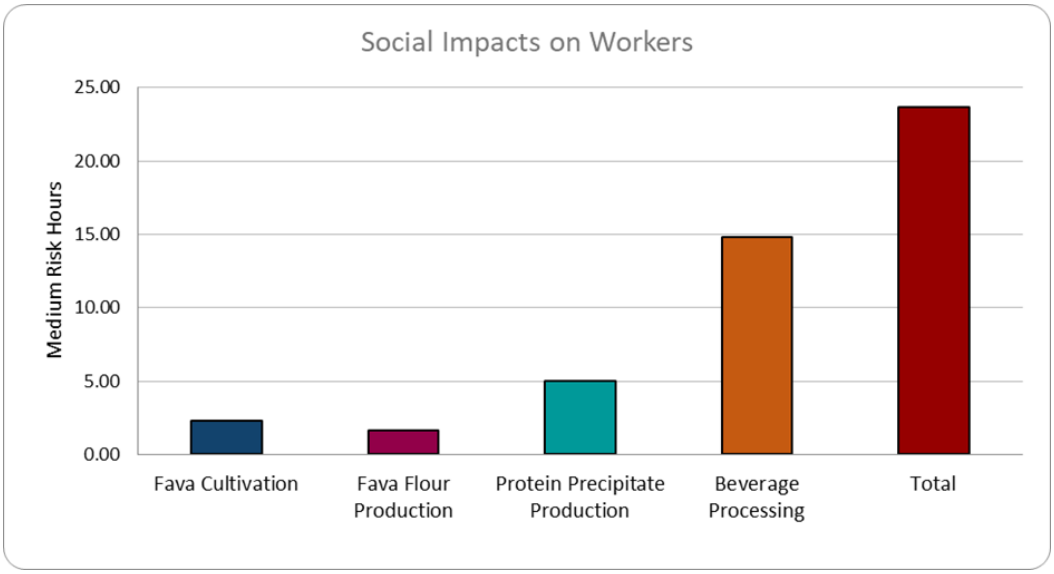



*Figure 50: Contribution of life cycle stages (Fava Cultivation, Fava Flour Production, Protein Precipitate Production, and Beverage Processing) to total social impacts on workers, expressed in medium risk hours*

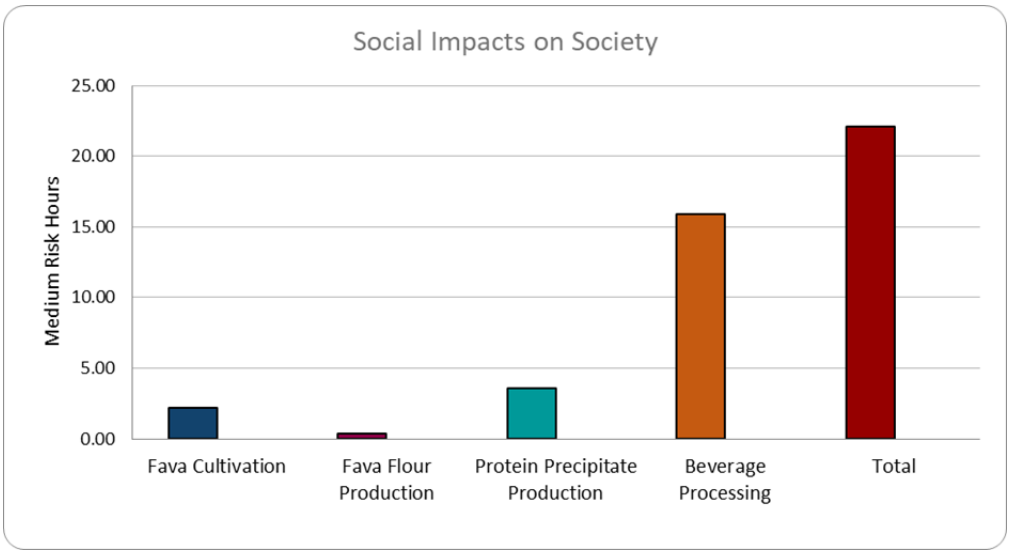



*Figure 51: Contribution of life cycle stages to total social impacts on society, expressed in medium risk hours*

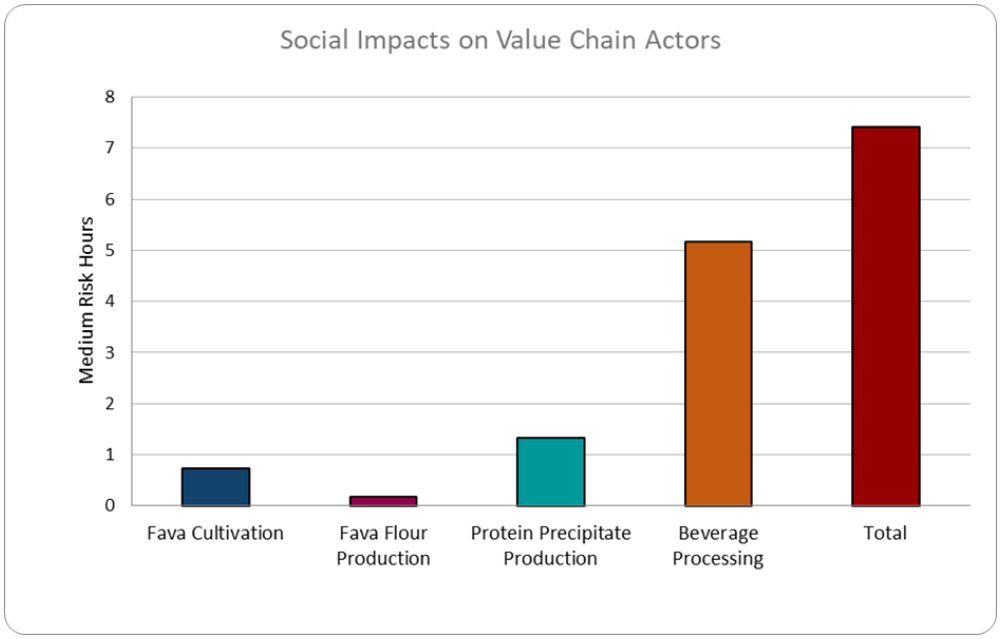



*Figure 52: Contribution of life cycle stages to total social impacts on value chain actors, expressed in medium risk hours*

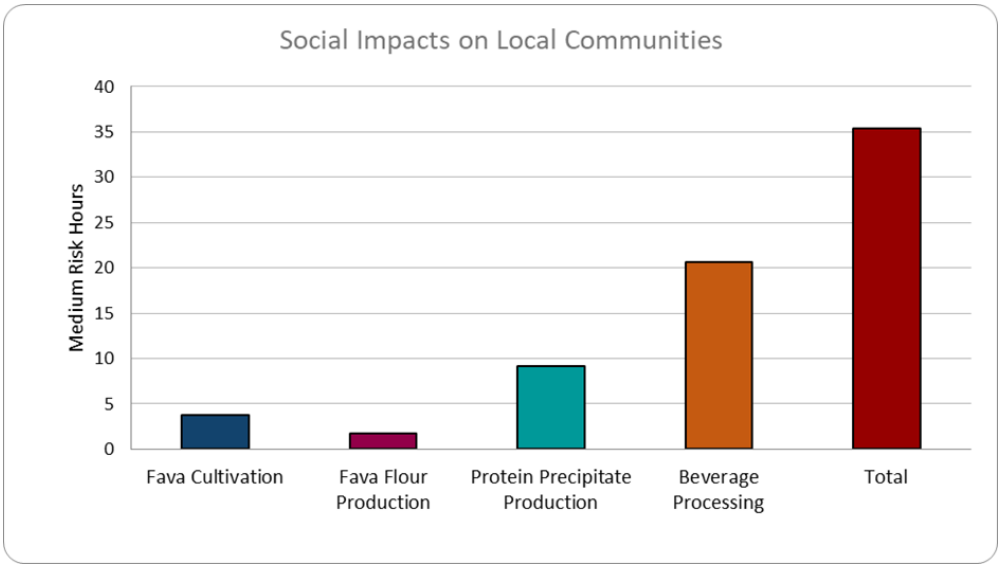



*Figure 53: Contribution of life cycle stages to total social impacts on local communities, expressed in medium risk hours*

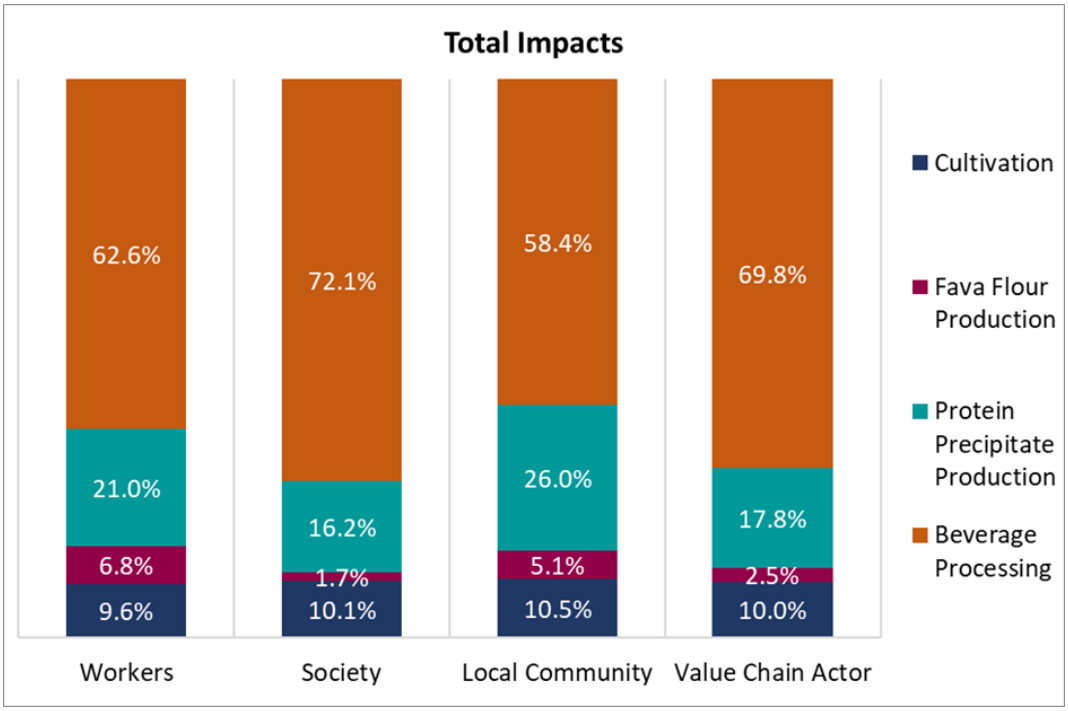



*Figure 54: Relative contribution of each life cycle stage to total social impacts across stakeholder groups, expressed as percentage of medium risk hours*

## 5.5. Energy Bar Production

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Blend Dry Ingredients | Faba Protein Isolate | In | kg | 25.3 |
| | Cocoa Fibre | In | kg | 5.9 |
| | Cocoa Powder | In | kg | 1.1 |
| | Electricity | In | kWh | 0.09 |
| | Protein Mixture | Out | kg | 32.3 |
| Ingredients Heating | Binding Syruo | In | kg | 36.3 |
| | Glycerol | In | kg | 7.8 |
| | Butter | In | kg | 8.9 |
| | Electricity | In | kWh | 10 |
| | Binders Mixture | Out | kg | 53 |
| Mixing | Protein Mixture | In | kg | 32.3 |
| | Binders Mixture | In | kg | 53 |
| | Water | In | kg | 14.8 |
| | Electricity | In | kWh | 0.95 |
| | Energy Bar Mixture | Out | Kg | 100.1 |
| Pressing | Energy Bar Mixture | In | kg | 100.1 |
| | Baking Paper | In | kg | 0.5 |
| | Electricity | In | kWh | 2 |
| | Energy Bar | Out | kg | 100.1 |
| Refrigerate | Energy Bar | In | kg | 100.1 |
| | Electricity | In | kWh | 1 |
| | Energy Bar | Out | kg | 100.1 |
| Cutting | Energy Bar | In | kg | 100.1 |
| | Electricity | In | kWh | 1 |
| | Energy Bar | Out | kg | 100.1 |
| Packaging | Beverage | In | kg | 100.1 |
| | Electricity | In | kWh | 0.7 |
| | PET/PE (1:3) Laminate | In | kg | 2 |
| | Bevrage | Out | kg | 100.1 |

*Table 44: Life Cycle Inventory of energy bar production*

| Impact Category | | Total | Energy Bar Production | | |
|---|---|---|---|---|---|
| | | | Cultivation | Protein Isolate Production | Energy Bar Production |
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 1.28E-01 | 3.14E-03 | 8.23E-02 | 4.28E-02 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 1.14E-01 | 2.96E-03 | 9.18E-02 | 1.96E-02 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 2.81E-04 | 5.34E-06 | 1.17E-05 | 2.64E-04 |
| | Fossil depletion [kg oil eq.] | 2.90E-02 | 2.30E-03 | 1.44E-02 | 1.23E-02 |
| | Freshwater Consumption [$m^3$] | 3.98E-02 | 2.09E-05 | 9.42E-05 | 3.96E-02 |

| | | | | | |
|---|---|---|---|---|---|
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 9.61E-05 | 6.42E-06 | 6.83E-06 | 8.29E-05 |
| | Freshwater Eutrophication [kg P eq.] | 2.76E-05 | 1.38E-05 | 1.45E-06 | 1.23E-05 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 5.25E-05 | 8.79E-06 | 3.15E-05 | 1.23E-05 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 9.00E-03 | 2.17E-03 | 7.78E-04 | 6.05E-03 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 1.85E-04 | 1.11E-05 | 3.34E-05 | 1.41E-04 |
| | Land use [Annual crop eq.*y] | 2.13E-01 | 1.10E-01 | 1.26E-04 | 1.03E-01 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 1.41E-04 | 1.09E-05 | 1.37E-05 | 1.17E-04 |
| | Marine Eutrophication [kg N eq.] | -1.45E-05 | 1.68E-07 | 2.94E-06 | -1.76E-05 |
| | Metal depletion [kg Cu eq.] | 9.49E-04 | 1.25E-05 | 1.04E-04 | 8.32E-04 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 6.59E-02 | 2.06E-03 | 4.13E-02 | 2.25E-02 |
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 4.09E-02 | 1.28E-03 | 2.56E-02 | 1.40E-02 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 2.52E-07 | 5.76E-09 | 1.58E-08 | 2.30E-07 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 4.80E-04 | 1.80E-05 | 3.60E-05 | 4.26E-04 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 2.11E-02 | 1.55E-03 | 6.74E-03 | 1.28E-02 |
| Endpoint | Damage to Human Health [DALY] | 4.45E-07 | 1.08E-08 | 1.93E-07 | 2.41E-07 |
| | Damage to Ecosystems [species*yr] | 1.13E-08 | 1.27E-09 | 5.82E-09 | 4.17E-09 |
| | Damage to Resources Availability [$] | 8.88E-03 | 9.76E-04 | 3.92E-03 | 3.98E-03 |

*Table 45: LCA results of energy bar production*

| Flow | | Unit | Value | €/Unit | Cost (€) |
|---|---|---|---|---|---|
| Utilities | Electricity | MJ | 566.64 | 0.04 | 22.67 |
| Water | Drinking Water | kg | 148 | 0.0025 | 0.37 |
| Auxiliary Materials | Cocoa Fibre | kg | 59 | 4.5 | 265.5 |
| | Cocoa Powder | kg | 11 | 14 | 154 |
| | Binding Syrup | kg | 363 | 3 | 1089 |
| | Butter | kg | 89 | 9 | 801 |
| | Glycerol | kg | 78 | 2.5 | 195 |
| | Baking Paper | kg | 5 | 3.25 | 16.25 |
| | PET/PE Laminate | kg | 20 | 3.5 | 70 |
| Labor | Working Hours | hr | 16 | 16.46 | 263.36 |
| Output | Energy Bar | kg | 1000 | Total | 2877.15 |

*Table 46: LCC inventory of energy bar production*

## 5.6. Legume-based Pasta Production

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Lentils Flour Production | Electricity | In | MJ | 205.485 |
| | Lentils | In | kg | 318.403 |
| | Water | In | L | 65.65 |
| | Lentils Flour | Out | kg | 262.6 |
| | Solid Wastes | Out | kg | 16.4125 |
| Chickpeas Flour Production | Electricity | In | MJ | 205.485 |
| | Chickpeas | In | kg | 318.403 |
| | Water | In | L | 65.65 |
| | Chickpeas Flour | Out | kg | 262.6 |
| | Solid Wastes | Out | kg | 16.4125 |
| Peas Flour Production | Electricity | In | MJ | 205.485 |
| | Peas | In | kg | 318.403 |
| | Water | In | L | 65.65 |
| | Peas Flour | Out | kg | 262.6 |
| | Solid Wastes | Out | kg | 16.4125 |
| Rice Flour Production | Electricity | In | MJ | 173.872 |
| | Rice | In | kg | 269.418 |
| | Water | In | L | 55.55 |
| | Rice Flour | Out | kg | 222.2 |
| | Solid Wastes | Out | kg | 13.875 |
| Pasta Production | Lentils Flour | In | kg | 262.6 |
| | Chickpeas Flour | In | kg | 262.6 |
| | Peas Flour | In | kg | 262.6 |
| | Rice Flour | In | kg | 222.2 |
| | Electricity | In | MJ | 432 |
| | Natural Gas | In | kg | 25.5 |
| | Crude Oil | In | kg | 17 |
| | Water | In | L | 310 |
| | Legume-based Pasta | Out | kg | 1000 |
| Pasta Packaging | Legume-based Pasta | In | kg | 1000 |
| | Electricity | In | MJ | 54 |
| | Corrugated Board Boxes | In | kg | 46.25 |
| | Kraft Paper | In | kg | 56.25 |
| | PET Film | In | kg | 20 |
| | PE Granulate | In | kg | 0.036 |
| | Printing Ink | In | kg | 0.186 |
| | Plastic Film | In | kg | 0.036 |
| | Folding Boxboard | In | kg | 56.25 |
| | Transporting Capacity | In | kgkm | 26375 |
| | Wooden Pallets | In | kg | 2.09 |
| | Packaged Legume-based Pasta | Out | kg | 1000 |

*Table 47: Life Cycle Inventory of legume-based pasta production*

| Process | Flow | In/Out | Value | Unit |
|---|---|---|---|---|
| Semolina Flour Production | Electricity | In | MJ | 790.325 |
| | Wheat | In | kg | 1224.63 |
| | Water | In | L | 252.5 |
| | Semolina Flour | Out | kg | 1010 |
| | Solid Wastes | Out | kg | 63.125 |
| Pasta Production | Semolina Flour | In | kg | 1010 |
| | Electricity | In | MJ | 432 |
| | Natural Gas | In | kg | 25.5 |
| | Crude Oil | In | kg | 17 |
| | Water | In | L | 310 |
| | Legume-based Pasta | Out | kg | 1000 |
| Pasta Packaging | Legume-based Pasta | In | kg | 1000 |
| | Electricity | In | MJ | 54 |
| | Corrugated Board Boxes | In | kg | 46.25 |
| | Kraft Paper | In | kg | 56.25 |
| | PET Film | In | kg | 20 |
| | PE Granulate | In | kg | 0.036 |
| | Printing Ink | In | kg | 0.186 |
| | Plastic Film | In | kg | 0.036 |
| | Folding Boxboard | In | kg | 56.25 |
| | Transporting Capacity | In | kgkm | 26375 |
| | Wooden Pallets | In | kg | 2.09 |
| | Packaged Legume-based Pasta | Out | kg | 1000 |

*Table 48: Life Cycle Inventory of legume-based pasta production*

| | Impact Category | Legume-based Pasta | Conventional Pasta |
|---|---|---|---|
| Midpoint | Climate change, default, excl biogenic carbon [kg $CO_2$ eq.] | 7.30E+00 | 1.05E+01 |
| | Climate change, incl biogenic carbon [kg $CO_2$ eq.] | 7.83E+00 | -4.93E+00 |
| | Fine Particulate Matter Formation [kg PM2.5 eq.] | 8.91E-03 | 6.97E-03 |
| | Fossil depletion [kg oil eq.] | 1.54E+00 | 2.67E+00 |
| | Freshwater Consumption [$m^3$] | 1.27E+00 | 3.05E-01 |
| | Freshwater ecotoxicity [kg 1,4 DB eq.] | 6.08E-03 | 7.29E-03 |
| | Freshwater Eutrophication [kg P eq.] | 2.35E-02 | 1.48E-03 |
| | Human toxicity, cancer [kg 1,4-DB eq.] | 1.55E-03 | 2.12E-03 |
| | Human toxicity, non-cancer [kg 1,4-DB eq.] | 2.95E-01 | 5.56E-01 |
| | Ionizing Radiation [Bq C-60 eq. to air] | 2.87E-02 | 2.71E-02 |
| | Land use [Annual crop eq.*y] | 1.64E+01 | 1.63E+01 |
| | Marine ecotoxicity [kg 1,4-DB eq.] | 7.27E-03 | 1.11E-02 |
| | Marine Eutrophication [kg N eq.] | 4.90E-03 | 1.60E-02 |
| | Metal depletion [kg Cu eq.] | 1.92E-02 | 1.68E-01 |
| | Photochemical Ozone Formation, Ecosystems [kg $NO_x$ eq.] | 3.76E+00 | 9.33E+00 |

| | | | |
|---|---|---|---|
| | Photochemical Ozone Formation, Human Health [kg $NO_x$ eq.] | 2.34E+00 | 5.80E+00 |
| | Stratospheric Ozone Depletion [kg CFC-11 eq.] | 4.74E-05 | 5.50E-05 |
| | Terrestrial Acidification [kg $SO_2$ eq.] | 5.08E-02 | 3.53E-02 |
| | Terrestrial ecotoxicity [kg 1,4-DB eq.] | 2.08E+00 | 2.84E+00 |
| Endpoint | Damage to Human Health [DALY] | 2.47E-05 | 1.53E-05 |
| | Damage to Ecosystems [species*yr] | 7.17E-05 | 1.38E-06 |
| | Damage to Resources Availability [$] | 4.86E-01 | 7.86E-01 |

*Table 49: LCA results of the base case scenario*

| Flow | | Unit | Value | €/Unit | Cost (€) |
|---|---|---|---|---|---|
| Utilities | Electricity | MJ | 1276.327 | 0.075 | 95.72 |
| | Natural Gas | kg | 25.5 | 0.70 | 17.85 |
| | Crude Oil | kg | 17 | 0.55 | 9.35 |
| Raw Materials | Lentils | kg | 318.403 | 0.60 | 191.04 |
| | Chickpeas | kg | 318.403 | 0.55 | 175.12 |
| | Peas | kg | 318.403 | 0.35 | 111.44 |
| | Rice | kg | 269.418 | 0.45 | 121.24 |
| Water | Water | L | 562.5 | 0.0025 | 1.41 |
| Solid Wastes | Solid Wastes Management | kg | 63.1125 | 0.15 | 9.47 |
| Packaging | Packaging Mateials | kg | Total of all packaging materials | | 230 |
| Labor | Working Hours | hr | 8 | 30 | 240 |
| Output | Legume-based Pasta | kg | 1000 | Total | 1202.64 |

*Table 50: Overview of osts associated with the production of the legume-based pasta*

| Flow | | Unit | Value | €/Unit | Cost (€) |
|---|---|---|---|---|---|
| Utilities | Electricity | MJ | 1276.327 | 0.075 | 95.72 |
| | Natural Gas | kg | 25.5 | 0.70 | 17.85 |
| | Crude Oil | kg | 17 | 0.55 | 9.35 |
| Raw Materials | Wheat | kg | 1224.63 | 0.25 | 306.16 |
| Water | Water | L | 562.5 | 0.0025 | 1.41 |
| Solid Wastes | Solid Wastes Management | kg | 63.1125 | 0.15 | 9.47 |
| Packaging | Packaging Mateials | kg | Total of all packaging materials | | 230 |
| Labor | Working Hours | hr | 8 | 30 | 240 |
| Output | Wheat Pasta | kg | 1000 | Total | 909.96 |

*Table 51: Overview of osts associated with the production of the conventional wheat pasta*