FrontAg#Nexus

Impact of Climate-Smart and Water-Saving Frontier Agriculture on the WEFE Nexus in Arid Mediterranean Regions

D1.2: Supply and value chain analysis of climate smart and water saving agri-food production systems

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PRIMA PARTNERSHIP FOR RESEARCH AND INNOVATION IN THE MEDITERRANEAN AREA

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Executive Summary

The Deliverable 1.2 focuses on the impact of climate-smart and water-saving frontier agriculture on the Water-Energy-Food-Ecosystem (WEFE) Nexus in Mediterranean regions. As part of the FrontAg Nexus project, the primary goal was to assess how innovative agricultural practices can enhance resource efficiency and sustainability across the WEFE Nexus. This document outlines the methodology for supply and value chain analysis of frontier agriculture, detailing approaches to model resource-sensitive value chains in the context of climate-smart agriculture. The analysis covers the value chains of selected frontier agricultural products: fish, insects, tomatoes, and strawberries. The report evaluates the functional, profitability, social, and environmental aspects of these value chains, examining how they align with WEFE resource efficiency goals. Each value chain is analyzed to assess the competitive advantages of frontier agriculture over conventional methods, identifying key innovations that enhance sustainability. Data collection involved interviews and discussions with stakeholders along the value chains, including smallholders, processors, and retailers. The environmental impact assessment methodology includes a life cycle assessment (LCA) for tomatoes in Morocco (UM6P) and the equivalent true cost approach for fish in Israel (BGU), and strawberries in Tunisia (Elbosten). Due to the unavailability of data from secondary sources, the environmental impact of the insect value chain in Italy (UNIBO) was discussed in a qualitative manner.

Key findings suggest that frontier agricultural innovations can provide substantial benefits in resource use efficiency, particularly in water conservation, energy use, and ecosystem health while also contributing notably to food security and socio-economic development in Mediterranean regions. This analysis will inform the development of policy frameworks to promote frontier agriculture and foster collaboration among key stakeholders, including farmers, industry actors, and policymakers, to build resilient and sustainable agri-food systems within the WEFE Nexus.

With the submission of D1.2, M1.2 “WEFE Nexus sensitive supply & value chain models, frontag context” is accomplished.

Executive Summary (bullet points)

Objective. The report evaluates the impact of climate-smart and water-saving frontier agriculture on the WEFE Nexus in Mediterranean regions.

Value chains analyzed

- Aquaponics
- Insects
- In soil and hydroponic tomatoes
- In soil and hydroponic strawberries

Methodology

- Functional, profitability, social, and environmental aspects of the value chains.

- Data collection through interviews and discussions with stakeholders along the value chains.
- LCA and TCA to evaluate environmental impacts.

Key findings

- Frontier agricultural practices enhance resource efficiency, especially in water conservation and energy use.
- Innovations in the analyzed value chains offer a competitive advantage over conventional agricultural methods.
- Overall, positive contributions to food security and socio-economic development in Mediterranean regions.

Outcomes

- Results will guide policy frameworks to promote frontier agriculture.
- Collaboration among farmers, industry actors, and policymakers is crucial for building sustainable agri-food systems within the WEFE Nexus.

Table of Contents

List of Figures

List of Tables

List of acronyms

DALY	Disability Adjusted Loss of Life Years
FAO	Food and agriculture organization
FGD	Focus group discussion
FNS	Food and nutrition security
FU	Functional unit
GDP	Gross domestic product
GHG	Greenhouse gas
GOP	Gross operating profit
ha	Hectare
IC	Intermediate consumption
kg	Kilogram
KPI	Key performance indicator
LCA	Life cycle assessment
MAD	Moroccan dinar
MAD	Moroccan Dirham
NGO	non-governmental organization
NPC	Normalized price coefficient
OP	Operating profit
SME	Small and medium enterprise
SOC	Soil organic carbon
TCA	True cost approach
TND	Tunisian dinar
ToBRFV	Tomato Brown Rugose Fruit Virus
USD	US dollar
VA	Value added
VC	Value chain
VCA4D	Value chain analysis for development
VSM	Value stream mapping
WEFE	Water, energy, food, ecosystem

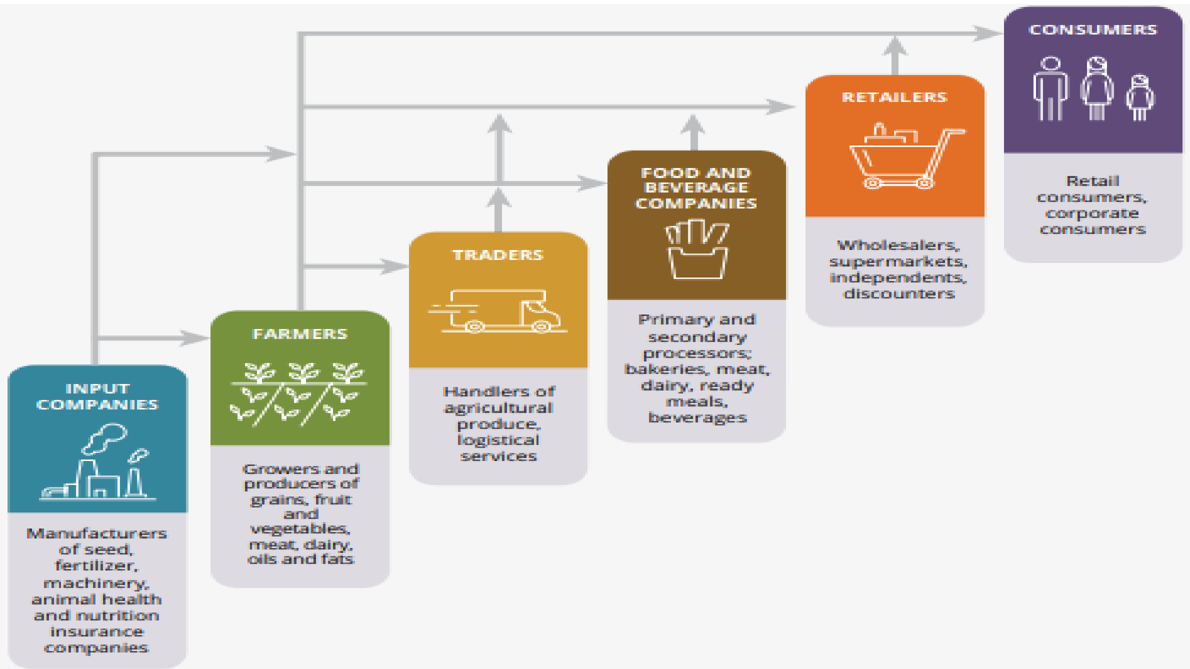
1. Introduction

A supply and value chain (in the following we will use only the term value chain) depicts the entire range of processes and activities that characterize the lifecycle of a product or service from production (including upstream value creation) to manufacturing and processing, to distribution, marketing, and retail, and finally to consumption (including waste and disposal across all stages) (TEEB, 2018). After the introduction, D1.2 outlines the methodology (Chapter 2) used to conduct the value chain analyses. The emphasis is on frontier agricultural production processes and corresponding products within the PRIMA project FrontAg Nexus.

Four FrontAg Nexus partners, BGU (P4), UNIBO (P5), UM6P (P7), and ElBosten (P8) undertook a value chain analysis. The products selected were fish, insects, cherry tomatoes, tomatoes, and strawberries, respectively.

1.1 Delineation of a Value Chain

A **value chain** comprises the entire set of procedures and actions over a product's lifecycle, from production through manufacturing and processing, distribution, marketing, and retail, and ultimately consumption (including waste and disposal at every stage) (TEEB, 2018). Thus, the following actors are considered: producers, suppliers, distributors, warehouses, retailers, and transportation companies. **Fehler! Verweisquelle konnte nicht gefunden werden.** depicts an example of supply and value chain taken from TEEB (2018) report.



Source: TEEB (2018: 8)

Figure 1: Typical food and beverage value chain.

1.2 Modelling WEFE Resource-sensitive Value Chains in the Context of Frontier Agriculture.

The objective of D1.2 is to model WEFE resource-sensitive value chains in the context of frontier agriculture. The lead partner of D1.2 is UM6P, the deliverable is due in Month 18, i.e., by the end of October 2024. The focus is on regional/national value chain analyses and encompasses three steps:

(i) Identification of profitable frontier agricultural innovations that promote the WEFE Nexus through primary (e.g., production) and secondary (e.g., processing) activities.
(ii) Estimation of the true costs and benefits of the value added in the primary and secondary activities. This knowledge will contribute to the informed creation of environmentally friendly agri-food systems for food and nutrition security (FNS). Furthermore, the wider societal acceptance will be estimated (TCI, 2022).
(iii) The supply and value chain analysis will reveal whether there is a competitive advantage (e.g., due to higher prices) of frontier agriculture in comparison to conventional agriculture.

Data will be generated based on interviews with farmers and other actors of the value chain as well as focus group discussions (FGDs) with stakeholders along the value chains, including smallholders, processors, and retailers. The completion of D1.2 also contributes to the identification and subsequent onboarding of 84+ innovation actors – e.g., rural and urban farming-based stakeholders, including refugees, women and young adults, start-ups, and small and medium-sized enterprises (SMEs) – to the demonstration pilots at the demonstration sites.

2. Methodology

As outlined in WP1, Task 1.2, the focus is on a **regional** (national) value chain analysis of frontier agricultural products. This section gives a descriptive overview of steps to follow in a supply and value chain analysis. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the four steps commonly followed by scholars to conduct a supply and value chain analysis. It is important to note that the complexity and resource requirements, smaller businesses or teams with less expertise may find it challenging to successfully adopt this approach.

Step 1 - Selecting a sector (desk research): The first step is to choose a product/sector that is relevant to the objective of FrontAg Nexus and the policy context, especially as FrontAg Nexus also aims at reducing the policy silos related to the WEFE Nexus (WP4). The sector should be defined in terms of the final product or service and the main activities involved in its production and delivery.

Value chains include every action and service needed to take a product or service from its inception to its final sale in regional, national, international, or local markets. These value chains consist of businesses, financial, and technical service providers that serve consumers, producers, processors, and input suppliers. Supply and value chains consist of both dynamic and structural elements and their performance is determined by the dynamics of actors' behavior, which are influenced by the value chain's structure.

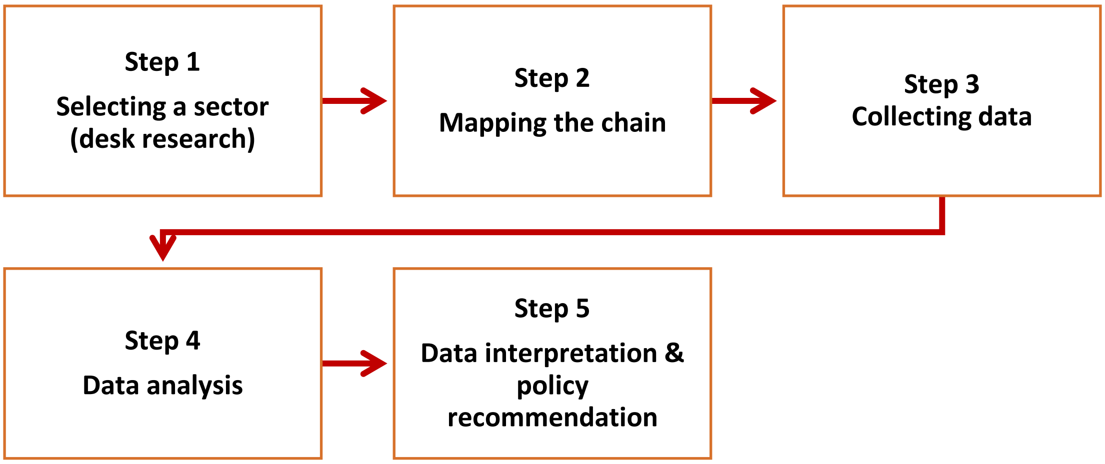


Figure 2. Steps to conduct supply and value chain.

Step 2 - Mapping the chain: The second step is to identify and describe the main actors and linkages in the value chain, both horizontally (among similar firms at the same chain level) and vertically (among firms at different chain levels, e.g., producer-processor-packaging, etc.).

Step 3 Collecting data: The third step (Fehler! Verweisquelle konnte nicht gefunden werden.) is to collect quantitative and qualitative data on the supply and value chain, using primary and secondary sources. The data should cover aspects such as the volume and value of production, trade, and consumption; the costs, revenues, and profits of different actors; the distribution of value added along the chain; the quality standards and requirements; the innovation and learning processes; and the social and environmental impacts (Figure 3). Data can be collected using:

- in-depth interviews with relevant actors in the chosen supply and value chain,
- focus group discussions (FGDs), whereby you bring together a single group or several groups of relevant actors together,
- and secondary statistics, e.g. from a national statistical office, a national farmer or processing association, or the Food and Agriculture Organization (FAO): https://www.fao.org/faostat/en/#data/QCL.

Step 4 Analyzing the results: The fourth step is to analyze, respectively to interpret the data and to draw conclusions on the dynamics of value creation and distribution in the value chain. FGDs with experts can facilitate this step. The analysis should address questions such as:

- How is value added, generated, and distributed among different actors?

- What are the sources of competitive advantages and disadvantages for different actors?
- How do governance structures affect the opportunities and constraints for upgrading?
- How do institutional factors influence the performance and outcomes of the value chain?
- How does participation in the value chain affect poverty, inequality, the environment, and innovation?

Step 5 Data interpretation & policy recommendation: The collected data should be carefully interpreted to assess the impact of frontier agricultural practices on the WEFE Nexus. This involves comparing key performance indicators (KPIs) such as resource efficiency, value creation, and environmental impact between frontier and conventional agricultural systems. The goal is to identify patterns and trends that reveal how these innovations influence resource use, production efficiency, and sustainability within the value chain. Based on these findings, policy recommendations should be made to support the wider adoption of climate-smart and water-saving practices. These recommendations will include incentives for smallholders and SMEs, as well as adjustments to regulatory frameworks that promote sustainable agriculture aligned with WEFE goals. Additionally, the findings will inform government interventions, such as financial support or subsidies, aimed at improving resource efficiency in water-scarce regions. The policy recommendations will emphasize the need for multi-stakeholder collaboration, encouraging partnerships between the private sector, non-governmental organizations (NGOs), and policymakers. Finally, the recommendations will outline next steps, including pilot projects or demonstration sites to test the policies and further refine strategies for scaling up these frontier innovations.

2.1 Agri-based Value Chain Analysis for Development (VCA4D)

A simplified version of the Value Chain Analysis for Development (VCA4D) methodological tool, developed by European Commission experts, will be used in FrontAg Nexus to analyze the supply and value chain of selected frontier agricultural products (Figure 4).

The VCA4D aims to understand to what extent the value chain improves income, enhances competitiveness, and whether it is both socially and environmentally sustainable. Thus, this approach is well suited for the WEFE Nexus focus in FrontAg Nexus. The sustainability assessment has four main components: (1) functional, (2) economic (here profitability), (3) environmental, and (4) social (Fabre et al. 2021; TCI, 2022). Figure 5 and Figure 6 show the four categories. The analysis enables decision makers with evidence-based information to support sustainable agri-food system and WEFE Nexus development strategies.

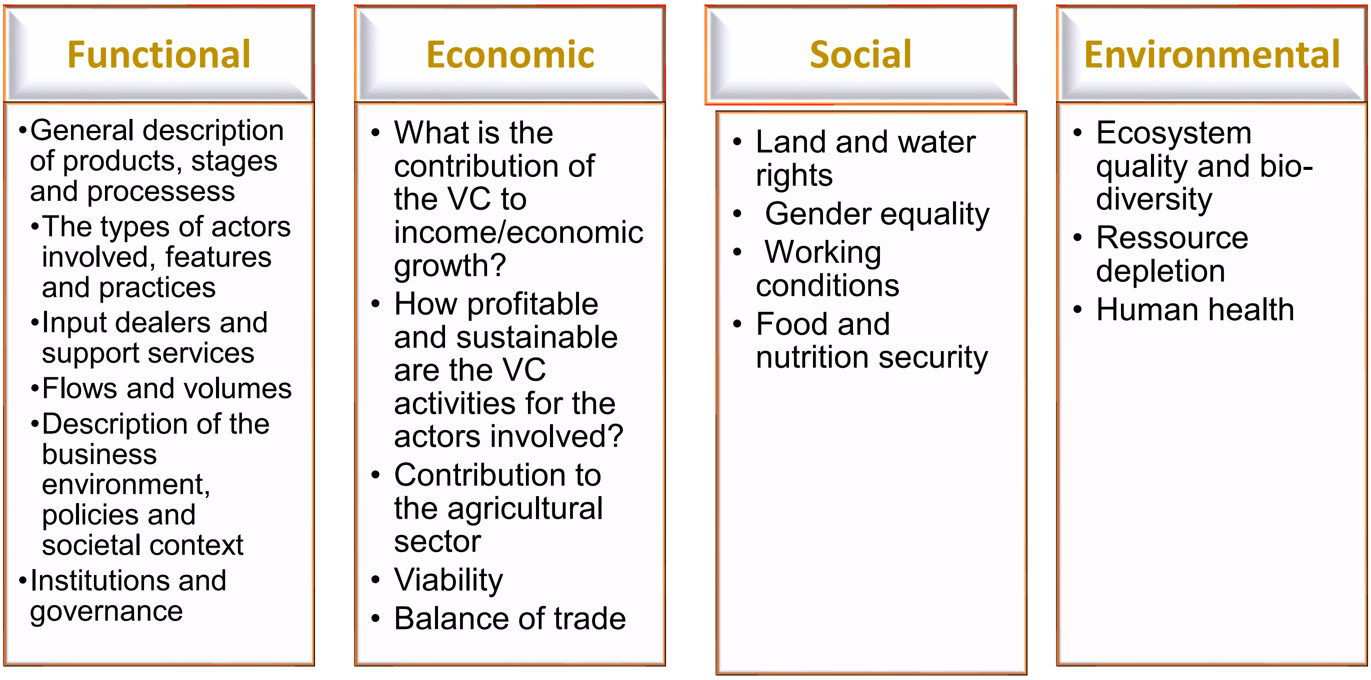
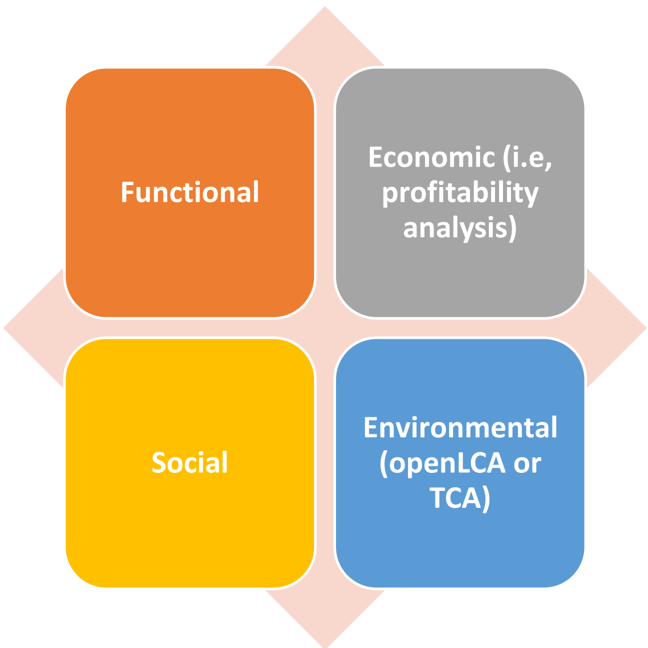


Figure 3: Analysis of the major impact categories of value chain.



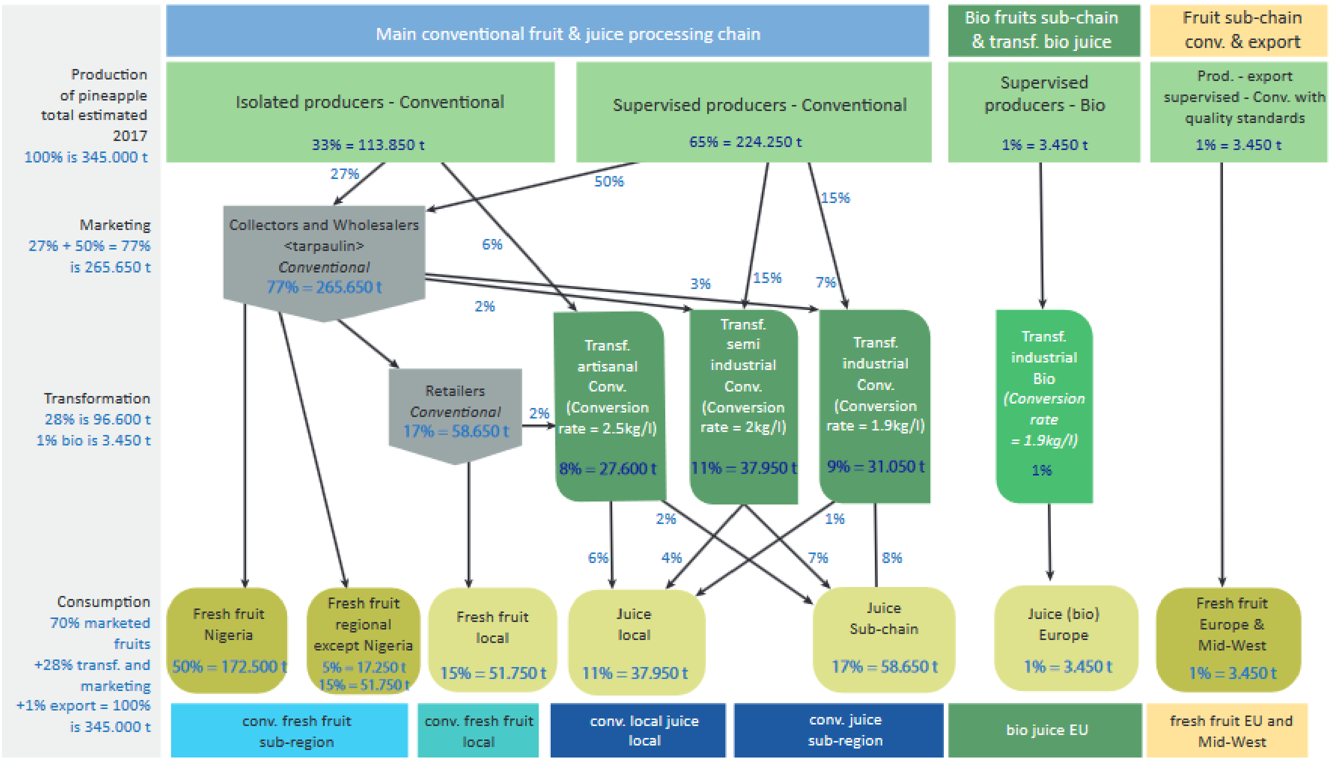
Notes: LCA = Life Cycle Assessment, TCA = True Cost Approach

Figure 4: Value Chain for Development (VC4D) analysis components.

2.2 Functional Analysis

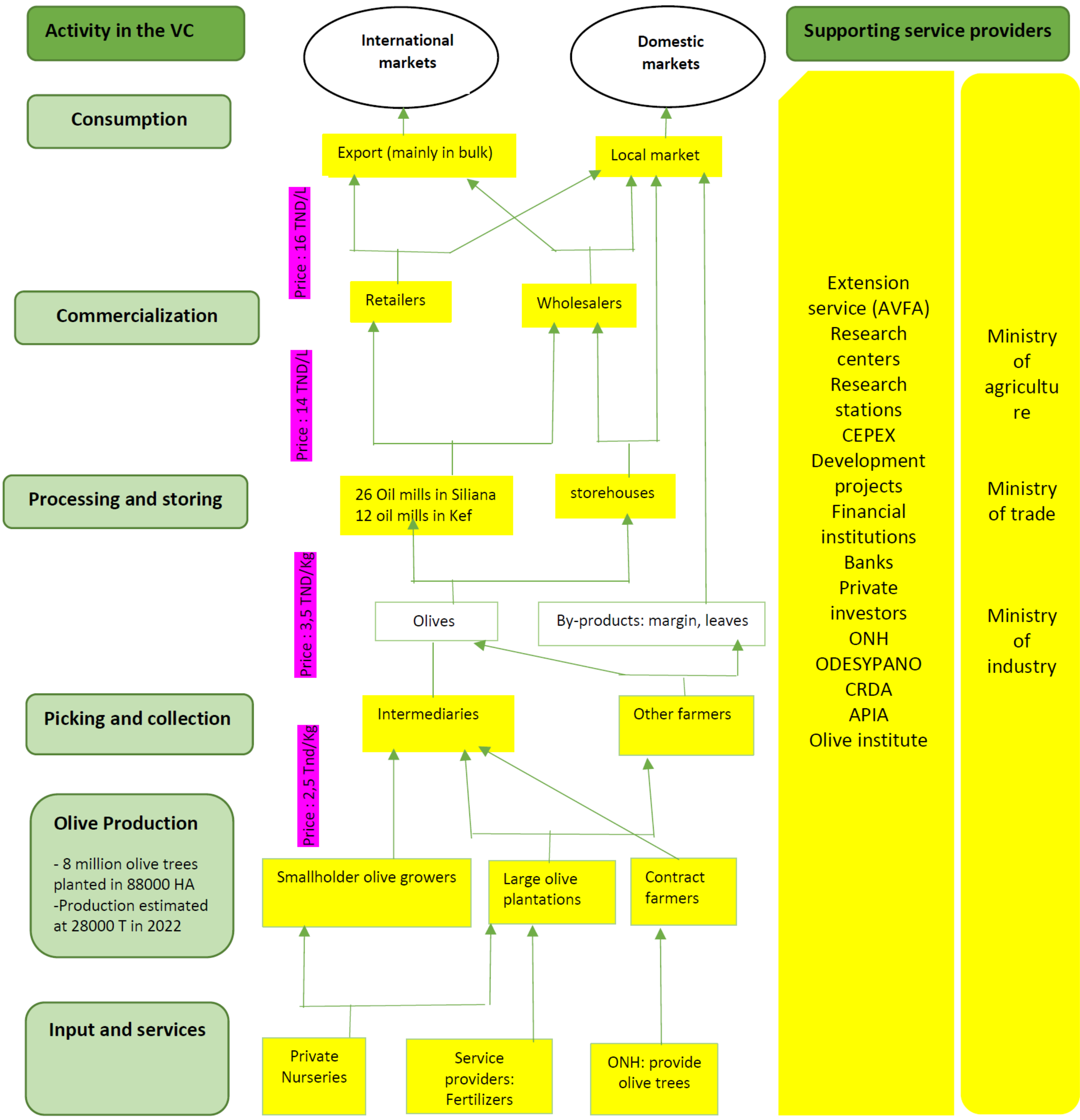
In the functional analysis, products, actors and their functions, flows, and governance are described, and a flow chart will be constructed. The functional and structural flow chart should also include the geographical scope, the governance structure, and the institutional environment of the chain (***Figure 7***).

Figure 5 (Desclee et al., 2020) and **Figure 6** (Dhehibi et al. 2023) are examples of a functional analysis conducted in Benin on pineapple and in Tunisia on olives, respectively, including the volumes moving through the chain. The two examples show that the functional depiction of a supply and value chain analysis can look very different from product to product. These graphical illustrations represent the value stream mapping (VSM) according to Taylor (2005) and contribute to identifying areas of improvement for production, processing, manufacturing, transporting, wholesaling, retailing, and waste reduction from farm to fork.



Source: Desclee et al. (2020: 1)

Figure 5. Main flows and sub-chains of pineapple producers in Benin.



Source: Dhehibi et al. (2023: 27)

Figure 6. Main flows and sub-chains of olive producers in northern Tunisia.

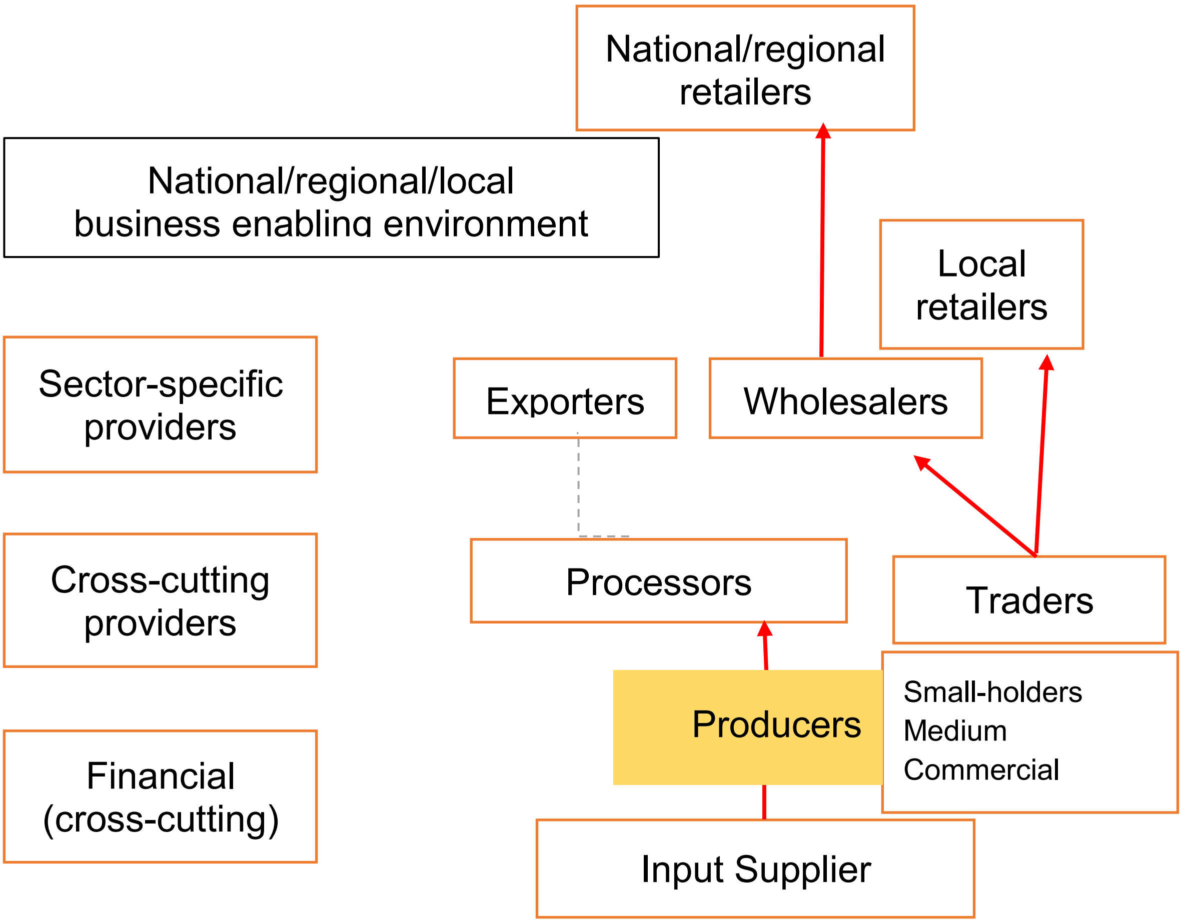


Figure 7: General functional supply and value chain depiction.

2.3 Profitability Analysis

Financial sustainability can be calculated using a benefit-cost analysis. For this, expenses, such as costs related to local and imported inputs, labor costs, and other operational costs (e.g., depreciation of investments) are set against revenues. The market value of home consumption, subsidies received directly for operations, and benefits provided to the external workforce (such as food and by-products) are all part of the profitability computation, with these benefits valued at the local market rate. The operating account (Fehler! Verweisquelle konnte nicht gefunden werden.) of each actor in the value chain builds on actual expense and revenue flows. It allows the calculation of the actor's **Operating Profit** (OP) and **Net Income**. The Excel template used to calculate profit can be downloaded here. The template was adapted from the INCiTiS-FOOD project.

Table 1. The operating account.

Expenses	Revenue
Intermediate consumption (IC) Goods and services used as inputs, e.g., seeds, fertilizer, pesticides. **Value added (VA)** • Wages and salaries [a)] • Land fees [b)] • Royalties • Financial charges (interest on loans) • Taxes on operations **Depreciation on investments** • Annual depreciation	**Production** • Sales • Home consumption **Subsidies for operations**
Gross Operating Profit (OP) = Revenue – Cost **Net income = Gross OP – Depreciation**	
Notes a) Without valuing unpaid family labor; b) In case of tenant farming, rent, sharecropping cost should be included.	

Source: Adapted from Fabre et al. (2021: 17)

While the value of paid labor is included, the value of (unpaid) family labor is not included in the costs in the profitability analysis. This indicates that the computations do not consider any so-called opportunity cost or shadow pricing associated with family labor. As a result, the resulting **operating profit (OP)** provides an accurate indicator of the actual return and sheds light on the precise income (Fehler! Verweisquelle konnte nicht gefunden werden.). It must be noted that his omission might lead to an underestimation of the actual costs and the economic contributions made by the supply chain. Unpaid family labor is not calculated as it is in the same way difficult to value. Plus, the farmer certainly has other crops/enterprises he is operating, so the profit we are calculating here is a net return for this particular crop.

The term **value added (VA)** describes what is produced by all actors within the value chain's boundaries, such as those engaged in the manufacturing, processing, transportation, or distribution of the VC-product under investigation. Value added by all actors within the value chain's boundaries is termed **Direct[1] VA**. Conversely, the VA by actors external to the supply and value chain, who provide intermediate goods and services to chain actors but do

[1] Direct actors are those who are directly involved in the processes of bring the product from production to consumption, i.e. those who take ownership and possession of the product.

not handle or process the chain product under investigation, is termed **Indirect VA**[2]. The total of direct and indirect VA is termed **Total VA**:

Total VA = Direct VA (VC actors) + Indirect VA (suppliers external to the VC)

Fehler! Verweisquelle konnte nicht gefunden werden. shows an exemplary computation of the direct and indirect VA by Coote et al. (2019).

Table 2. Example of an operating account for the whole vanilla value chain.

	IC in VC	IC off VC	Total IC	Taxes	Wages	Financial costs	Capital depreciation	Net Operating profits	Total ValueAdded
Small-scale vine-owning households	0	1 869 808,0	1 869 808,0	0,0	0,0	0,0	0,0	42 080 192,0	42 080 192,0
Medium-scale vine-owning households	0	4 257 582,0	4 257 582,0	0,0	615 060,0	0,0	0,0	51 897 358,0	52 512 418,0
Large scale vine-owning households	0	5 187 701,0	5 187 701,0	0,0	762 150,0	0,0	0,0	69 820 149,0	70 582 299,0
Cross-border traders	48 015 000,0	2 754 170,0	50 769 170,0	5 871 500,8	0,0	0,0	0,0	1 564 329,2	7 435 830,0
Medium-scale traders	28 635 000,0	1 634 000,0	30 269 000,0	3 691 620,0	28 800,0	0,0	245 200,0	1 660 380,0	5 626 000,0
Large -scale exporter	112 380 000,0	2 748 100,0	115 128 100,0	15 641 080,0	1 160 000,0	15 000,0	258 750,0	21 737 070,0	38 811 900,0
Total		**18 451 361,0**	**207 481 361,0**	**25 204 200,8**	**2 566 010,0**	**15 000,0**	**503 950,0**	**188 759 478,2**	**217 048 639,0**
VC production (PGK) (IC off VC + Total Value Added)	235 500 000,0								

Notes: IC = intermediate commodity, e.g., input costs
Source: Coote et al. (2019: 68)

2.4 Social Impact Analysis

According to the VC4D framework, the analysis of social sustainability focuses on assessing established and potential consequences of the supply and value chain operations in an array of six indicators.

- Working Conditions
- Land and Water Rights
- Gender Equality
- Food and Nutrition Security
- Social Capital, and Living Conditions

The data required for the social sustainability analysis is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

[2] Indirect actors are those who have an influence on the value chain, but who so not take direct ownership and possession of the product. External influences that impact on the value chain include economic, environmental and socio-cultural forces.

Table 3. Measurement indicators of the social sustainability analysis.

1. Working conditions • Respect for labor rights • Child labor • Job safety • Job safety • attractiveness	**4. Food and Nutrition Security** • Availability • Accessibility • Utilization • Stability
2. Land and water rights • Equity • Compensation • Land tenure	**5. Social capital** • Membership in organizations • Information availability
3. Gender equality • Gender pay gap • Decision-making power • Access to resources & service • Leadership	**6. Living Conditions** • Health services • Housing • Education and training

Source: Adapted from Fabre et al. (2021: 29) and TCI (2021)

Questions to be asked to assess whether the value chain is socially sustainable follow Fabre et al. (2021: 31). The answer is based on a categoric system (**Tick:** not at all moderately/low substantially high), a so-called social profile radar (**Fehler! Verweisquelle konnte nicht gefunden werden.**) can be depicted. In the following, the 6 dimensions of social impact and relevant questions are summarized.

Working conditions (Main themes: respect of international norms; respect of contracts; risk of discrimination and forced labor; job safety; child labor and education):

Are working conditions throughout the VC *[add here the name of your chain, e.g. strawberry, etc.]* socially acceptable and sustainable?

Tick: not at all moderately/low substantially high

Do VC operations in [*e.g. strawberry, etc.*] contribute to improving working conditions?

Tick: not at all moderately/low substantially high

Land and water rights (Main themes: equity and security of access to land/water resources; transparency of procedures, e.g. to register land; arbitration procedures in case of resource conflicts; compensation procedures in case of unjust use or destruction of a natural resource):

Are the land rights implemented throughout the VC *[e.g. strawberry, etc.]* socially acceptable and sustainable??

Tick: not at all moderately/low substantially high

Are the water rights implemented throughout the VC *[e.g. strawberry, etc.]* socially acceptable and sustainable??

Tick: not at all ☐ moderately/low ☐ substantially ☐ high

Gender equality (Main themes: inclusion/exclusion of women/vulnerable groups in certain activities; access to resources, goods and services related to land, credit, extension services, inputs, etc.; participation in decision-making, e.g., regarding income; responsibility and empowerment in collective processes; arduous working conditions):

Based on your perception, what percentage of the

- farm labor on of [*e.g. strawberry production, etc.*] is constituted by women: ___ %
- labor in processing of [*e.g. strawberry production, etc.*] is constituted by women: ___ %
- labor in marketing (retailing) of [*e.g. strawberry production, etc.*] is constituted by women: ___ %

Throughout the VC *[e.g. strawberry, etc.]*, do actors foster and put into practice gender equality?

Tick: not at all ☐ moderately/low ☐ substantially ☐ high

Food and nutrition security (Main themes: contribution of the VC to the availability, accessibility and stability of food resources; food diversification; nutritional quality; price instability):

Do VC activities *[e.g. strawberry, etc.]*, contribute to upgrading and securing the food and nutrition conditions?

Tick: not at all ☐ moderately/low ☐ substantially ☐ high

Social capital (Main themes: Strength and representativeness of producers' organizations; information sharing, e.g. among producer organizations or with the extension service; level of trust among actors; participation in decisions and community activities; taking traditional practices into account):

Is social capital enhanced by VC operations and equitably distributed throughout the VC on *[e.g. strawberry, etc.]*?

Tick: not at all ☐ moderately/low ☐ substantially ☐ high

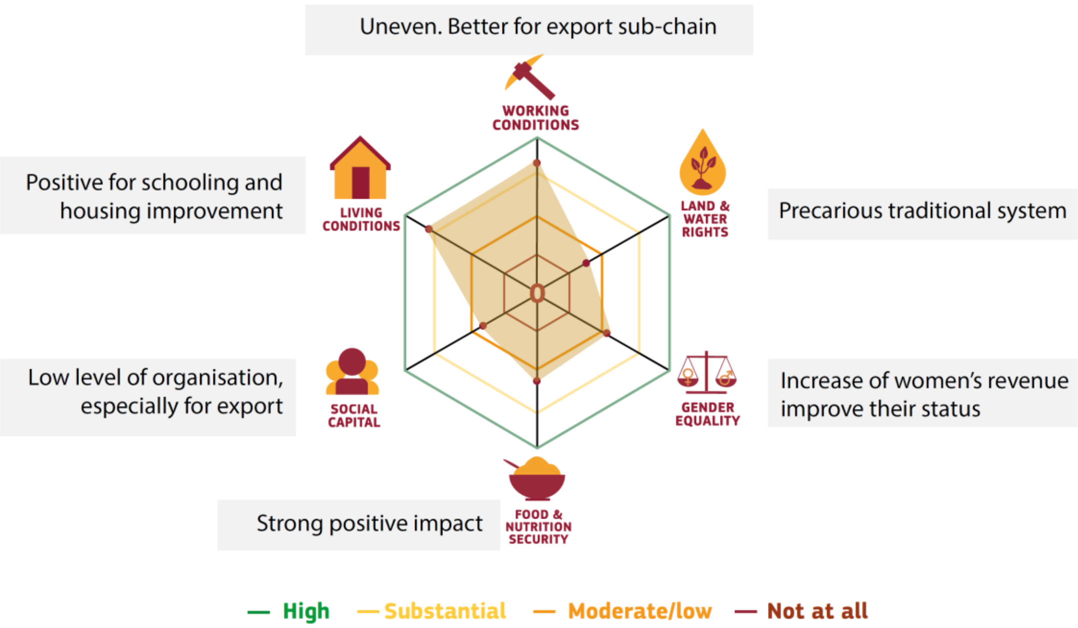
Living conditions (Main themes: Access to facilities and services: health, education, training, housing, water, and sanitation; quality of these infrastructures):

Are the general living conditions (i.e., better access to health services, education, improved housing) of the laborers in the production of [*e.g. strawberry, etc.*] and along the value chain improving?

Tick: not at all □ moderately/low □ substantially □ high

Do the VC activities of [*e.g. strawberry, etc.*] contribute to improving the living conditions of the actors through acceptable facilities and services?

Tick: not at all □ moderately/low □ substantially □ high



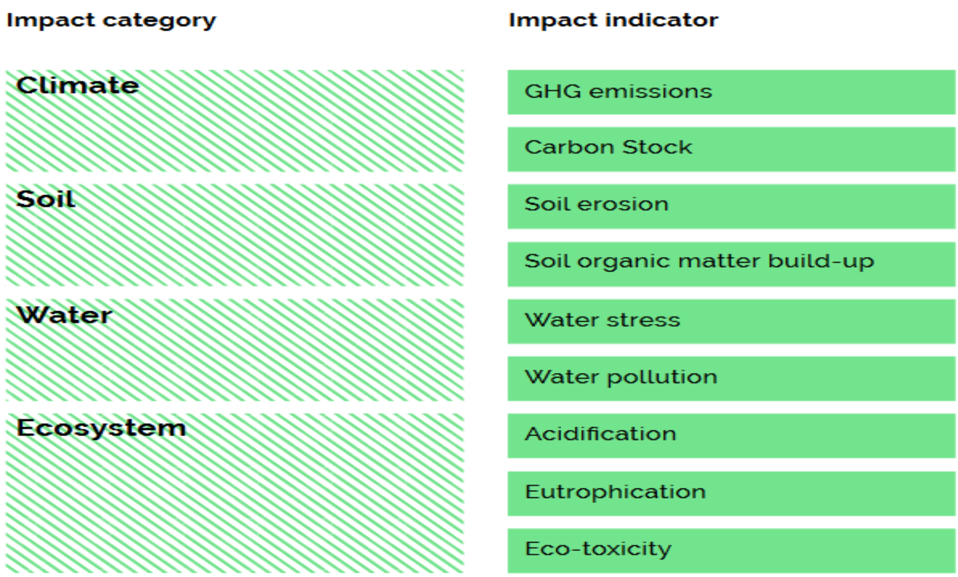
Source: Adapted from Fabre et al. (2021: 31)

Figure 8. Example of a social profile radar as part of the social impact analysis.

The social impact of business activities within the supply and value chain is a crucial consideration, which includes aspects such as living standard, gender equality, and working conditions. Nevertheless, conventional supply and value chain analysis approaches usually restrict their emphasis on economic sustainability. These tools can reveal operational and strategic inconsistencies, but they frequently ignore the social facets of sustainability that are essential for long-term value generation. A paradigm shift in both, thinking and scientific techniques is required to get past these constraints. The VC4D approach is more inclusive, comprehensive, and holistic. This might entail using new and varied data sources, increasing stakeholder participation throughout the value chain, and creating sophisticated analytical tools that are more adept at navigating and dissecting the subtleties of cross-cultural social dynamics and their collateral impacts.

2.5 Environmental Impact Analysis

The environmental analysis is primarily concerned with resource depletion, ecosystem quality, biodiversity, and human health risks and their interaction with climate change. The analysis takes both qualitative and quantitative approaches for the environmental value chain analysis. While quantitative approaches involve numerical analysis, such as measuring emissions, energy consumption, and other measurable environmental aspects, qualitative methods use non-numerical analysis, such as expert views, descriptions, and categorizations of environmental consequences. The most common tool used to analyze the environmental impact of production is the Life Cycle Assessment (LCA) accompanied by an exploratory assessment of biodiversity risks. The LCA was used for the environmental impact analysis of tomatoes in Morocco (Chapter 5). Another approach for assessing the environmental impact is the True Cost Approach (TCA), which was used for the environmental impact analysis of the value chains in Israel (Chapter 3) and in Tunisa (Chapter 6). The environmental impact analysis of the insect farming case in Italy (Chapter 4) is limited to a qualitative one, due to lack of data. The reason for this was that the environmental impact analysis for the tomato value chain in Morocco was done within the framework of a Master thesis (see Footnote 4). **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the main indicators used to measure the environmental impact assessment of a value chain.



Source: TCI (2022: 23)

Figure 9. Environmental impact indicators.

2.5.1 Important LCA Resources

To estimate the environmental impact, open-access software packages are available.[3] These are:

OpenLCA: A free LCA (environmental sustainability) modeling software used by academics and businesses all over the world.

OpenLCA data: https://www.openlca.org/lca-data/

There are quick and important background reading materials on the VC4D methodology and sample case studies to be found **here**.

2.5.2 The True Cost Accounting Approach (TCA)

The True Cost Approach (TCA) proposed by the True Cost Initiative (TCI, 2022) has been applied to evaluate the environmental cost-benefit of agri-food production. The TCA methodology accounts for the negative impacts induced by agri-food production activities. In this framework, only two indicators—'carbon stock' and 'soil organic matter buildup'—are considered to account for positive impacts (i.e., long-term carbon sequestration in agricultural soil and trees). For all other indicators, no positive effects are recognized, as they either do not exist or result in negative externalities affecting human health and social costs (TCI, 2022). This approach focuses primarily on the monetization of externalities within the context of TCA methodology, as outlined by The Economics of Ecosystems, Biodiversity, and Economics Foundations (TEEB, 2018).

This approach fulfills four important requirements concerning the impact of externalities on environmental, social, and human health (TCI, 2022):

1. It is compatible with Life Cycle Assessment (LCA) methodologies, as seen in LCA software such as SimaPro and Open LCA.
2. It measures environmental externalities and has the potential to value social and human externalities.
3. It is pragmatic, requiring no extensive knowledge of impact pathways.
4. It is transparent, relying on readily available data and valuation based on the marginal prevention costs of best practice techniques (end-of-pipe or system integrated).

The TCA is based on the marginal prevention (abatement) cost approach, fulfilling the aforementioned requirements regarding the impact of externalities on environmental, social, and human health (TCI, 2022). The marginal emission abatement costs refer to the costs per unit of emission that are required to contain a negative impact to a defined negligible effect.

The TCA outlines three main impact indicators: natural capital, human impact, and social impact. The environmental impact assessment focuses on the natural capital indicator,

[3] SimaPro is a licensed software but free to academic users from developing countries.

which is divided into four key subcategories: climate, soil, water, and ecosystem impacts. The impact indicators for these sub-categories are summarized in Table 4. The cells highlighted in red indicate areas that were not covered. Nine impact categories are considered to analyze the environmental impact: GHG emissions, carbon stock, erosion, soil organic carbon build-up, water stress, water pollution, acidification, eutrophication, and eco-toxicity.

Table 4. Impact indicators and required data for environmental impact assessment based on the True Cost Approach.

Category	Impact indicator	Data required	Level
Climate	GHG emissions	Yield, fertilizer use, crop protection, energy use, land use changes, crop residue management, tillage and green manure	Cultivation
		Energy use	Processing
		Fuel combustion	Storage & transport
	Carbon stock	Land use changes, crop residue, management, changes in tillage and/or green manure, management, changes in tillage and/or green manure, use, organic fertilization	Cultivation
Soil	Erosion	Slope, precipitation, soil erosion prevention management	Cultivation
	Soil organic carbon build-up	Land use changes, crop residue management, changes in tillage and/or green manure use, organic fertilization	Cultivation
Water	Water Stress	Location, crop, irrigation (yes/no)	Cultivation
	Water Pollution	Fertilizer application in units N and P	Cultivation
Ecosystem	Acidification	Fuel use, fertilizer use, crop protection uses	Cultivation
		Fuel use, material use	Processing
		Fuel use	Storage & transport
	Eutrophication	Fuel use, fertilizer use, crop protection uses	Cultivation
		Fuel use, material/substance use	Processing
	Eco-toxicity	Crop protection use	Cultivation
		Energy use, material use	Processing

Source: Adapted from TCI (2022).

3. Value chain analysis of fish in aquaponics and RAS, BGU (P4), Israel

3.1 Functional Analysis

A comprehensive functional analysis of the value chain of fish in Israel focuses on two species: Tilapia and Barramundi. These species were selected due to their popularity among Israeli consumers, rapid growth rates, and status as kosher food. The analysis encompasses the various stages of the value chain, from input supply to final consumption, highlighting key activities, actors, and governance structures. This analysis also incorporates data from previous studies and published papers to provide a detailed overview of the value chain (see ***Figure 10***).

Species and production. Tilapia (*Oreochromis* spp.) is known for its adaptability to diverse water conditions and rapid growth rates, accounting for 38% of Israel's aquaculture production in 2022. The annual production of Tilapia in Israel is approximately 2 kilo tons. Barramundi (*Lates calcarifer*), valued for its high-quality meat and fast growth, is steadily increasing in production due to high export demand, with an annual production of about 0.5 tons (Sharon, 2023).

Types of producers. Small producers, typically family-run fish farms less than 2 hectares in size, primarily serve local markets and often face challenges such as limited access to advanced technologies and financial resources. In Israel, small-scale producers account for about 25% of total fish production (FAO, 2011). In contrast, large-scale producers are commercial enterprises with extensive operations, often spanning over 10 hectares, catering to both domestic and international markets. These large producers benefit from economies of scale, allowing for more efficient production and distribution processes. Large-scale operations contribute most to domestic fish production. Both small- and large-scale operations are considered commercial producers, driven by market demands and profitability, adapting their practices to maximize profits. Most producers use conventional methods, including commercial feed and regular health management practices, ensuring consistent production outputs and meeting market demand. A niche market segment comprises organic producers who focus on organic practices, avoiding synthetic inputs and emphasizing sustainability. This segment caters to a growing demand that prioritizes environmental sustainability and health-conscious products.

Processing. The processing of fish in Israel is carried out by a mix of artisanal, semi-industrial, and industrial processors. Artisanal processors, mainly serving local markets, use traditional methods involving manual labor and small batch production, preserving traditional techniques. Artisanal processing contributes to about 23% of the processed fish market. Semi-industrial processors, combining modern technologies with traditional methods, operate on a medium scale with advanced processing techniques and broader distribution channels. Large-scale industrial processors utilize automated systems and advanced machinery to handle large quantities of fish, ensuring uniformity and high standards. Industrial processors dominate the market with a 56% share (Kimhi, 2024).

Governance structure. The governance structure within the value chain includes contract farming, this contract is prevalent among small-scale producers. Contract farming ensures stable markets through agreements specifying quantity, quality, and price, providing security for producers and enabling them to plan production and investments with greater certainty. Approximately 10% of small producers engage in contract farming agreements.

Yield estimates and farm gate prices. Yield estimates in intensive farming systems indicate that Tilapia can produce 50-80 kg per cubic meter, while barramundi yields can range from 30-50 kg per cubic meter under optimal conditions (Timmons, 2018). The average yield for Tilapia in Israel is 30-80 kg per cubic meter, while barramundi achieves around 25-50 kg per cubic meter. Farm gate prices average $4.50 per kilogram for Tilapia and $8.00 per kilogram for Barramundi, with variations depending on market conditions and production costs (Sharon, 2023).

Detailed description of value chain stages. The first stage involves the provision of essential inputs and technology for aquaculture. Hatcheries supply fish fry, while feed manufacturers provide specialized aqua feed formulated for the nutritional needs of Tilapia and Barramundi. Biotechnology tools, such as selective breeding and genetic enhancements, are employed to improve growth rates, disease resistance, and overall fish health. Research indicates that the use of advanced biotechnology can increase productivity by up to 10-35% (FAO, 2024a).

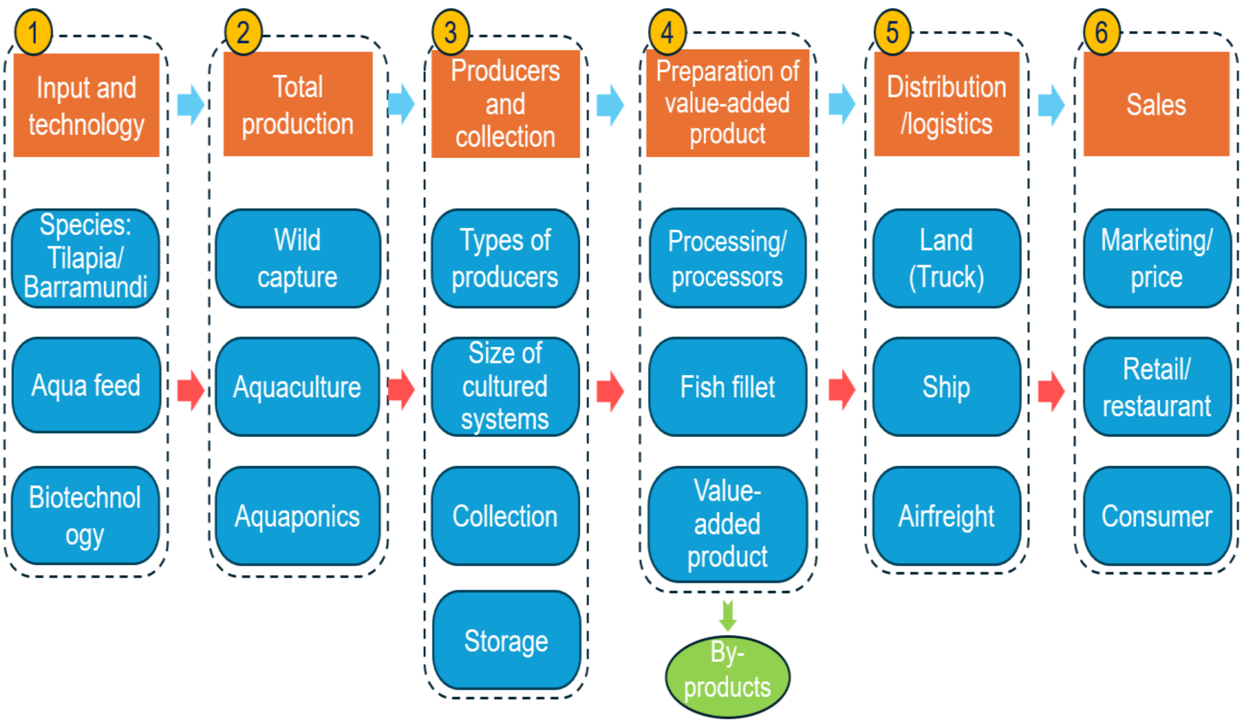


Figure 10. Main flows and sub-chains of fish in Israel.

In the total production stage, fish are either captured from the wild or produced through aquaculture and aquaponics systems. Aquaculture is the dominant method in Israel due to its ability to control environmental factors and optimize production. The adoption of recirculating aquaculture systems (RAS) has significantly enhanced water use efficiency, which is crucial in arid regions. Approximately 70% of aquaculture operations in Israel use RAS to conserve water (FAO, 2011).

The production stage involves various types of producers, ranging from small family-run farms to large commercial enterprises. The size of cultured systems varies, with some employing extensive aquaculture practices and others using intensive methods. After harvesting, fish are collected and stored appropriately to maintain their quality until they reach the processing facilities. Efficient storage and collection practices can significantly reduce post-harvest losses by up to 20%.

Processing involves cleaning, filleting, and packaging the fish, with facilities adhering to health and safety standards. Artisanal processors focus on traditional methods, semi-industrial processors employ advanced techniques, and industrial processors handle large volumes. By-products from processing, such as fish oil and meal, are also utilized, adding economic value. Value-added products can increase the market value by up to 50% (Kimhi, 2024).

Processed fish are transported to markets through various logistics channels, including land (trucks), sea (ships), and air (airfreight). Cold chain management is critical during this stage to ensure the fish remain fresh until they reach retailers or export markets. Maintaining an efficient cold chain can extend the shelf life of fish products by up to 5 days. The final stage involves marketing and selling the fish through supermarkets, fish markets, and online platforms. Retail operations comply with standards and consumer protection laws, ensuring product quality and safety. The fish are then purchased and consumed by households, restaurants, or institutions. Effective marketing strategies can boost sales by 20-30%.

Vertical integration is common in large-scale operations, ensuring efficiency and quality control across multiple stages of the value chain. Horizontal collaboration through cooperatives enhances bargaining power and resource sharing among small-scale producers. Regulatory oversight by government agencies ensures compliance with production standards, health and safety regulations, and environmental monitoring. NGOs and research institutions support sustainable aquaculture practices through training, resources, and technological advancements. Regulatory frameworks are critical in maintaining sustainable aquaculture practices.

3.2 Profitability Analysis of Aquaponics at BGU

In the value chain of Tilapia and Barramundi production in Israel, profitability is a crucial metric to assess the financial sustainability of operations. This analysis applies a benefit-cost framework to calculate financial sustainability by setting operating expenses against revenue streams from production. The operating profit and net income of actors within the value chain are computed based on actual expense and revenue flows, as shown in Table 1.

Cost Components. Aquaculture production incurs several types of expenses, including intermediate consumption (IC) costs, labor, and marketing costs. **Table 5** outlines the various expenses incurred by a typical fish farming operation in Israel. Intermediate consumption includes:

- **Fingerlings:** The initial investment in fish fry for Tilapia and Barramundi is 634€ annually, ensuring a consistent production base.
- **Seedlings:** For integrated systems (e.g., aquaponics with lettuce), the cost of seedlings amounts to 1165€ annually.
- **Fish feed:** A significant cost component, fish feed amounts to 5216€ per year, as high-quality feed is essential to maximize fish growth and health.
- **Nutrient additions and micronutrients:** These are essential for plant growth in aquaponic systems and ensure nutrient balance in water. The cost for these inputs totals 12,354€ (11,459€ for nutrients and 903€ for micronutrients).
- **Electricity and water:** Efficient water and energy use are crucial for aquaculture, especially in Recirculating Aquaculture Systems (RAS). The electricity cost of 12,675€ and water cost of 328€ are typical for intensive aquaculture systems in arid regions.
- **Consumables and lab costs:** These costs amount to 3220€ annually, covering routine expenses for fish farm operations.
- **Transport, maintenance, and marketing:** The cost of transporting fingerlings (8280€€) and seedlings (2760€) is crucial for securing the initial stock. Maintenance costs of 7360€, bookkeeping expenses of 1311€, insurance of 506€, and marketing expenses of 13,248€ are other significant operational costs.
- **Expert consultancy (5 years only):** The 13,800€ allocated for expert consultation (if necessary) ensures technical guidance in the initial phase of the operation.
- Overall, the **total annual costs total 84,680€** for the entire system, including fish and plant production.

Revenue Components. The revenue streams are based on fish and lettuce production, with mean prices and production quantities:

- Fish production: With an annual output of 4,362 kg of fish (primarily Tilapia and Barramundi) at a mean price of 5€ per kilogram, fish production generates 20,015€ in revenue.
- Lettuce production: Lettuce, cultivated in the integrated aquaponics system, yields 196,476 kg annually, which, at 1€ per kilogram, results in 214,650€ in revenue.
- Thus, the **total annual revenues from both fish and plant production is 234,665€**.

Operating Profit (OP). By comparing the total expenses with the total revenue, the operating profit can be calculated. Without factoring in expert consultation costs (which apply for only five years), the annual profit of operating the aquaponics system is 58,906€. If the expert's fee is included, the operating profit is reduced to 45,106€. This illustrates that the profitability of aquaculture operations can vary significantly based on the need for external technical support and other variable costs.

Value Added (VA). The analysis also considers additional worker wages and family income, contributing to the overall value-added component. The total annual wages for additional workers amount to 77,280€, and the family income from the operation is 27,600€, summing up to 104,880€ in total value added.

The profitability of fish and lettuce production in Israel, as depicted in this value chain, is robust, with potential for higher profit margins under optimized conditions. Key factors affecting profitability include input costs (especially feed and electricity), expert consultation, and the scale of production. Producers who can operate without reliance on external experts in later phases and minimize costs through efficient energy use or integrated farming systems (e.g., aquaponics) can significantly increase their margins.

Table 5. The operating account of aquaponic value chain analysis, BGU, Israel.

Expenses	Yearly € Costs		Kg/year and head/year	Mean price	Annual revenue in €
Intermediate consumption (IC)		Production			
Fingerlings	634 €	**Fish**	4362 kg	5 €	20,015 €
Seedlings	1,165 €	**Lettuce**	196476 heads	1 €	214,650 €
Fish feed	5,216 €			SUM	234,665 €
Nutrient addition	11,450 €				
Micronutrients	903 €				
Electricity	12,657 €				
Water	328 €				
Consumables	3,220 €				
Lab	1,840 €				
Transport fingerlings	8,280 €				
Transport seedlings	2,760 €				
Maintenance	7,360 €				
Bookkeeping and account	1,311 €				
Insurance	506 €				
Expert (5 years only)	13,800 €				
Marketing	13,248 €				
SUM	84,680 €	70,880 €			
Value added (VA)					
Additional worker wage	77,280 €				
Family income	27,600 €				
SUM	84,680 €				
-------------------------------------		without expert			
Operating Profit (OP)* **	45,106 €	58,906 €			

3.3 Economic Analysis

The value chain of Tilapia and Barramundi production in Israel contributes significantly to the national economy, with a positive financial return for actors. As seen in ***Table 5***, net income remains positive, with an operating profit of 45,106€, confirming the financial viability of the value chain. Aquaculture contributes approximately 1% to Israel's agricultural gross domestic product (GDP), with Tilapia and Barramundi accounting for around 0.2%. The sector includes around 10 producers, with roughly 200 workers involved across production, processing, transport, and retail. Upstream and downstream activities engage an estimated 50 and 80 workers, respectively, underscoring the sector's role in job creation and its economic importance to the agriculture industry.

3.4 Social Impact Analysis

Aquaponics, as an emerging agri-food technology, has not yet been widely adopted in Israel. As a result, conducting a comprehensive social impact analysis at this stage is not feasible due to the lack of relevant data and societal integration.

3.5 Environmental Impact Analysis of Aquaponics and Conventional Aquaculture Systems

The primary objective of this analysis is to evaluate the environmental impact of aquaponics, an emerging climate-smart, water-saving technology with significant environmental benefits. Specifically, we applied the True Cost approach (TCI, 2022) to compare the environmental performance of aquaponics with separate Recirculating Aquaculture Systems (RAS) and conventional lettuce production, assessing the entire process from cradle to farm gate, including transportation to retailers.

Data for the aquaponics system was collected at the BGU experimental lab established as [art of the FrontAg Nexus project, covering one full year of fish and lettuce production from November 2023 to June 2024. Annual yields were 2,000 kg of lettuce and 750 kg of fish, produced within a 15 m² aquaponic system.

The environmental impact categories considered in this analysis include climate, soil, water, and ecosystem health. Impact indicators not covered in this analysis are highlighted in red (see ***Table 4***). The nine impact indicators assessed include GHG emissions, carbon stock, erosion, soil organic carbon (SOC) buildup, water stress, water pollution, acidification, eutrophication, and ecotoxicity. For more details refer to **Section 2.5.2**.

The functional unit (FU) is defined as 1 kg of marketable-quality lettuce and 1 kg of fish, harvested at the farm gate in 2024. The system boundary spans from cradle to gate (see **Figure 11**).

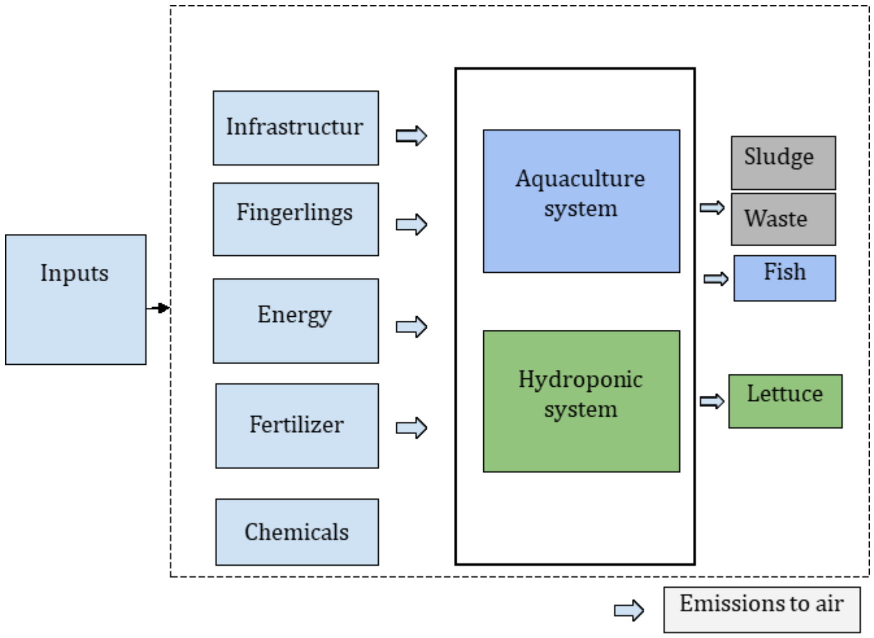


Figure 11. The system boundary, fish and lettuce value chain, BGU, Israel.

Results. The environmental impact analysis relies on data from the BGU experimental farm, considering a one-year harvest cycle (cultivation from November 2023 to June 2024). Lettuce undergoes multiple growing cycles, though only one cycle was used in the analysis for fish production. The aquaponics area under study is 15 m², while data for Recirculating Aquaculture Systems (RAS) and open-field lettuce production were drawn from secondary literature. In cases where data specific to Israel or similar agro-ecological zones were unavailable, average emissions were used.

The results reveal that aquaponics has the lowest environmental impact in most categories compared to RAS and open-field (OF) systems. This result aligns with other studies (Ravani et al., 2024; Greenfeld et al., 2021). This is anticipated, as aquaponics avoids the use of chemical fertilizers, pesticides, and other agrochemicals (Peng Chen et al., 2020). However, energy consumption is significantly higher in aquaponics relative to the other systems.

The true cost calculation. The true cost approach (TCA) provides the procedures to estimate environmental impact indicators across the three impact categories, along with monetization factors that represent the actual potential externalities of ari-food production systems. The impact of the different production systems was calculated using nine impact factors according to the TCA. True costs for each category were calculated as follows:

$$TC_{ic} = \textit{emissions per kg x monetization factor}$$

The total true cost for each system is the sum of all true costs across the impact categories:

$$TC_{total} = TC_{ghg} + TC_{cs} + TC_{se} + TC_{soc} + TC_{ws} + TC_{wp} + TC_{ac} + TC_{eu} + TC_{ec}$$

Where:

- ∉ TC_{total} = total true cost
- ∉ TC_{ghg} = true cost of green house gas emission
- ∉ TC_{cs} = true cost of carbon stock
- ∉ TC_{se} = true cost of soil erosion
- ∉ TC_{soc} = true cost of soil organic carbon build up
- ∉ TC_{ws} = true cost of water stress
- ∉ TC_{wp} = true cost of water pollution
- ∉ TC_{ac} = true cost of acidification
- ∉ TC_{eu} = true cost of eutrophication
- ∉ TC_{ec} = true cost of ecotoxicity

The results indicate that the aquaponics system demonstrates the lowest emissions in all impact categories, except for water stress (see **Table 6**). The high-water stress values in aquaponics are attributed to the system's operation in a dry climate with substantial water scarcity. Additionally, aquaponics has a positive carbon stock contribution, enhancing environmental sustainability by accounting for the opportunity cost of land disturbance that would otherwise release carbon.

The true costs of each environmental impact indicator are considered in this analysis as shown in **Table 6**. The costs of aquaponics (3.00€) are the lowest with 3.00€, followed by 9.50 for open field lettuce and 11.00€ for RAS.

Table 6. True cost estimation of aquaponic, RAS and greenhouse in soil lettuce, BGU, Israel.

Impact indicator	Monetisation factor (at base year)	Aquaponics kg CO_2 e 1kg fish + 1 lettuce		RAS kg CO_2 e (per 1kf fish)		Source	CL kg CO_2 e (per 1kg of lettuce)		Source
		Emissions	TC	Emissions	TC		Emissions	TC	
GHG emissions	116 EUR/tonne CO_2eq	2.00	0.23	3.50	0.41	Jones et al (2022)	0.70	0.08	Emery & Brown (201)
Carbon stock	±116 EUR/tonne CO_2 eq	-3.00	-3.48						
Soil erosion	27.38 USD/tonne soil	na	na	na	-		nd		
SOC build-up	±100 EUR/tonne SOC emission or build-up		0	0.001		Waller (2024)	1.70	0.17	Wang et al. (2024)
Water stress	1 EUR/m^3 of water use	0.1	4.0	1.50	0.15	Jones et al. (2022)	0.25	0.25	(Emery & Brown, 2016)
Water pollution	4.70 EUR/kg PO_4eq	0	0	0.05	0.05	Greenfeld et al. (2021)	0.05	0.23	*Eutrophying Emissions per Kilogram of Food Product*, n.d
Acidification	8.75 EUR/kg SO_2eq	0	0	0.10	0.47	Waller (2024)	0.2	1.75	Wang et al. (2024)
Eutrophication	4.70 EUR/kg PO_4eq	0.01	0.05	0.05	0.445	Emery & Brown (2016)	0.05	0.23	*Eutrophying Emissions per Kilogram of Food Product*, n.d
Eco-toxicity	340 EUR/kg Cu eq	0.006	2.04	**0.02**	0.09	Ravani et al. (2024)	**0.02**	6.8	(Emery & Brown, 2016)
Total true cost in €			**3.14€**		**11.00€**			**9.50e**	

Notes: SOC = Soil organic carbon; TC = True costs; Notes: RAS = Recirculating aquaculture systems, OF = Open field

4. Value chain analysis of insects, UNIBO (P5), Italy

4.1. Functional Analysis

This value chain analyses the farming of the insect *Galleria mellonella* (aka. greater wax moth or honeycomb moth) production in Italy and aims to identify and describe the main steps in the value chain, from the supply of insect feed to the end use of the insects as feed. The data to develop the value chain analysis have been retrieved online, from interviews and articles.

Species and production. The *G. mellonella* or honey mealworm is an insect rich in proteins and lipids which make mealworms an essential supplement in the diet of domestic and farm animals. Its production is not very common in Italy, given the novelty of insect farming, and cases of commercialization are mainly linked to hobby use (e.g. to feed domestic reptiles, bait for sport fishing). However, enormous potential is linked to improving the nutrition of farm animals such as chickens or fish, and some companies in Italy are already starting to move in this direction (Italian Cricket Farm, 2024).

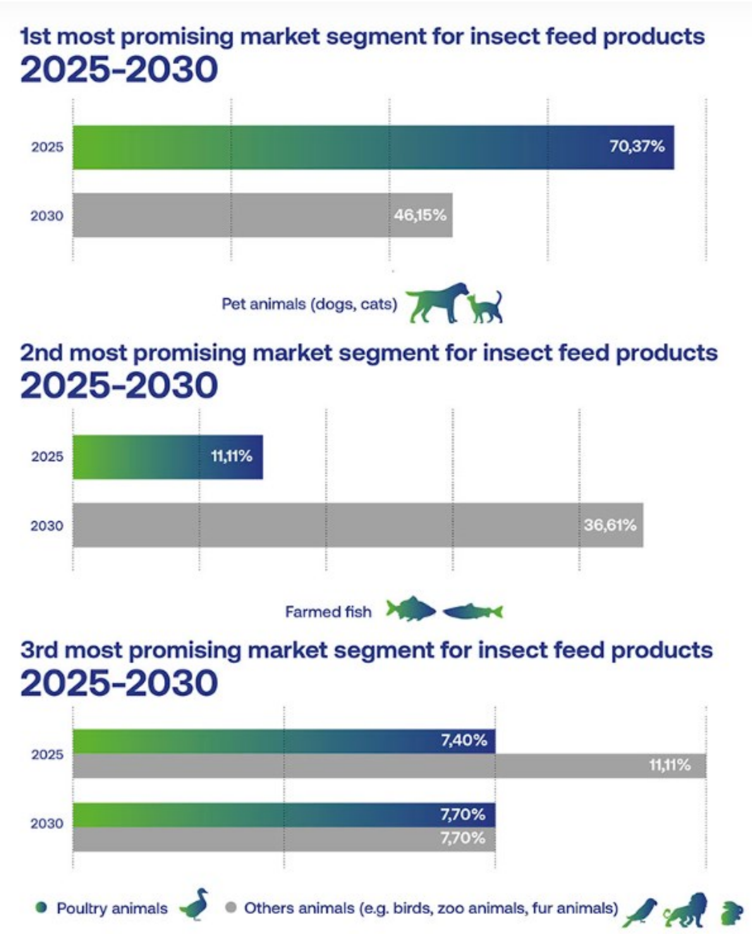
Types of producers. Although there are few examples and limited information available on Galleria mellonella producers, existing companies seem to mainly produce on small-scale. An incubator (dimension 540x1300x550 mm) could produce around 15 kg of larvae per production cycle (around 40 days from egg phase). However, considering the possibility that the mealworm could serve as livestock feed, an increase in large-scale producers is certainly desirable (Veldkamp et al., 2023). Possible applications could also consider a direct production and consumption of the insect inside the same company as animal feed, for instance, for fish or insects. Differently from other insects' productions, this species is not smelly, therefore could also produce in closed by offices or houses.

Processing. The insect is mainly found in the market alive or dry, packed in plastic bags or boxes, while the processing to obtain flour is not common. The producer is also often the processor, packaging the insect in an artisanal process. However, the potential increase of large-scale production may require the presence of semi-industrial or industrial processors in the future. If used directly in the same company, it would not need packaging.

Governance structure. In Europe and Italy, the regulation of insect production as animal feed and human food has been taking the first steps in recent years. At the moment, *G. mellonella* can be used as feed of different animal species. In Europe, the mealworm could be used as live or dried, whole or processed as flour or as an extract of proteins and fats. However, not every type of insect processing can be supplied to every animal species. For instance, the fats extracted from the mealworm can be supplied to pets, fish, chickens, ruminants and pigs, while the alive mealworm cannot be supplied to ruminants (IPIFF, 2024; Alia Insect Farm, 2020). Use of *G. mellonella* in the human diet is still forbidden.

The production of insects for animal feed and pets is growing rapidly around the world. With around 4,000 tons of insect-extracted proteins and nearly 10,000 tons of insect-based feed products in 2022, insect feed production is expected to increase rapidly in the coming years. Based on overall investments, the sector could reach a total turnover of around 2 billion €

per year by the end of the 2020s. This growth will materialize with the construction of new plants and/or the expansion of existing infrastructures (Italian Cricket Farm, 2024). Figure 12 represents the estimated growth for the insect feed market between 2025 and 2030.



Source: Italian Cricket Farm, (2024)

Figure 12. Estimated growth of insect feed products between 2025-2030.

Figure 13 outlines the functional analysis of Galleria mellonella production at UNIBO, Italy.

Yield estimates and farm gate prices. The estimated yield is around 10 kg m^{-2}, considering that a plastic box with the dimension of 24x12 cm (normally used in small-scale production systems) could allow the production of 300 g of insects for one box over 40 days of production cycle (from egg phase). A standard incubator for *Galleria mellonella* production could contain around 48 boxes.

The farm gate price of the insect alive can vary depending on the company. However, the mean price is around 90-100 € kg^{-1} (Insect Novel Ecologic Food, 2024).

Detailed description of value chain stages. The first stage of insect production, and in particular of *G. mellonella*, is the supply of production inputs and growing equipment. Feed suppliers, both of industrial materials and organic waste, as well as energy suppliers, are the first actors of the value chain analysis (Leipertz et al., 2024). In case of *G. mellonella*, raw material is supplied to insect producers that will subsequently process it to generate the feed for the insect diet.

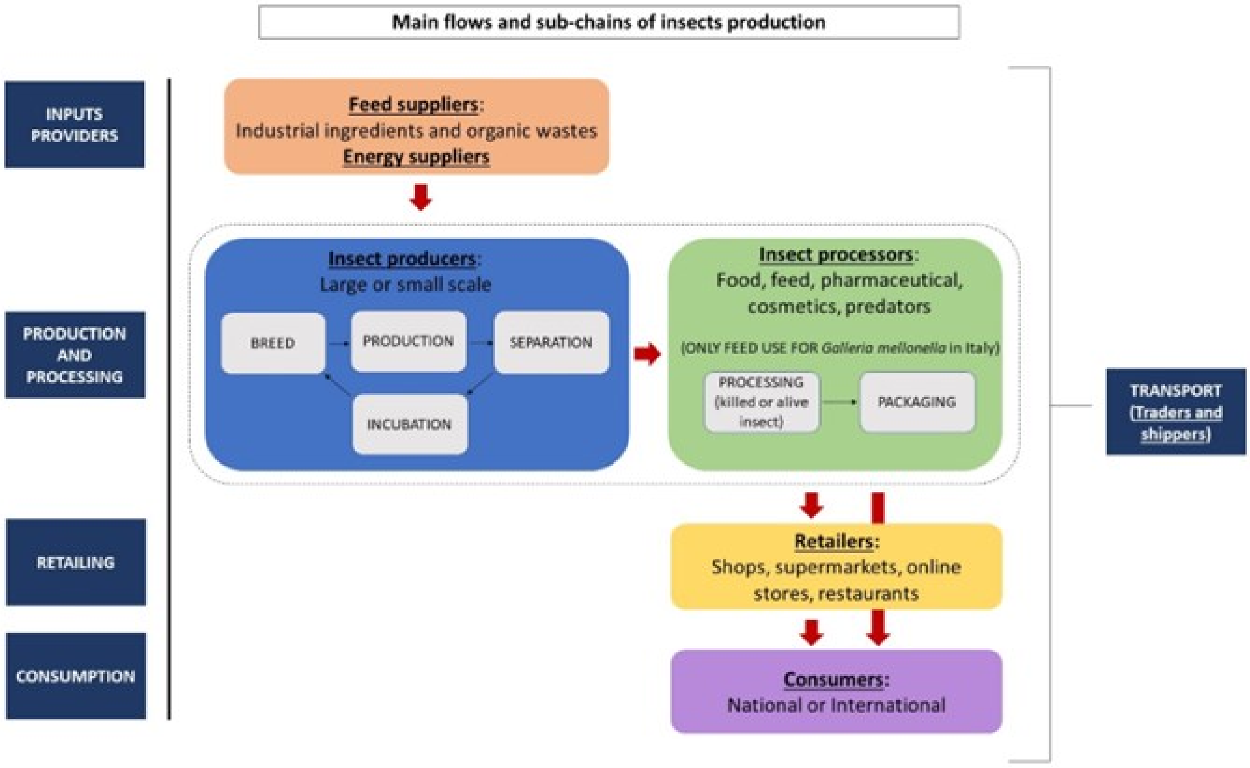


Figure 13. Functional analysis of *Galleria mellonella* production, UNIBO, Italy.

Production of the insect. As already mentioned, the production of *G. mellonella*, is mostly on small-scale, although the insect farming sector already presents technology and automation for large scale production of some species (Viscon Group, 2024). The phases of *G. mellonella* production include breeding in nursery, production of larvae, separation of larvae destinated to consumption form larvae destinated to reproduction, and incubation of larvae destinated to reproduction to restart the process.

Processing of the larvae. The larvae that will be sold should be processed before. Processing could be held both by the producer and by third-part companies. Currently, *G. mellonella* is mainly used as live insect, packed in boxes by the producer. Small producers of *G. mellonella* can either sell the product to retailers such as animal shops (both on-line and physical), or directly to the final consumer.

At every stage of production, transport and logistics are involved. In the case of selling of the alive animal, the assurance of a sane and of quality product reaching the final consumer is important to consider, applying refreshing bags in the shipped boxes when necessary.

4.2 Profitability Analysis of G. mellonella at UNIBO

The cost-benefit analysis performed for *G. mellonella* production showed that the system is still not economically profitable (Table 7). In particular, the annual estimates considered the cost of diet ingredients, the energy required from the incubator for insect growth and from the oven and mixer for feed preparation, the labor, and the depreciation of the equipment (original prices of the equipment over 20 years: incubator: 700€, oven: 500€, mixer: 600€, boxes (48 boxes): 288€) considering 20 years of duration.

Table 7. Cost-benefit analysis of *Galleria mellonella* production.

Expenses	Yearly Costs in €		Kg/year and head/year	Mean price (€) per kg	Mean revenue (€) per year
Intermediate consumption		Production			
Milk powder	448.88 €	Galleria mellonella	135 kg	104.00 €	14040.00 €
00 white flour	58.05 €				
Corn flour	67.50 €			SUM	14040.00
Wholemeal flour	64.13 €				
Debittered brewer's yeast	71.60 €				
Italian raw wax	496.80 €				
Wildflower honey	870.75 €				
Glycerine	199.13 €				
Energy	2770.20 €				
Labor	8100.00 €				
Mixer	30.00 €				
Oven	25.00 €				
Incubator	35.00 €				
Boxes (48)	6.40 €				
SUM	13243.43 €				

Operating Profit (OP)***	796.57 €				

Other expenses such as land rent or expert consultation were not considered, hypothesizing a production on owned land and the necessity of basic knowledge for the setup of the system. Funds and subsidies were not considered as well. The price of the live worm was set around 104 € per kg based on on-line findings. Considering a yearly production of 135 kg (15 kg per production cycle, considering 9 cycles), the revenue would be around 14,040 €. Considering expenses of 13,243 € per year, the **operating profit would be of 797€ per year**. Such a small profit can be mainly attributed to the elevated cost of the diet, highlighting the necessity to develop research on alternative diets based on wastes to obtain economic profitability and circularity of the system. The low productivity of the system may also be a reason for the low profitability. Therefore, ways to increase production should be considered and ameliorated.

4.3. Economic Analysis

Due to the novelty of this value chain in Italy and lack of data, no economic analysis was undertaken.

4.4. Social Impact Analysis

Due to the novelty of this value chain in Italy and lack of data, no social impact analysis was undertaken.

4.5. Environmental Impact Analysis

Insect farming is an emerging production system that has several environmental benefits (Møller et al.,2024; Modahl & Brekke, 2022; Philis et al., 2019). However, insect production, particularly *Galleria mellonella* is not widely practized as a controlled production system, particularly not in Italy. Moreover, there is a lack of comparative data, so a quantitative environmental impact assessment could not be conducted. However, ***Table 8*** provides a summary of the environmental pros and cons based on available literature.

The most important environmental benefits of insect farming relate to a low requirement of land, water, and feed compared to traditional livestock farming, reducing the strain on natural resources. Insects produce fewer GHG and ammonia, contributing to lower air pollution. Additionally, they can be fed with organic waste, which helps in waste management and recycling, i.e. circular economy. Overall, insect farming presents a sustainable and eco-friendly alternative to conventional protein-based feed (but also food).

However, there are risks associated with insect farming, including the potential for disease outbreaks in high intensity systems, the need for strict biosecurity measures, and the possibility of invasive species escaping into the wild (Huis et al. 2017; Lange et al. (2023). Proper management and regulation are essential to mitigate these risks and ensure the sustainability of insect farming. A concise summary of the environmental benefits of insect farming in comparison with livestock and fish farming is depicted in **Table 8**.

Table 8. Environmental impact of insect production – qualitative approach.

Impact Indicator	Livestock Farming	Insect Farming	Fish farming	References
Global Warming Potential (GWP)	Higher emissions on average cattle produce around 99.48 kg CO_2-eq per kg of beef.	Lower emissions; for instance, mealworms produce around 2.7 kg CO_2-eq per kg of protein.	Moderate emissions: for instance, salmon farming produces around 11.9 kg CO_2-eq per kg of fish.	Møller et al. (2024), Modahl & Brekke (2022), Philis et al. (2019)
Land Use	Significant land use, e.g., 1 kg of beef requires around 20 m² of land.	Minimal land use: insects can be farmed vertically, reducing land requirements.	Moderate land use: fish farming requires less land compared to livestock.	Møller et al. (2024), Smetana et al. (2023), Bohnes & Laurent (2018)
Water Use	High water consumption: On average, 1 kg of beef requires around 15,415 litres of water.	Lower water consumption: mealworms require around 4,000 litres of water per kg of protein.	Moderate water use: fish farming requires significant water for aquaculture systems.	Pavanello et al. (2024), Modahl & Brekke (2022)
Feed Conversion Efficiency	Lower efficiency: on average, livestock require around 8 kg of feed per kg of beef.	Higher efficiency: on average, insects require around 2 kg of feed per kg of protein.	Moderate efficiency: on average, fish have a feed conversion ratio of around 1.2 to 1.5.	Ruckli et al. (2021), Smetana et al. (2023), Philis et al. (2019)
Eutrophication Potential	Higher potential due to nutrient runoff from manure.	Lower potential, as insect farming produces less nutrient runoff.	Moderate potential: nutrient runoff from fish farms can contribute to eutrophication.	Pavanello et al. (2024), Smetana et al. (2023), (Bohnes & Laurent (2018)
Acidification Potential	Higher potential due to ammonia emissions from manure.	Lower potential, as insect farming produces less ammonia.	Moderate Potential: fish farming can contribute to acidification through feed and waste management.	Ruckli et al. (2021), Modahl & Brekke (2022)

5. Value chain analysis of tomatoes, UM6P (P7), Morocco[4]

5.1. Functional Analysis

Value chain overview. The tomato production process involves several stages, starting with agricultural production, which includes the cultivation of seedlings in local nurseries, on-farm production, and harvesting. This process is then followed by post-harvest treatment at the commissioning station and concludes with the distribution of tomatoes to various countries by lorry. These sequential steps are depicted in **Figure 14** and further explained below.

Farming Process. The farming process starts at local nurseries where tomato seedlings are cultivated. The process from seed to delivery of the seedling spans approximately 50 days, although this duration can vary slightly with seasonal changes, taking about 60 days during the colder winter months and reducing to 40 days in the summer. The stages include seeding, germination, grafting, and growing. In addition, regular irrigation and fertilization are critical throughout this phase to ensure healthy plant development.

Once the seedlings are mature, they are picked up or delivered to the farms. The tomatoes are then planted in coco coir substrates in metallic greenhouses. To protect against pests and environmental factors, the greenhouses are outfitted with plastic covers and side nets. Manual labor is predominantly used for plant handling and care. Farming activities include consistent irrigation, fertilization, and plant protection measures. Greenhouse heating is not installed due to the moderate climate in the region all year around.

Approximately 2.5 months after planting, the first tomatoes are ready for harvest. The harvesting season lasts for around 8 months. Harvesting is performed manually to ensure careful handling of the fruits.

[4] The value chain analysis of tomatoes in Morocco is largely based on the Master thesis of Kappeler (2024). The student was hosted and supported in the analysis throughout by UM6P. Section 5.4 has been added to the analysis later by UM6P.

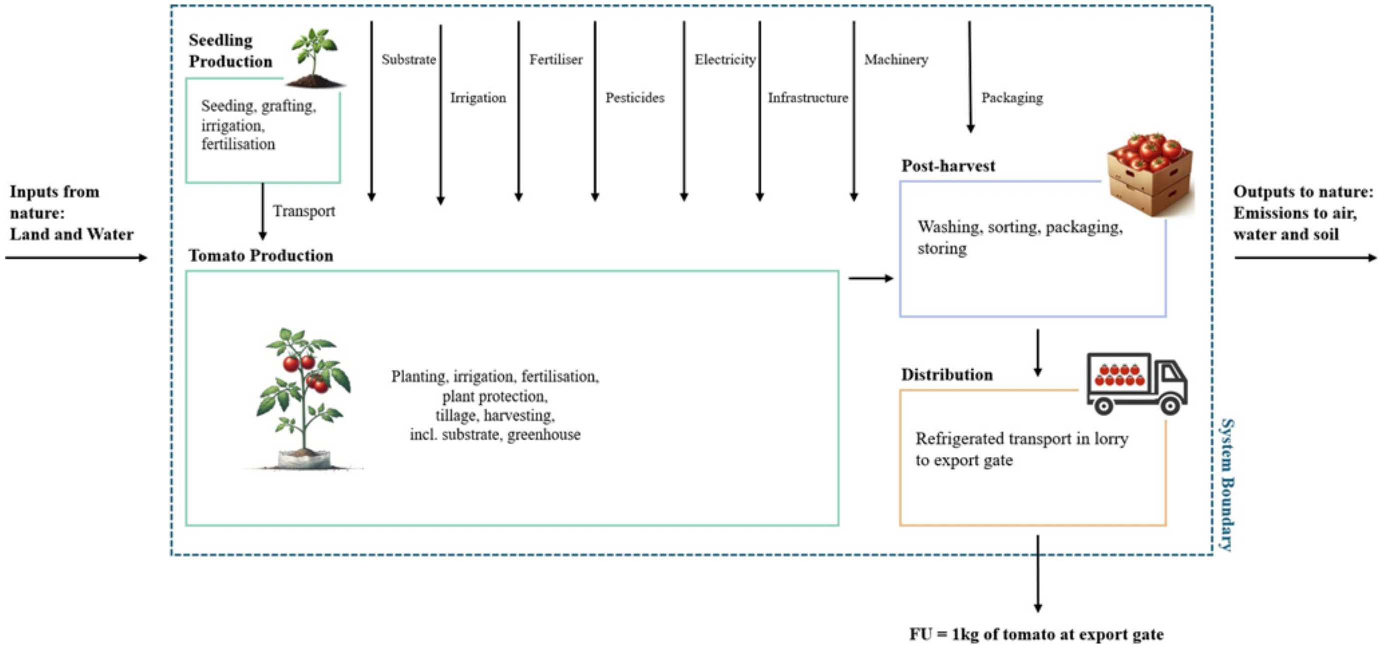


Figure 14. Value chain overview of tomato production, UM6P, Morocco.

Transport to commissioning station. Post-harvest processes, the logistics of tomato distribution depend on the size and structure of the farm. In some cases, cooperatives (e.g., Copag) are involved, while in other instances, vertically integrated supply chains manage the pickup and subsequent processes directly. To maintain freshness, the harvested tomatoes are transported to commissioning centers the same day they are picked. The temperature in the vehicle is set around 20°C, a crucial step to gently reduce the tomatoes' field temperature. At the centers, the tomatoes are initially stored at 20°C before further processing. They avoid direct cooling to 4 °C to avoid damaging the delicate fruits.

Cleaning and Sorting Process. The post-harvest processing of tomatoes begins with a cleaning process. Initially, the tomatoes are brushed to remove dirt or dust. Subsequently, they undergo a quick water wash before being dried. This process lasts only a few seconds. Following the cleaning, the tomatoes are conveyed through an advanced sorting system. The technology is designed to detect and remove tomatoes that do not meet the preset standards requested from the European retailer, such as incorrect sizes or visible defects like brown spots.

Packaging and Quality Control. Once sorted, the tomatoes undergo the packaging process. Round tomatoes are placed in larger cartons (i.e., around 6 kg), while cherry tomatoes are packed directly into smaller-sized plastic containers. Employees perform this task manually and visually carry out a secondary quality control check to ensure all packaged tomatoes meet the high-quality standards expected on the market.

Following packaging, they stack the cartons on pallets and put them into an overnight storage facility, maintaining temperatures between 4 and 6 °C. This step ensures freshness until shipment.

State Regulations and Controls. Before leaving the commissioning center, each shipment must pass through two important state-imposed controls: normalization and quality control. These controls are in place to maintain the high standards of exported Moroccan tomatoes and preserve their market reputation. A state officer visits daily to oversee these checks and provides an authorization signature. If a shipment fails these tests, it is not permitted to leave the hub.

Transport and Distribution to Europe. The tomatoes are then transported to Europe primarily via refrigerated lorries that travel via Tangier. Some farms also use a ferry service from Agadir twice a week; however, this option is less frequent, although more cost-effective compared to lorry transport, which is almost twice as expensive. Once in Europe, the tomatoes are distributed across various countries, with France being the largest importer, followed by the United Kingdom. According to EU data, Morocco is the leading non-EU tomato producer for the European market, exporting 560,000 tons in 2022 and 500,000 tons in 2023. These figures highlight Morocco's role in the European tomato market, while other countries such as Turkey make a smaller contribution, exporting half of this volume to Europe (EC, 2024).

5.2. Profitability Analysis of hydroponic tomato production in Morocco

Hydroponic tomato production, while offering several agronomic benefits, involves higher initial investment costs compared to traditional soil-based methods. The major cost factor in the additional investment is the substrate bags for cultivation. At the same time, however, hydroponic farming reduces ongoing expenses related to key inputs such as fertilizer and water Closed-loop systems, which collect surplus water, realize further input savings. One farm with a closed system reported savings of up to 30% in water and fertilizer usage. However, such closed hydroponic systems are not yet widespread in the region studied, only the largest farm of the 3 farms visited employed this technology. Presently, a challenge affecting these potential savings is the Tomato Brown Rugose Fruit Virus (ToBRFV), since the virus prevents the reuse of water due to the risk of disease transmission. As a result, the nutrient-rich water must instead be given to neighboring farms growing crops not susceptible to the virus. The farmer mentioned that the water is provided to them free of charge. This cancels out the potential savings in water and fertilizer costs under the current conditions. For the substrate, there is a similar problem. Normally, substrates can be reused for up to four years. However, due to contamination risks from ToBRFV, substrates must now be replaced annually. The used substrate is sold to raspberry growers, who value it for its favorable pH value; this sale recovers around 40% of the original substrate costs. Yet, this increases annual expenses and operational complexity.

Table 9 lists the relative agricultural expenses for hydroponic open- and closed-loop, soil-based, and cherry tomato cultivation. For the open-loop hydroponic system (case 1), the major cost drivers are the greenhouse and fertilizer, accounting for 20% and 17% of total agricultural costs, respectively. This is followed by seedlings, plant protection, and employment costs, each contributing around 12 to 16% of the total costs. In the closed-loop hydroponic system (case 2), fertilizer is not the primary cost driver, but it still accounts for 13% of the total costs.

Table 9. Relative agricultural expenses for hydroponic open- and closed-loop, soil-based and cherry tomato cultivation.

	Case 1	Case 2	Case 3	Case 4
	Tomato open loop	Tomato closed loop	Tomato in soil	Cherry tomato open loop
Expenses				
Canarian plastic green house	20%	21%	20%	15%
Substrate	8%	8%	0%	6%
Seedlings	12%	13%	12%	24%
Water	3%	2%	3%	2%
Fertilizer	17%	13%	25%	13%
Plant protection	12%	12%	12%	13%
Employment costs	16%	17%	16%	18%
Management fees	3%	3%	3%	2%
Transport to commissioning station	2%	2%	1%	1%
Extra costs	2%	2%	0%	1%
Closed-loop installation	0%	2%	0%	0%
Other costs traditional cultivation				0%
(Mulching, tillage, …)	0%	0%	3%	0%
Financing costs	5%	5%	5%	5%

Note: All cost categories > 10% are colored in red. In each category, the two highest categories are highlighted in darker red color.

The calculations in Table 9 assume for the closed-loop scenario (case 2) the reuse of nutritious water, which usually would be the case. The greenhouse is the main cost driver at 21%, followed by employment at 17%, with seedlings and plant protection accounting for approximately 13% of the total costs. For traditional cultivation (case 3), the primary cost burdens are fertilizer, comprising around 25% of the total costs, and greenhouse at 20%. Seedlings, plant protection, and employment costs each contribute about 10 to 15%, such as case 1. In cherry tomato production (case 4), seedlings are the main cost driver, accounting for 24% of the total costs, followed by employment costs at 18%. Greenhouse maintenance, fertilizer, and plant protection each make up around 12 to 16% of the total costs. Notably, water for irrigation represents a small part of the total agricultural costs in all cases.

Furthermore, interviewees mentioned that recent external events like the COVID-19 pandemic and the ongoing war in Ukraine have impacted the economic environment for agriculture. They stated that since these events increased the costs of around 15% for fertilizers and 25% for pesticides. Furthermore, rising energy costs are raising costs related to energy-intensive inputs such as water pumping and irrigation.

When analyzing the value chain, including packaging and transport, agricultural production represents approximately 30 to 35% of the costs for cases 1 to 3 (**Table 10**). Packaging constitutes around 40%, and transport makes up about 30% of the total costs for these cases. For cherry tomato production (case 4), agricultural costs account for approximately 45% of the total costs. Packaging contributes 35%, while transport accounts for 20% of the total costs. Table 6 provides an overview of the relative expenses in the value chain for all cases.

Table 10. Relative expenses in the value chain for hydroponic open- and closed-loop, soil-based and cherry tomato cultivation.

	Case 1	Case 2	Case 3	Case 4
Processes	Tomato open loop	Tomato closed loop	Tomato in soil	Cherry tomato, open loop
Agricultural Production	33%	32%	35%	46%
Packaging	37%	38%	36%	36%
Transport	30%	30%	29%	18%

In Morocco, water is a critical limiting resource. Historically, farmers have relied on the accessible and economically viable option of groundwater for irrigation. Until today, this method has not presented major disadvantages and has remained cost-effective. The analysis shows that irrigation only contributes to a small part of the total costs. However, recent developments indicate that groundwater levels are dropping, with increasing salinization and degradation being observed (El-Ghzizel et al., 2021). This environmental degradation not only raises ecological concerns but also raises operational costs for farmers due to the need for deeper drilling. Moreover, beyond a depth of approximately 200 meters, the water quality deteriorates significantly, becoming too saline for agricultural use. Faced with these challenges, farmers are looking for alternative water sources. One option is desalinated seawater. In Agadir, a coastal city in the Souss Massa region, Morocco hosts a desalination plant. Despite this facility, the demand for desalinated water currently exceeds its supply, with access largely limited to larger farms. The cost of desalinated water is at Moroccan Dirham (MAD[5]) 10 per cubic meter, of which half is subsidized by the state, leaving farmers to pay the remaining MAD 5 per cubic meter. In comparison, groundwater

[5] 1 MAD is equivalent to 0.092744 € on 15.02.2024, during the survey period.

costs only around MAD 2 per cubic meter, making it a more cost-effective option in the short term. Yet, the ongoing depletion and increasing salinity of groundwater, compounded by rising energy costs for pumping, are making this resource long-term less sustainable and more expensive.

In the context of the VCA4D, understanding the gross operating profit (GOP) and the VA is relevant for assessing the profitability of the farm business (Table 11). The analysis shows a positive GOP for the average producer price received in 2022 for all cases. However, the analysis indicates that open-loop hydroponics (case 1), compared to traditional cultivation (case 3), generates approximately 40% more profit. Lower fertilizer input, lower water costs, and a higher yield per hectare balance out the investment costs in the substrate. In a closed-loop hydroponic system (case 2), additional savings are realized, resulting in around 20% more profit compared to the open-loop hydroponic system (case 1), due to further reductions in water and fertilizer usage. According to the analysis, cherry tomatoes (case 4) are 50% more profitable compared to closed-loop hydroponic round tomatoes (case 1). VA per hectare is estimated at around MAD 135’000 (USD 13’500) per hectare for round tomatoes and MAD 190’000 (USD 19’000) for cherry tomatoes, likely underestimated since other factors as described in Fabre et al. (2021) are not considered in the analysis.

Table 11. Gross operating profit (GOP) for the four cases of tomato production.

	Case 1	**Case 2**	**Case 3**	**Case 4:**
	Tomato, open loop	Tomato, closed loop	Tomato in soil	Cherry tomato, open loop
Yield (kg/ha)	250,000	250,000	234,000	150,000
Total costs per ha (MAD/ha)	562,328	537,075	567,904	761,696
Total revenue per ha (MAD/ha)	683,750	683,750	639,90	945,000
GOP per ha (MAD/ha)	121,423	146,675	72,086	183,304
GOP per ha (USD/ha)	12,142	14,668	7,209	18,330

In the region examined, farmers generally cultivate both cherry and round tomatoes, but a shift towards exclusively growing cherry tomatoes is notable among the farms visited. Specifically, one out of three farms focused solely on cherry tomato varieties, and one of the other farmers plans to switch to only growing cherry tomatoes in the upcoming season. This shift is driven by the economic dynamics of tomato production; the farmers highlighted that the price pressures on round tomatoes can be so severe that their production sometimes becomes unprofitable. Although cherry tomatoes have lower productivity and higher demands on labor and inputs per kilogram produced compared to round tomatoes, their increased market price makes them more profitable. This makes the cultivation of cherry tomatoes a strategic economic decision as the analysis shows.

5.3. Economic Analysis

Contribution to growth. In 2022, Morocco's overall GDP was reported to be MAD 1,330 billion (USD 130.91 billion) (World Bank, 2023), with the agricultural sector contributing approximately 9.7% to the national economy, equivalent to an estimated MAD 129,661 million (USD 12,761.048 million). The country produced 1'388'542 tons of tomatoes, with an average producer price of USD 3050 per ton, culminating in an estimated market value of MAD 4,235,053 million (USD 416,809 million) in 2022. Within the agricultural sector, that implies that tomato production contributes about 3.3% to the total agricultural value produced. Moroccan tomato production contributes roughly 0.3% of the overall GDP. Tomatoes represent about 32.1% of the GDP generated from vegetable production. In Morocco's agricultural sector tomatoes, potatoes, and apples account for most of the value creation, following olives and wheat. These statistics are derived from data provided by the Food and Agriculture Organization's databank and include all sorts of tomatoes (FAO, 2024b).

Income Distribution. In 2022, Morocco exported 80% of its tomato production overseas, which corresponds to 740,660.97 tons. The total revenue generated from those exports amounted to approximately MAD 10,410,537 million (USD 1,024,593 million). This translates to an average income of MAD 14.1 (USD 1.38) per kilogram of export. FAO statistics report an average producer price of MAD 3.05 (FAO, 2024b). Considering the entire value chain, the agricultural sector generates MAD 11.05 per kilogram of tomato. Our research shows that the costs associated with commissioning are about MAD 4.45 per kilogram. Thus, the remaining margin after deducting the costs for commissioning from the value generated outside the agricultural sector is MAD 6.60. That means the farmer's share of the revenue generated from each kilogram of tomatoes exported, when calculated as a percentage of the export revenue, is 25%. The commissioning station's share is 32%. Various other entities involved in the value chain, such as traders, presumably split the remaining 44%.

Competitiveness in the international context. The normalized price coefficient (NPC) provides insights into Moroccan tomato production's competitiveness in the international context. The NPC is calculated by dividing the product's domestic price by its international parity price. For Moroccan tomatoes, the NPC is calculated as follows:

$$NPC = \frac{0.711 USD/kg}{2.61 USD/kg} = 0.27$$

The NPC value below 1 indicates that the domestic value is lower than the international market price, suggesting that the overall value chain remuneration is lower than it would be if priced at international parity. This can be interpreted as a competitive advantage in the global market because it implies that Morocco's production cost allows for the sale of tomatoes at a lower price while still maintaining market presence. On the global tomato market, Morocco is the third largest exporter of tomatoes after Mexico and the Netherlands. In 2022 Morocco surpassed Spain, traditionally a major producer, moving Spain to the fourth position (EC, 2024).

Morocco's competitive advantage in tomato production is explained by two main factors. On the one hand, the labor costs are relatively low. For instance, in Spanish tomato production, as shown in Torrellas et al. (2012), labor accounts for around 60% of the total costs, whereas our results show labor costs around 15 to 20% of the total costs. On the other hand, it is the climatic advantage that provides an environment that is ideal for tomato cultivation. In the region, there is no need for greenhouse heating or cooling infrastructure year-round. This advantage allows Moroccan farmers to operate with lower production costs during the winter months compared to their European counterparts, such as the Netherlands, where heating greenhouses is necessary during the winter (Torrellas et al., 2012).

Although the value chain remuneration is lower than under the international parity price, access to international markets provides Moroccan farmers with opportunities to earn higher revenues compared to selling locally, where prices are lower. Hydroponic production, which yields higher quality tomatoes, is especially well-suited for these export opportunities. However, integration into the global market also exposes farmers to the volatility of prices, which fluctuate in response to events such as changes in supply and demand, weather conditions, pests, diseases, and strategic agricultural decisions at both local and international levels. Interviewees highlighted the unpredictability of prices and their high variability, noting that during periods of very low prices, the costs associated with packaging and transport can exceed the selling price, making exports economically unviable. In such scenarios, tomatoes are diverted to the local market, which increases local supply and consequently drives prices down. While this situation benefits local consumers by making tomatoes more affordable, it adversely affects farmers' incomes. Interviewees pointed out that, next to water scarcity, the main challenge for them is market volatility. They mentioned that round tomato prices in recent years have fluctuated between MAD 1.5 per kilogram and MAD 10 per kilogram. The extreme price of MAD 10 per kilogram in 2023 was an outlier, driven by an acute supply shortage. Farmers mentioned that price pressure on cherry tomatoes is less severe compared to round tomatoes.

5.4. Social Impact Analysis

The radar chart (Figure 15) evaluates various aspects of the social analysis of tomato production in the Sous Massa region of Morocco. A questionnaire was prepared based on the questions suggested by Fabre et al. (2021) and as outlined in Section 2.4 above. The questionnaire assessed different factors related to working conditions, gender equality, access to water and land, living conditions, and food security. This questionnaire was then distributed to 5 stakeholders in the tomato production value chain. The scores in the radar chart represent the average results obtained from the responses of the stakeholders. In the radar chart, “Not at all” was assigned a score of 1, “Weak/Moderate” a score of 2, “Substantial” a score of 3, and “Very High” a score of 4.

Gender equality is crucial in the tomato production value chain, as women play a major role, especially in plant nurseries and sorting stations. Due to the increasing limitations on groundwater, the Moroccan government has launched a major seawater desalination project that will support the sustainability of tomato production in the Souss Massa region. Tomato production meets the domestic market's needs and contributes to Morocco's food security. However, a balance between exports and the internal market must be maintained during the winter period.

Tomato producers and exporters are well-organized, forming associations and federations to advocate for their rights and interests. They engage in ongoing discussions with the government to improve the sector's quality and attractiveness. More efforts are needed from both, the private and public sectors to improve work and living conditions. Salaries are often very low, and inflation is rising. There is also a lack of formal contracts and health insurance, particularly in tomato farming sites. In some cases, children from impoverished regions leave school to work on tomato farms.

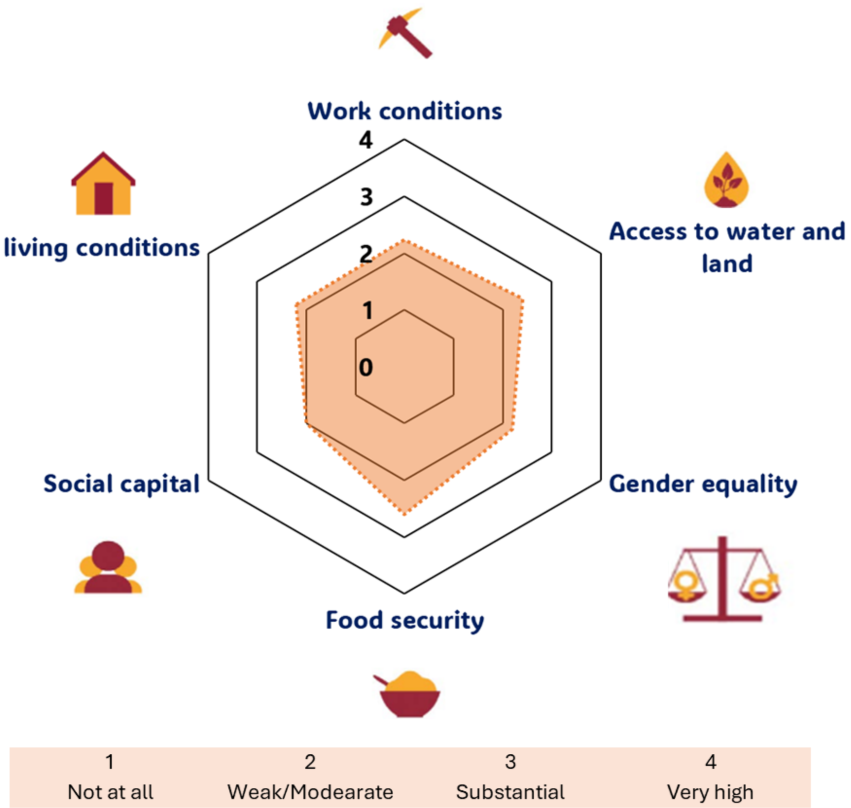


Figure 15. Radar diagram of the social analysis of tomato production in the Souss Massa region of Morocco.

5.5. Environmental Impact Analysis

The environmental impact analysis in Morocco is based on a LCA (see **Section 2.5.1**), whereby the overview of the results begins with findings from ReCiPe 2016, a harmonized life cycle impact assessment method at midpoint and endpoint level (Huijbregts et al. 2017).

The present analysis is focusing on endpoint-level results (Table 12). Cases 1 to 4 are analyzed to determine their environmental impact, whereby subcases are built.

Among the analyzed cases, the lowest environmental footprint on the ecosystem damage is observed in case 2b, the closed-loop hydroponic system utilizing 40% desalinated water and 60% solar energy for irrigation. Closed-loop hydroponics (case 2a and 2b) outperforms open-loop hydroponics (case 1a and 1b) and traditional cultivation (case 3) by approximately 20%. The latter (case 3) exhibits a comparable environmental impact to the open-loop hydroponic (case 1a and 1b), with a slightly lower impact than the open-loop without desalinated seawater and solar energy (case 1a) by 5% and a slightly higher impact than the open-loop with desalinated water and solar energy (case 1b) by 1%. Moreover, the transition to 40% desalinated seawater in hydroponic scenarios 1b and 2b compared to 1a and 2a without desalinated seawater yields a positive impact on ecosystems due to reduced water consumption, resulting in a 6% improvement in the open-loop (case 1) and 5% in the closed-loop (case 2).

Table 12. Total damage of each case to each damage (=endpoint) category.

Damage category	Unit	Case 1a, open-loop	Case 1b, open-loop	Case 2a, closed-loop	Case 2b, closed-loop	Case 3, in soil	Case 4a, cherry
Human health	**DALY**	1.04E-06	1.03E-06	8.93E-07	8.88E-07	9.89E-07	1.60E-06
Ecosystems	**species.yr**	4.33E-09	4.08E-09	3.42E-09	3.25E-09	4.13E-09	6.34E-09
Resources	**USD2013**	3.21E-02	3.20E-02	3.14E-02	3.14E-02	3.12E-02	4.25E-02

Notes: DALY = Disability Adjusted Loss of Life Years

In terms of human health, closed-loop hydroponics (case 2a and 2b) emerge as the most favorable performer. The damage to human health is about 10 to 14% lower than in the open- loop scenario (case 1a and 1b) and traditional cultivation (case 3). Case 3 presents a comparable impact on human health as Case 1 (a and b), with deviations of 4 to 5%. With or without the use of desalinated seawater and solar energy, scenarios a) and b) in open- and closed-loop hydroponics (cases 1 and 2) have similar impacts on human health. Although solar energy has a positive impact on human health as the analysis in Appendix C.1 shows, the overall system's effect is marginal, resulting in a reduction in the impact on human health by less than 1%. Regarding resource depletion, the hydroponic open- and closed-loop and the traditional cases (cases 1, 2, and 3) manifest a comparable impact, with the open-loop (case 1) and the traditional cultivation (case 3) deviating by approximately +/- 1% from the closed-loop (case 2), indicating no significant variation.

Despite utilizing the same cultivation technique as open-loop hydroponic round tomato production (case 1), case 4 involves the production of cherry tomatoes instead of round tomatoes. Cherry tomatoes exhibit the highest environmental impact across all categories. The analysis indicates that cherry tomatoes have a higher impact per functional unit (FU) compared to round tomatoes, particularly evident in the higher impact on human health and ecosystem quality by around 50% and by around 30% on resources, respectively. No alternative cultivation scenarios for cherry tomatoes are explored in this study. *Figure 17* illustrates the relative contribution of each case compared to the case with the highest impact in each endpoint category.

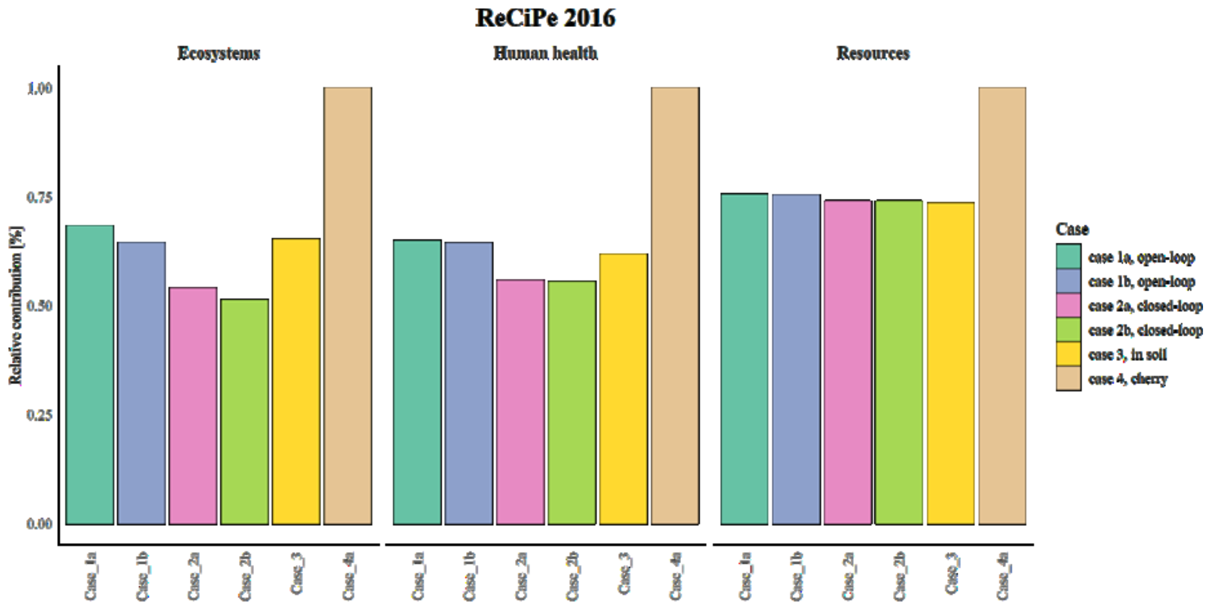


Figure 16. Relative contribution of each case compared to the case with the highest impact to each damage (=endpoint) category.

6. Value chain analysis of strawberries, ElBosten (P7), Tunisia

6.1. Functional Analysis

The company elBosten phytagri has certified the Camarosa strawberry variety, which is not just a new variety of plants and rootstocks created by Mabrouka. It is the result of several years' work through an ambitious research and development program to be the first private producer of 100% Tunisian strawberry plants.

In addition to Camarosa, elBosten cultivates the Savana, Sabrina, and RedSara strawberry varieties, all renowned for their high productivity and consistent quality. Savana is perfect for early production, producing large, intensely red fruit throughout the season. Sabrina, a robust mid-season variety, is known for its conical, medium-sized, bright-red fruits, which are highly valued by the processing industry for their consistent and well-colored pulp. RedSara, another early producer, offers delicious, medium to large-sized fruit right up to the end of the harvest.

Setting up the demonstration pilot ‘strawberries produced in hydroponics’ at elBosten required openness to innovations. (i) The initial step involved designing the hydroponic greenhouse layout to ensure an efficient growing environment. (ii) Following the greenhouse design that optimizes growing conditions for the selected strawberry varieties, essential equipment was sourced locally to construct not only the greenhouse but also the hydroponic system. Retailers supplied smaller tools and components, while wholesalers were engaged for the bulk purchase of specialized or large-scale equipment required to build and operate the greenhouse efficiently (see also Figure 17).

In the following, several central terms in relation to food value chains in Tunisia, especially with regard to strawberries, are outlined.

Regulatory Compliance. Adheres to national agricultural policies and quality standards set by the Ministry of Agriculture, ensuring safety and quality for domestic and international markets.

Strategic Planning and Equipment Acquisition. Involves detailed planning for the greenhouse layout and procurement of necessary equipment from local retailers and wholesalers, ensuring efficient resource utilization.

Variety Selection and Certification. Cultivates certified strawberry varieties like Camarosa, Savana, Sabrina, and RedSara, supported by an ambitious research & development (R&D) program aimed at enhancing productivity and quality.

Sustainable Practices. Employs sustainable practices such as efficient fertigation, pest management, and optimal water salinity management, addressing water scarcity issues in Tunisia.

Market Focus. Targets the local market to support domestic consumption and the local economy, using sales channels like on-farm sales and local souks.

Financial Management. Manages high costs of seedlings and cultivation through stringent financial management to ensure profitability and financial viability.

Production Forecasting. Adapts to changing conditions with proactive production forecasting, anticipating significant increases in production despite challenges.

Stakeholder Engagement. Engages with local cooperatives and agricultural unions to address common challenges and promote best practices.

Figure 17 illustrates the strawberry value chain in hydroponics. It is divided into several key sections, which are connected to show the flow of activities and resources in the functional analysis of the strawberry value chain in Tunisia.

Strawberry Varieties and Cultivation. elBosten cultivates several certified strawberry varieties, including Camarosa, Savana, Sabrina, and RedSara. These varieties are selected for their high productivity, market appeal, and ability to thrive under the controlled conditions of the greenhouse. The plants are sourced from local nurseries or companies that specialize in supplying young strawberry plants suited to the Tunisian environment. Once planted, the strawberries are maintained through regular fertigation, pest management, and water salinity optimization.

Local Nursery. Plants are purchased from local nurseries or companies that supply young strawberry plants. These nurseries supply the different varieties of strawberry plants, each suited to the specific conditions and desired outcomes of the plantation.

Fertigation and Maintenance. Once the inputs are secured, the planting stage involves setting up the strawberry plants in the fields. This is followed by continuous maintenance activities, including regular watering, fertilization, pruning, and protection against diseases and pests. These activities are essential to ensure the plants grow healthily and produce a high yield.

Strawberry Varieties and Cultivation. elBosten cultivates several certified strawberry varieties, including Camarosa, Savana, Sabrina, and RedSara. These varieties are selected for their high productivity, market appeal, and ability to thrive under the controlled conditions of the greenhouse. The plants are sourced from local nurseries or companies that specialize in supplying young strawberry plants suited to the Tunisian environment. Once planted, the strawberries are maintained through regular fertigation, pest management, and water salinity optimization.

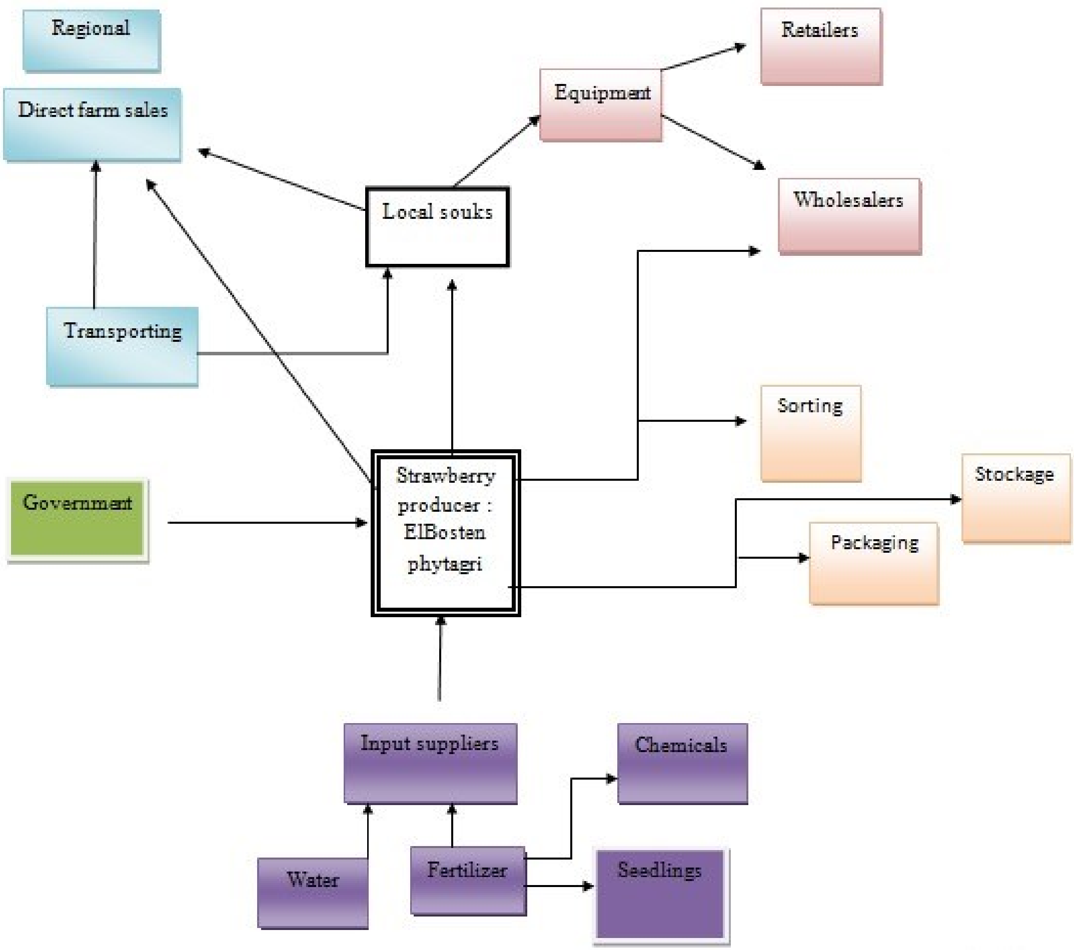


Figure 17. Activities involved in the cultivation of strawberries using a hydroponic greenhouse method.

Fertilization and Maintenance. elBosten applies imported fertilizers and pesticides to promote healthy growth and protect plants against pests. Maintenance services include plant pruning, treatment, and pest and disease protection.

Irrigation. elBosten uses a combination of locally pumped water and purchased water to ensure optimum salinity for the plants. Due to the fall in the water table in Tunisia, water salinity has increased. High water prices incentivize farmers to increase water use efficiency through innovations such as hydroponic systems.

Harvest. The strawberry harvest in Tunisia begins in March and runs for six months. Timely and efficient harvesting is critical to maintain the quality of the strawberries.

Processing and Packaging. After harvesting, the strawberries undergo sorting, where they are categorized based on size, quality, and other factors. This is followed by packing, where the sorted strawberries are prepared for distribution. Proper processing and packaging are vital to preserve the quality and extend the shelf life of the strawberries.

Distribution and Logistics. The strawberries are then distributed through various channels. On-farm sales allow direct sales to consumers at the farm, providing fresh produce directly to end-users. Additionally, strawberries are distributed to local markets through informal channels, including local souks (traditional markets). These markets play a significant role in sales, reaching a wider consumer base.

Strawberry Market. The primary market for elBosten's strawberries is the local market, focusing on domestic consumption. elBosten sells its strawberries on-farm and in local souks (traditional markets). This ensures that the produce reaches the consumers fresh.

6.2. Profitability Analysis of strawberries grown in hydroponics in Tunisia

The operating profit of Elbosten in 2024 for the first season was negative, at approximately -5,948.11€. The profitability analysis of Elbosten's strawberry cultivation in hydroponics reveals that the production system is facing financial challenges. Even with various cost optimizations and a 30% increase in revenue, the business remains unprofitable, still showing a net loss of about 5,658.46€ with a negative profit margin of -261.01% (***Table 15***).

Further optimistic scenarios, including a 50% revenue increase and additional cost reductions, still resulted in a net loss of approximately 4,436.57 EUR and a negative profit margin of -136.43%. This suggests that, while revenue increases and cost optimizations can improve the financial situation, they are not yet sufficient to bring the strawberry production based on hydroponics into profitability.

At present, Elbosten has started the second strawberry season of 2024. This is expected to improve the operating profit on an annual basis, although it will still likely remain negative. Assuming there are no costs for seedlings and a 20% reduction in fertilizer use, electricity costs will also be reduced due to photovoltaic installations.

For the business to become profitable, more adjustments are necessary. These could include further cost reductions, scaling up production, or exploring new revenue opportunities to diversify income streams. A strategic review of farming practices, resource efficiency, and potential partnerships may also be beneficial to improve overall profitability in the long term.

Table 13. Profitability analysis of strawberries grown in hydroponics, elBosten, Tunisia (Jan. -April 2024).

Category	Costs (€)	4 harvests in 1 season	Quantity (kg)	Mean revenue per year (€)
Electricity	295.63	1	549	811.50
Fertilizer + treatment	2,598.19	2	675	726.76
Water (purchase of low-salinity water tanks)	295.63	3	211	234.42
Land rent	0	4	410	363.62
Plants	1,396.80	**Total**	1,845	**2,136.31**
Fuel and transport	1,200.00			
Labor for setting up greenhouse	1,306.68			
Total	**7,092.93**			
Material costs (**K1:O38**):	1,718.26			
Equipment (**Q1:U38**):	568.94			
Total depriciation (€)	2,287.20			
Operating Profit (OP) in €	**-5,861.47**			

Notes: Equipment represents the depreciated amount, the depreciation rate is 15%.

Comparatively, Elbosten has conducted a profitability analysis for a soil-based strawberry cultivation system. The following key points have been identified (Table 16):

- **Total Annual Expenses:** Approximately 4,054.24€
- **Total Annual Revenue:** 1,054.93€
- **Operating Profit:** -3,759.16€
- **Profit Margin:** -431.17%

The analysis shows that the soil-based strawberry production system is also operating at a loss. The expenses, including electricity, fertilizer, seedlings, fuel, and equipment depreciation, are higher than the revenue generated from strawberry production. This results in a negative profit margin of -431.17%, indicating that the current setup is not financially sustainable.

In summary, both the hydroponic and soil-based systems face challenges that prevent profitability. On the one hand, the hydroponic system, although more expensive, generates more revenue and has a lower negative profit margin, indicating a better balance between costs and output. On the other hand, the soil-based system, while cheaper to maintain, generates less revenue and has a higher loss ratio, highlighting the need for increased yield or significant cost reductions.

Considering that there exist many soil-based strawberry operations in Tunisia with a profit, ElBosten will evaluate whether there are enterprise specific reasons that have led to the loss. At present, the lessons learned by Elbosten are:

1. **Hydroponic System:** Focus on cost optimization (e.g., energy efficiency, maintenance costs) and further improve yield to maximize the potential for higher revenue generation.
2. **Soil-Based System:** Explore ways to increase production efficiency and boost yield. Diversifying crop production could also help enhance revenue.

Careful consideration and targeted strategies will be required to turn either system profitable and sustainable in the long run.

Table 14. Profitability analysis of strawberries grown in soil, elBosten, Tunisia (Jan. -April 2024).

Category	Costs (€)	4 harvest in 1 season	Quantity (kg)	Revenue per year (€)
Electricity	499.32	1	186.415	275.55
Fertilizer + treatment	1,973.00	2	312.5	336.46
Seedlings	842.84	3	300.083	333.38
Fuel and Transport	739.08	4	123.502	109.53
Labor for setting up greenhouse	0			
		Total	922.5	**1,054.93**
Total	**4,054.24**			
Material costs (K1:O38):	439.35			
Equipment (Q1:U38):	320,50			
Total depreciation (€)	759,85			
Operating Profit (OP) in €	**-3759,16**			

Notes: One TND is divided into 1,000 millimes.

6.3. Economic Analysis

The production of strawberries in Tunisia was 43,640 tons in 2019 and is forecast to change by an average of 1.55%. The country had an estimated 1,624.00 ha under strawberries cultivation.

The strawberry harvest for the 2024 season is due to start at the beginning of March in the governorate of Nabeul, according to Imed el Bey, President of the Regional Agricultural Union, in a statement to the Daily Assabah on Wednesday February 21, 2024 (el Bey 2024). It will continue for six months, strawberries being the main spring fruit in Tunisia.

He forecasts a 20% increase in regional production compared with 2023, so that output will reach 20,000 tons in 2024, compared with 16,000 tons in 2023. In the meantime, early strawberries are currently sold at high prices. At the height of the season, however, these prices should be between 6 and 8 TND, as they were last year.

The agricultural manager pointed out the problems encountered by growers, including water scarcity and the high cost of seedlings (1 TND 200 millimes per plant, compared with 360 millimes not so long ago). The cost of cultivating one hectare has risen to 76,000 TND compared with 50,000 TND previously, according to el Bey (2024), who mentioned a consequent decline in the area cultivated, i.e. 360 ha compared with 580 ha the previous year. The Governorate of Nabeul accounts for 90% of national strawberry production, 60% of which comes from the Korba Delegation.

6.4. Social Impact Analysis

The Elbosten project, under the broader framework of the FrontAg Nexus, aims to address multiple social challenges by focusing on sustainable agricultural practices and resource management. The key social impacts include:

Working conditions

- Most employment contracts are verbal and based on trust.
- Child labor is not widespread, with a few cases of children aged 14 to 17 involved in strawberry sorting and packing.
- Seasonal workers, who often include women, can face difficult working conditions. Issues are low wages, unsafe transport, and inadequate health and safety measures.
- Strawberry growing is highly seasonal, resulting in a high demand for labor during planting and harvesting periods. This temporary employment opportunity is interesting to the rural population due to otherwise limited employment opportunities.

Social Viability

- **Local Employment:** By focusing on local markets and engaging with local cooperatives, elBosten Phytagri supports local employment and contributes to community development. This social integration strengthens the farm's viability.
- **Stakeholder Engagement:** Active engagement with agricultural unions and local stakeholders ensures that the farm’s activities are aligned with community needs and industry best practices, fostering social acceptance and support.

Gender equality

- Women are involved throughout the strawberry growing cycle, from planting to harvesting, with 80%.
- In North Africa, and particularly in Tunisia, gender discrimination is low, as a significant proportion of women participate in value chain management at all levels in the agricultural sector.

- Despite the women's important role in the strawberry value chain, their labor contribution is often undervalued and thus underpaid compared to their male counterparts. They also lack decision-making power.
- Women are heavily involved in strawberry cultivation. Empowering women through fair wages and leadership roles in cooperatives can promote gender equality.
- Research projects and women-led farming organizations are essential in this respect.

Food and nutrition security. Increased income from strawberry cultivation can improve the food security of farm families. Diversification of strawberry production can also reduce dependency on staple crops and improve dietary diversity.

Living conditions. In general, the living conditions of the workers in the agricultural value chains are improving. This is most notable in the summer season, when farms compete for workers of the high-value seasonal fruits (e.g., melon, watermelon, grapes) to pick and process them.

Sustainable cities and communities. Developing strawberry agro-tourism can boost local economies. Sustainable agricultural practices contribute to the environmental health of rural communities.

Climate change mitigation and adaptation. Adapting to climate change is essential. Strawberries are sensitive to temperature variations. Thus, it is essential to implement adaptation strategies. Cultivating strawberries in a controlled environment such as a greenhouse and minimize water use by relying on hydroponics contributes to climate change mitigation and adaption in farming.

Partnerships for goals. Collaborative efforts between governments, NGOs, the private sector and international organizations can foster the sustainable development of the strawberry sector. Sharing knowledge and resources is essential to achieving these goals

6.5. Environmental Impact Analysis of Hydroponic and in Soil Strawberry

The primary objective of this analysis is to assess the environmental impact of the strawberry value chain using different production techniques in Tunisia. Specifically, we compared the environmental performance of hydroponic and conventional strawberry cultivation systems, considering the entire process from cradle to farm gate, including product transport to retailers.
The environmental impact assessment is based on the True Cost Accounting (TCA) approach (TCI, 2022). For more details refer to **Section 2.5.2**. The environmental impact assessment focuses on the natural capital indicator, which is divided into four key subcategories: climate, soil, water, and ecosystem impacts. For the case of strawberries in Tunisia, the cells highlighted in red indicate areas that were not covered in the analysis (**Table 15**). The 9 impact categories considered are the GHG emissions, carbon stock, erosion, soil organic carbon build-up, water stress, water pollution, acidification, eutrophication, and eco-toxicity.

Table 15. Impact indicators considered in the environmental impact assessment of strawberries, elBosten, Tunisia.

Category	Impact indicator	Data required	Level
Climate	GHG emissions	Yield, fertilizer use, crop protection, energy use, land use changes, crop residue management, tillage and green manure	Cultivation
		Energy use	Processing
		Fuel combustion	Storage & transport
	Carbon stock	Land use changes, crop residue, management, changes in tillage and/or green manure, management, changes in tillage and/or green manure, use, organic fertilization	Cultivation
Soil	Erosion	Slope, precipitation, soil erosion prevention management	Cultivation
	Soil organic carbon build-up	Land use changes, crop residue management, changes in tillage and/or green manure use, organic fertilization	Cultivation
Water	Water Stress	Location, crop, irrigation (yes/no)	Cultivation
	Water Pollution	Fertilizer application in units N and P	Cultivation
Ecosystem	Acidification	Fuel use, fertilizer use, crop protection uses	Cultivation
		Fuel use, material use	Processing
		Fuel use	Storage & transport
	Eutrophication	Fuel use, fertilizer use, crop protection uses	Cultivation
		Fuel use, material/substance use	Processing
	Eco-toxicity	Crop protection use	Cultivation
		Energy use, material use	Processing

Data were collected from two cultivation systems of a Tunisian SME, ElBosten: one hydroponic and one conventional greenhouse strawberry farming system. These data were complemented by data from different secondary sources. The functional unit (FU) is 1 kg of strawberries of marketable quality at the farm gate harvested in 2024. The system boundary is from cradle to gate (Figure 18).

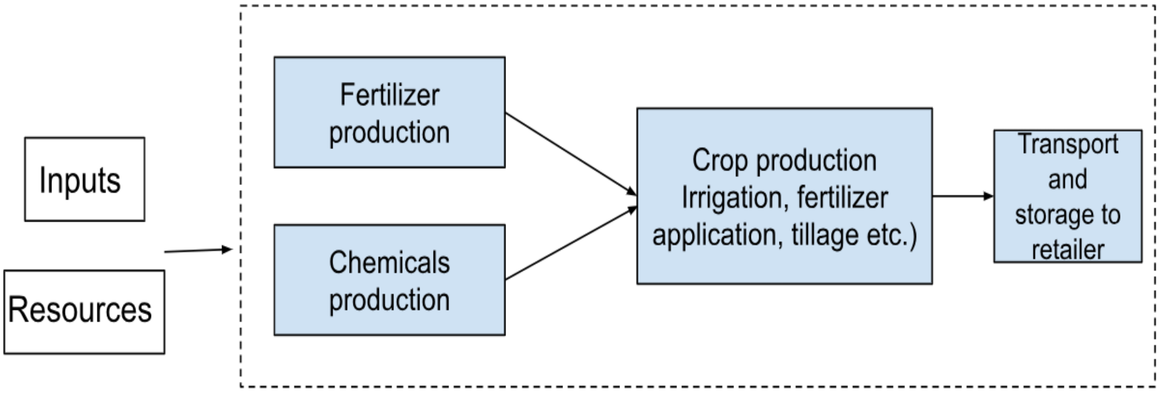


Figure 18. System boundary.

As shown in **Figure 19**, the hydroponic system has a total CO2 equivalent of 0.21 kg CO2e/kg, while the soil-based strawberry system has 0.33 kg CO2e/kg. These figures indicate that the hydroponic system demonstrated a lower environmental impact per kilogram of produce compared to soil-grown strawberries. Additionally, the hydroponics system yields a higher output in terms of productivity (3.7 kg/m2 vs 1.85 kg/m2). The highest GHG emissions were attributed to energy consumption in hydroponics and fertilizer application in both systems. This suggests that transitioning to renewable energy sources, such as photovoltaics and using organic substrates like vermicomposting (where insects and worms convert organic waste into fertilizer) could significantly reduce the environmental impact of both cultivation methods.

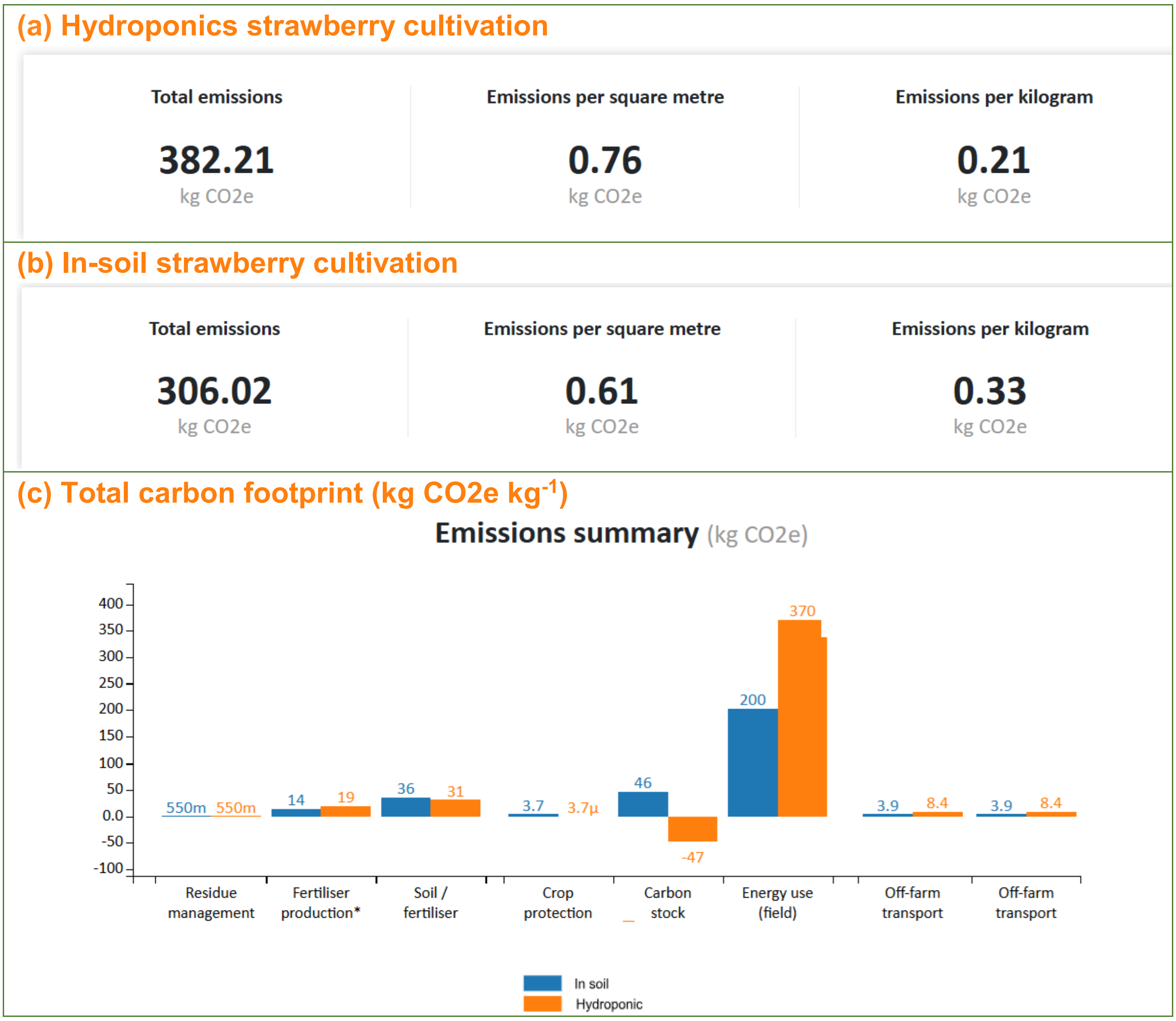


Figure 19. Comparison of hydroponic and conventional strawberry CO2 emissions.

The total true cost for each impact indicator (sum of all costs) was calculated, as shown in Table 16. Results indicate that the true cost (externality) of hydroponic farming is lower, in monetary terms, compared to conventional strawberry farming, based on 2022 prices (-3.4€ for hydroponics vs. 11.6€ for conventional). The negative value for hydroponics indicates an overall net benefit. However, greenhouse gas emissions are similar for both systems, as soil-grown strawberries are also cultivated in a greenhouse. Energy consumption, however, is higher for hydroponic strawberries.

For the carbon stock calculation, a negative (benefit) value was assigned to hydroponics using the estimated emission value of in-soil strawberry farming. As shown in Figure 20, the eutrophication impact is similar for both systems, as the hydroponic farm has not yet implemented water treatment. Overall GHG emission costs are higher for in-soil cultivation, which is also responsible for increased soil erosion. The findings demonstrate that hydroponic systems represent best practices for both economic and environmental considerations, particularly when resources like water and land are limited.

Table 16. True cost estimation of hydroponic and conventional greenhouse in soil strawberry, elBosten, Tunisia.

Impact category	Impact indicator	Monetization factor (at the base year)	Used tool	Hydroponics		In soil	
				Emissions per FU	TC per kg	Emissions per FU	TC per kg
Climate	GHG emissions	116€/ton[a)] CO_2eq	Cool farm	0.210	0.02	1.61	2.30
	Carbon stock	±116€/ton CO_2 eq	Cool farm	-47	-5.45	46	5.06
Soil	Soil erosion	27.38 USD/ton soil	Revised Universal Soil Loss Equation	0.00	0.00	0.024 (Belaid et al. 2018)	0.60
	SOC build-up	±100€/ton SOC emission/buildup	Cool farm	0.01	0.001	0.01	1.00
Water	Water stress[6]	1€/m³	Aqueduct WRA*	1.90E+01	0.002	0.5 M3	0.50
	Water pollution	4.70€/kg PO_4eq	Grey Water Footprint Guidelines	0.15	0.71	0.37	0.50
Eco-system	Acidification	8.75€/kg SO_2eq	USEtox	0.001	0.0087	0.001	0.00875
	Eutrophi-cation	4.70 €/kg PO_4eq	USEtox	0.015 (Romero-Gámez et al. 2020)	1.27	0.37 [b)] (Romero-Gámez et al., 2020)	1.7
	Eco-toxicity	340 €/kg Cu eq	USEtox	No data	No data	No data	-
Total					**-3.4€**		**11.6€**

Notes: a) Year 2022 prices. b) year 2014 prices. *Water Risk Atlas. 1 EUR = 1.1 USD was used. FU = Functional unit; SOC = Soil organic carbon; TC = True costs

[6] An extremely high water stress level was assumed, and the crop water requirement was based on FAO (2022) data.

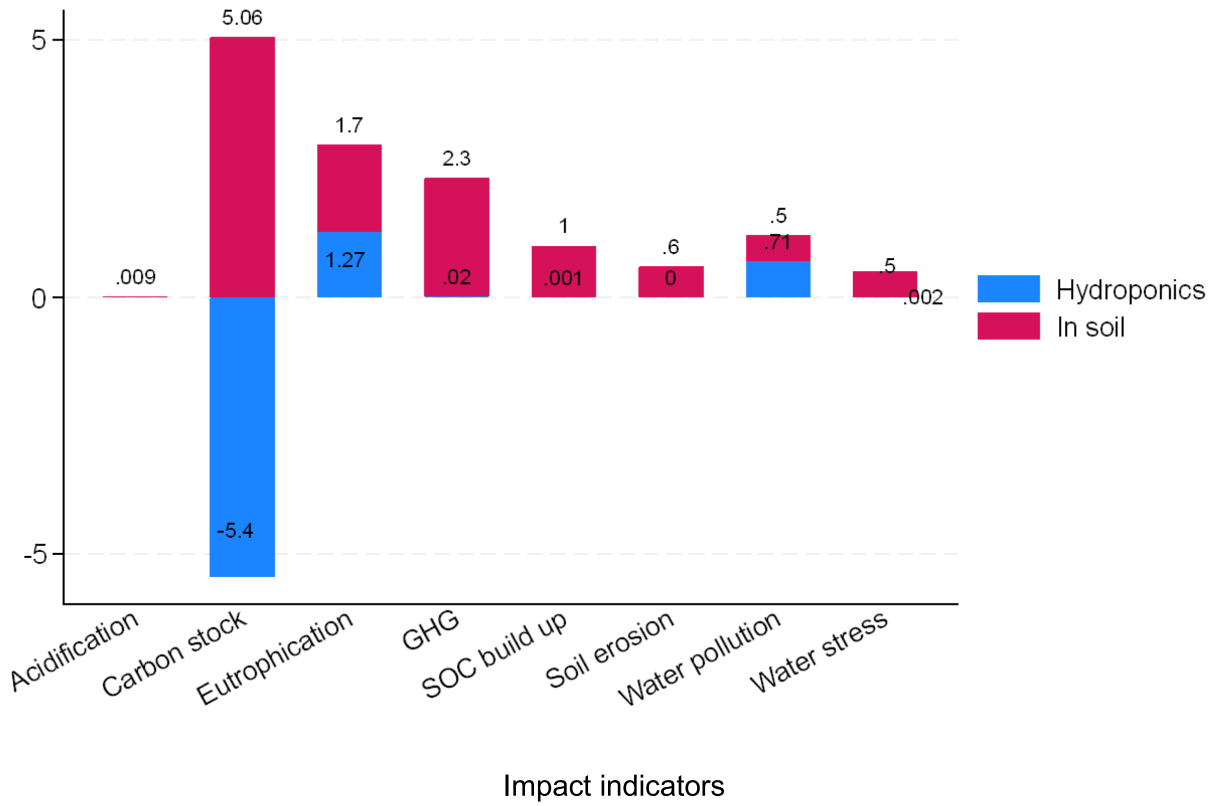


Figure 20. True cost comparison of hydroponic and in-soil strawberry production by impact indicators.

Overall, both hydroponic and soil-grown strawberries have their pros and cons. Hydroponic systems offer significant environmental benefits, particularly in water use efficiency and reduced pesticide application. However, they require a controlled environment and can have high initial setup costs. Soil-grown strawberries, while more traditional, have a higher environmental impact due to water use, pesticide application, and land requirements.

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