Sustainability assessment of hydroponic tomato farming systems for Souss-Massa region

Thesis Research Project

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ABSTRACT

One strategy to solve the severe environmental problems of Moroccan horticulture, especially water scarcity, is to upgrade agricultural methods by introducing high-tech greenhouses equipped with closed-loop hydroponic systems. However, these technologies are unprecedented in the country, and the implications for the environment remain unknown under local conditions.

Using life cycle assessment with a functional unit of one kilogram of tomatoes at greenhouse gate, this study aimed to predict the environmental impacts and the hotspots of two different closed-loop hydroponic systems if they were deployed in the Souss-Massa region, the biggest producer of the country. 18 mid-point indicators from ReCiPe were used, highlighting the most relevant ones for the region: use of net freshwater (UNFW), terrestrial ecotoxicity (TET), freshwater eutrophication (FE), and global warming (GW). A field trip to Agadir, the capital of the region, also helped to collect different views on the transition to these technologies.

The impact assessment revealed that artificial lighting would be the main contributor to 17 categories due to electricity being generated from oil and coal. To a lesser extent, landfilling of waste would also impact most of the categories. A new scenario with renewable energy showed that the impact from lighting can be drastically reduced by around 80% for GW, TET, and FE and by 34% in the case of UNFW. Contrarily, waste plastic recycling does not significantly influence the LCA results since the more abundant organic waste is a larger contributor.

For Souss-Massa to sustainably transit to hydroponic systems, it is essential that electricity consumption for lighting is drastically reduced and/or switched to clean sources. Organic waste needs to be revalorized by implementing composting processes or biodigesters. Lastly, the field trip exposed some key challenges to transit to more sustainable hydroponic farming systems: gaining the trust of farmers, finding financial support, and promoting collaboration between growers and the local community.

ACKNOWLEDGEMENTS

With this thesis project, I put an end to a two-year adventure that started by just googling my interests, “Industry” and “Environment” in search of a Master’s program not sure where. Suddenly, despite I had very little idea of what Industrial Ecology meant, I knew that was the path I wanted to take. The adventure took me to a wonderful and dynamic country where a bike becomes indispensable as it provides freedom. The international environment of Leiden University and TU Delft (and essentially the entire Netherlands) made it easy to meet fascinating individuals from whom I learned more than I can remember, from cooking recipes to growing fungi-based coffins.

This report is the result of the last 6 months of work but, more importantly, of collaboration with many other people that helped me to complete this final sprint. For that reason, I would like to thank them. Thank you to my supervisors Dr. José M. Mogollón and Dr. Bernhard Steubing for their guidance and advice. Thank you to my fellow colleagues from the Interdisciplinary Thesis Lab on Sustainable Horticulture organized by LDE Centre for Sustainability, and to its coordinators: Coen Hubbers, Jan van den Ende and Esther van der Ent. I will never forget the precious time spent in Morocco with them. I also want to thank all the professionals, researchers, and students involved in the project, always willing to share their knowledge and time.

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To all,

thank you for getting me to this point.

CONTENTS

1. INTRODUCTION

1.1. Horticulture in Souss Massa

The horticultural sector worldwide is facing numerous challenges that threaten to disrupt food supply. Due to climate change, arable land is shifting towards polar regions, causing Europe and Africa to lose over 15% of their productivity (Zhang and Cai, 2011). In addition, a globalized world and changing environmental conditions provide an opportunity for pests to spread and thrive in new areas bringing along diseases that reduce the yield of farmers (Skendžić et al., 2021). At the same time, global population keeps growing, demanding more food from horticulture while occupying the increasingly limited space.

In Morocco and particularly in Souss-Massa region, horticulture is one of the main drivers of the economy and the reason why agriculture is the most important sector in the country accounting for 12% of the GDP (The World Bank, 2021) and employing over 30% of its population (La Banque Mondiale, 2019). However, horticulture is also responsible for the overexploitation of natural resources which, in case of water, are alarmingly scarce. Due to climate change, the country is increasingly suffering from longer draughts and higher temperatures (Lionello et al., 2008) which, added to a rapidly growing population, exerts an immense pressure on the environment to supply food to the local population and the increasing European market.

Souss-Massa region (Figure 1) is one of the twelve regions in Morocco and home to a population of 2.7 million inhabitants. It is bordered by the Atlantic Ocean on its western side and crossed by the Anti-Atlas Mountain range. Thanks to its mild climate and the two river basins that give their names to the region and irrigate its land, Souss-Massa has become the biggest producer of crops in the country as it exports more than 50% of the vegetables of Morocco (soussmassa.ma, 2018). However, the area is not immune to the environmental problems connected to horticulture that affect freshwater availability and the toxicity of terrestrial and aquatic ecosystems.

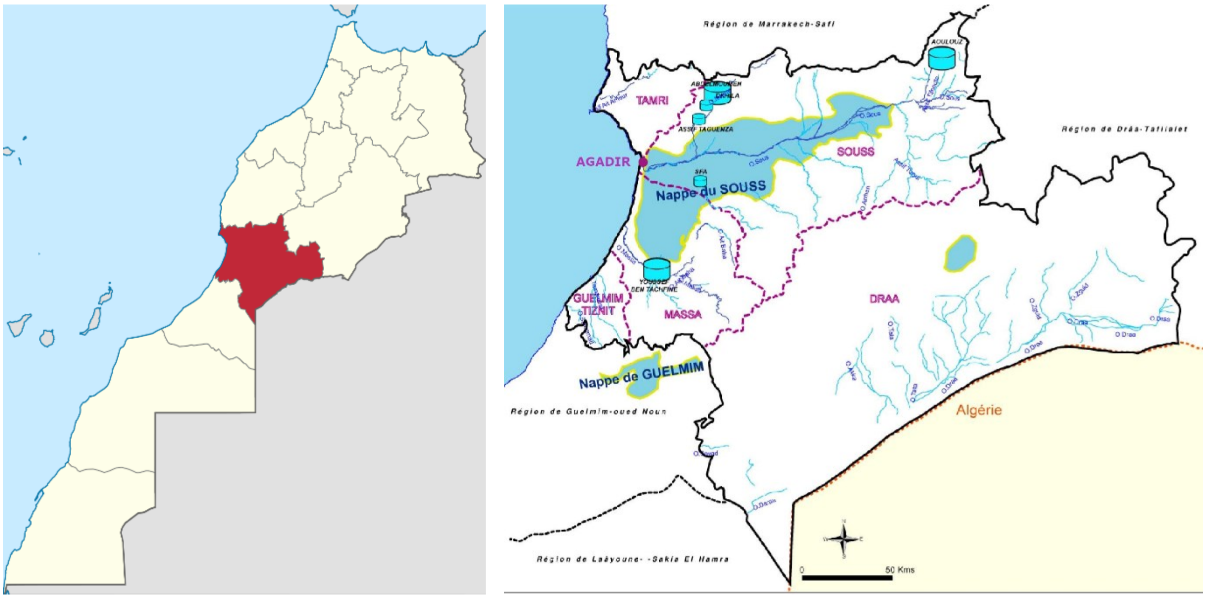


Figure 1 Souss-Massa region within Moroccan territory (left) and main provinces and water bodies (right).

As in the rest of Morocco, water scarcity is the main challenge. Here, horticulture is responsible for 90% of the water consumption which clearly clashes with the critical condition of hydric reservoirs, suffering from a deficit of 290 million cubic metres per year (Choukr-Allah et al., 2016). The overexploitation of groundwater wells is allowing marine water to intrude threatening the quality of ecosystems with its salinity. The reason behind this disproportionate withdrawal is not only the size of the sector but, more importantly, the inefficiency of the agricultural methods. Despite its hyperarid climate, 44% of the cultivated land is irrigated, being flooding the most common technique (Choukr-Allah et al., 2016).

This mismatch between environment and practices not only cause the depletion of water resources but also its pollution, as well as that of the soil, with chemical fertilizers and pesticides. At national level, it is estimated that 1500 tonnes of nitrates leach each year into the soil, while 7500 tonnes of pesticides are applied (Malki et al., 2017). An increasing trend is to satisfy the demand with desalinated water, which is not free of impacts due to its energy intensity extraction and the residues that it generates. Moreover, this approach only tackles the availability of water while the other impacts remain unsolved. Consequently, new strategies must be designed focusing on reducing the demand of natural resources in order to bring real sustainability to the region.

To increase productivity, local farmers have slowly moved their production into greenhouses that now occupy 6500 ha in Souss-Massa region (Hirich et al., 2017). This type of cultivation, called protected horticulture, allows some crops such as tomatoes, cucumbers, or chillies, to be cultivated in enclosed environments that, to a greater or lesser extent, provide protection from the weather and pests while giving considerable control over the conditions to the farmer and extending the duration of the harvest season (Barbosa et al., 2015). Nevertheless, the greenhouses currently being used in Souss-Massa are primitive and, therefore considered low-tech. Canarian greenhouses, as they are called, are normally smaller than 1 ha and covered by plastic sheets held in place by vertical wooden supports and a metal network. Openings between adjacent plastic sheets facilitate the provision of ventilation and water discharge. Their main disadvantages are poor construction and ventilation, lack of climate control, high humidity, low CO2, bad insulation, and weak light radiation. What is more, since farmers still grow crops on the ground, high water consumption and soil pollution remain present. As a consequence of all these problems, yields are low and of bad quality with a high percentage of unmarketatable products. Furthermore, after a short lifespan of 10 years, the fragile structure starts breaking down, opening the door to pests and diseases (Stanghellini et al., 2017). Waste generated from decaying greenhouses is poorly collected and, if so, treated in barely managed landfills (Dahchour and Hajjaji, 2020).

Due to all these circumstances, it is undisputed that more efficient agricultural techniques are required in the region. High-tech greenhouses such as the ones found in the Netherlands provide an opportunity since they can grow crops with a minimal water footprint, as well as a lower consumption of fertilizers and essentially no use of chemical pesticides. This is achieved by using the Venlo type glasshouse which is equipped with a climate control system, heating, active ventilation, soil-less cultivation, and a closed irrigation and fertilization (fertigation) system, features that are combined with natural pest control and pollination practices. As an example, high-tech greenhouses could potentially reduce the water footprint of tomatoes, the most predominant protected crop in Souss-Massa, by 95% (Nederhoff and Stanghellini, 2010).

1.2. From Low-tech to High-tech via hydroponics

Although still scarce, high-tech greenhouses are starting to pop-up in Morocco. They are normally run by big companies or located in research institutes. An example of the second case is the Centre of Excellence in Horticulture (CEH), in Agadir, the capital of Souss-Massa region. The centre is born out of the necessity to develop, teach and promote more efficient agricultural methods, but it also serves as an experimental facility to test the performance of advanced technologies in the hot and dry conditions of Morocco. The present study is conducted under the scope of the same project and specifically aims at hydroponic systems which are a promising opportunity to upgrade Moroccan horticulture. The goal is to evaluate the environmental impacts of these kind of systems, adjust them prior to their implementation and thus ensure that sustainability is highly considered during the transition to more advanced technologies.

"Hydroponics" is a technique of growing plants in nutrient solutions out of soil with or without the use of an inert medium (Sharma et al., 2019). Another characteristic is that the solution is collected afterwards and disposed of (open irrigation) or recirculated (closed irrigation). Hydroponic systems are almost always used inside a greenhouse although there are some farms using it outdoors or in hybrid setups that combine both (Mimaflor.es, 2017). Hydroponic systems provide two main significant advantages in the context of Souss-Massa compared to soil-based cultivation:

- No need for soil that might be infected or can incubate diseases, decreasing the amount and quality of yield.
- Water and nutrients are conserved, which reduces the consumption and pollution by leaching.

As previously mentioned, this technique is compatible with but not limited to the use of an inert growing media, also called substrate. The most common substrates in hydroponics are peat, rockwool and coconut coir, being the latest option preferable due to the negative environmental issues associated with the extraction and production of the other alternatives (Xiong et al., 2017). In the other hand, it is also possible to cultivate crops putting their roots directly in contact to the water flow. One of the many techniques is the nutrient film technique (NFT) in which roots are introduced in a constantly running flow of aerated enriched water. This practice is widely used for the cultivation of small leafy crops like lettuce or celery but it has hardly been introduced to bigger crops like tomatoes or cucumbers, that are grown on substrate instead.

Due to these undeniable advantages, the present study was carried out to analyze in more detail the feasibility of implementing hydroponic farming within the context of Souss-Massa agriculture. The reference crop were tomatoes as it is the most cultivated protected crop in the sector. The focus was put on the environmental perspective by identifying the main impacts and hotspots and discussing strategies to minimise and tackle all the negative effects. The final goal is to ensure that sustainability is highly considered during the transition to a more responsible agriculture in Morocco, that could eventually be transferred to other countries in the MENA region.

In the next sections, both systems are described in detail.

2. HYDROPONIC TOMATO FARMING SYSTEMS

In this study two alternative hydroponic systems for the cultivation of tomatoes were evaluated to assess their sustainability in the context of Souss-Massa region. These systems represent a major leap forward compared to the cultivation methods currently used in the ubiquitous canarian greenhouses in Morocco. The reason for evaluating these highly advanced greenhouses and no other intermediate technologies is to gain insight into all the possibilities available for the development of Moroccan horticulture in the long term. Likewise, traditional methods are not included in the analysis due to its demonstrated environmental impacts which rules them out as viable options (Stanghellini et al., 2017). This will enable the development of a vision toward which efforts may be directed. The results of this evaluation will point to priorities and subsequently will draw a roadmap to be followed.

The first alternative resembled the conventional techniques and technologies currently being used in a high-tech greenhouse in the Netherlands to grow tomatoes. It is worth noting that this system aims at being an averaged representation of the very diverse hydroponic cultivation methods used in the Netherlands nowadays. Environmental conditions, resources and the tomato varieties are just a few of the many critical factors that force farmers to develop and adapt their own practices.

The second system was more advanced and implemented techniques that have not yet been commercially used but have the potential to increase efficiency, reduce costs and enhance sustainability during cultivation. These techniques have already been successfully tested in the Westland region between 2014 and 2015 (van Staalduinen, 2015) under the commercial name of FUTAGROW system, which will be used hereafter to refer to this system.

Both systems make use of a high-tech greenhouse, a type of greenhouse with certain advanced characteristics that are described in the next subsection, followed by the description of the individual characteristics of each system.

2.1. High-tech greenhouse

High-tech greenhouses in the Netherlands are normally made of glass and have a size of 7 ha on average (EcoInvent 3.9.1., n.d.). They are equipped with systems for heating, climate control, lighting and closed fertigation. A boiler delivers heat through a network of pipes located at ground and plant levels. The CO_2 from combustion is reinjected into the greenhouse to boost photosynthesis. Fans and autonomous windows help to regulate CO_2 levels and humidity. LED grow lights are installed at 4 meters high to supplement the deficit of sunlight. Fertilization and irrigation are simultaneously delivered using a dripping system. Plants are not grown in soil but in substrate, placed on top of gutters so the excess of water can be collected. This way, water is purified and recirculated after nutrients absorbed by the plants are restored. Pest control is provided by means of sticky yellow tape distributed all along the crop to monitor plagues. If needed natural pest control are applied. Chemical pesticides are avoided to not kill the bees that are used for pollinating the flowers.

For this study, the material used for the outer structure was plastic instead of glass since it is a cheaper and more feasible alternative for Morocco. Other than that, all characteristics of a high-tech greenhouse were included.

2.2. Conventional hydroponic system

As mentioned before, this system represents the most common hydroponic cultivation practices in the Netherlands. Particular systems might differ as a result of specific conditions and crop varieties. For this study, cultivation of tomatoes was divided in six phases: seed production, sprouting, grafting, nursery, maturing and harvest.

Seed production

In this phase two varieties of seeds need to be produced. The first one is used to produce the rootstock while the second forms the scion and thus determine the tomato species that is produced. For the Moroccan case, seeds were assumed to be supplied from the Netherlands although producers are distributed around different parts of Europe. Since seed production falls out of the scope of the project no more details are given about this process.

Sprouting

Seeds are sowed in a propagation tray filled with substrate. The tray is made of plastic, reusable several times and contains cells of about 4x4x4cm. The company in charge of doing this is called propagator and for the case of Morocco is considered to be located close to the farm site. For the sprouting of the rootstock seeds, instead of loose substrate, it is more common to use plugs which are little discs of compacted substrate enclosed in a biodegradable net. When plugs get wet, they expand and can host the seed. The net allows the propagator to transplant the seedling without producing any shock to the root ball. After approximately 5-7 days the sprouts emerge and two weeks later, the seedlings are big enough to be grafted together.

Grafting

In this process one seedling of each type, a rootstock and a scion, are taken and their stems cut at the same height. The upper part of the scion variety is attached to the lower part of the rootstock using a plastic clip. The remaining parts of the seedlings are discarded. After the grafted seedling heals and shows new growth, in around one week time, is taken to the nursery.

Maturing

This phase covers the life of the plant since it is grafted until the first harvest. In the conventional system, the first four weeks of maturing take place at the nursery and the next five at their final spot in the greenhouse. In the nursery, the plugs that host the rapidly growing grafted seedlings are inserted in the so-called substrate blocks, similar to plugs but bigger in size, about 10x10x4 cm. As they grow, seedlings need to be spaced between each other, so the branches do not overlap. After four weeks, the grow block is taken to the greenhouse and placed on top of a substrate slab, a long block of compacted substrate packed in a LDPE film. Unlike plugs and growing blocks, slabs are not fertilized. Separation between plants is about 50cm in the same row and 80 cm between rows, which translates into a density of 2.5 plants/m^2. A drip is connected to the block to provide water and nutrients and the gutter underneath the slab collects the excess of water. The plant is also trellised with a hanging thread to maintain it vertically. The first harvest takes place five weeks after the arrival to the greenhouse.

Harvest

On average, plants produce one truss of tomatoes per week and keeps in production for 40 weeks. However, production varies along the life stage of the plant. During the first nine weeks of harvest, productivity is considerably higher and progressively slows down towards the old age of the plant. Additionally, this vigour of youth is also reflected in a reduced impact of diseases and thus, the plants require less attention. Conversely, fertilization requirements increase over time. Taking the dose of an old plant as a reference, young harvestable plants require 80% of the dose while maturing plants require just 40% (Fajardo, 2018).

Annual yield varies widely from variety to variety. Cherry tomato plants, e.g., produce around 25 kg/m^2 while the biggest varieties can produce up to 100 kg/m^2 (de Gelder et al., 2005). For this study, the "brioso" species was taken as reference, a medium sized tomato with an expected yield of 40 kg/m^2/yr in conventional hydroponic farming.

2.3. Futagrow hydroponic system

The Futagrow system has the goal of increasing further the productivity of high-tech greenhouses (van Staalduinen, 2015). The idea behind it is to make better use of the space and the sunlight, so the high costs of construction and maintenance are divided by a larger yield. In this system, the initial seedlings are produced the same way but several features are added during harvest:

1. The distance between rows of plants is halved, doubling the plant density. This allows for capturing 95% of the sunlight. However, it also brings two trade-offs. First, while sunlight is more efficiently captured (it does not reach the floor), lower branches are shadowed and do not receive enough radiation. Secondly, the accessibility of workers to the plants is restricted by too narrow corridors. These trade-offs are solved with features 2, 3 and 4.

2. Intermediate lighting is installed to provide radiation to the lower branches. This gives control to the farmer over the exact amount of light that is given to the plant.

3. Gutters can be lifted so accessibility to the plants is restored. This also allows to regulate the exposure of plants of different height.

4. Plants are grown in short, alternated cycles. Plants located in odd and even rows are at different stages of growth. While ones are maturing the others are being harvested. After nine weeks they interchange roles: the maturing plants produce their first harvest, and the older ones are removed and substituted by a new seedling. This keeps the greenhouse full of younger plants that are healthier, more productive and consume less fertilizer. Beside a more intensive labour, the disadvantages of this practice are the increased consumption of

expensive seedlings and substrate and the generation of additional waste. These disadvantages are solved with features 5 and 6.

5. Use of Nutrient Film Technique (NFT) which instead of solid substrate only uses water to deliver the nutrients to the roots. The plant is held using just a plug and the roots are in direct contact with the water flow. Despite a more intense flow of water, the water consumption stays the same as the water is still recirculated. This technique forces to slightly modify the production of seedlings at the propagator. Plants grown in liquid media are especially vulnerable during transplant. For this reason, after grafting they are moved directly to their final spot at the greenhouse.

6. To reduce the cost of seed supply, seedlings are obtained directly from sideshoots from the plant in the adjacent row. The only exception are the first seedlings of the season as they are obtained from the propagator, as per usual in conventional farming.

The main advantage of this system is an increase of 20% yield per square meter as it was demonstrated (van Staalduinen, 2015). Furthermore, fertilizer could theoretically be reduced by 10% per kilogram of tomatoes, according to fertilizer requirements depending on the age. Although this was not confirmed in the report from 2015, this variable was implemented in the present study.

The system, however, also comes with some drawbacks that were observed during and after the test from 2015. Firstly, the increased humidity in the greenhouse needs to be managed. Additional materials are required, such as liftable gutters. Seed companies do not agree with the use of sideshoots for propagation and demand a payment for each plant propagated, regardless of the use of seeds, reclaiming the rights over the variety. Fertigation by means of NFT brings some challenges and risks as the water must keep running. A breakdown affecting the irrigation would be fatal for plants after only a couple of hours in comparison to one-day safety margin in conventional cultivation thanks to the water buffering capacity of substrate. Ultimately, the system becomes more complex and labour intensive, which hinders its implementation by farmers that might be short-handed or not experienced enough.

All these features and their interrelation extracted from the report by van Staalduinen (2015) have been synthesized in the scheme shown in Figure 2. It Is worth mentioning that although features are added to solve the drawbacks of features upstream, they could also be implemented independently. For example, the propagation from sideshoots could be implemented in the conventional system without changing anything else. This is also relevant in the case of NFT which has the potential to reduce consumption and waste.

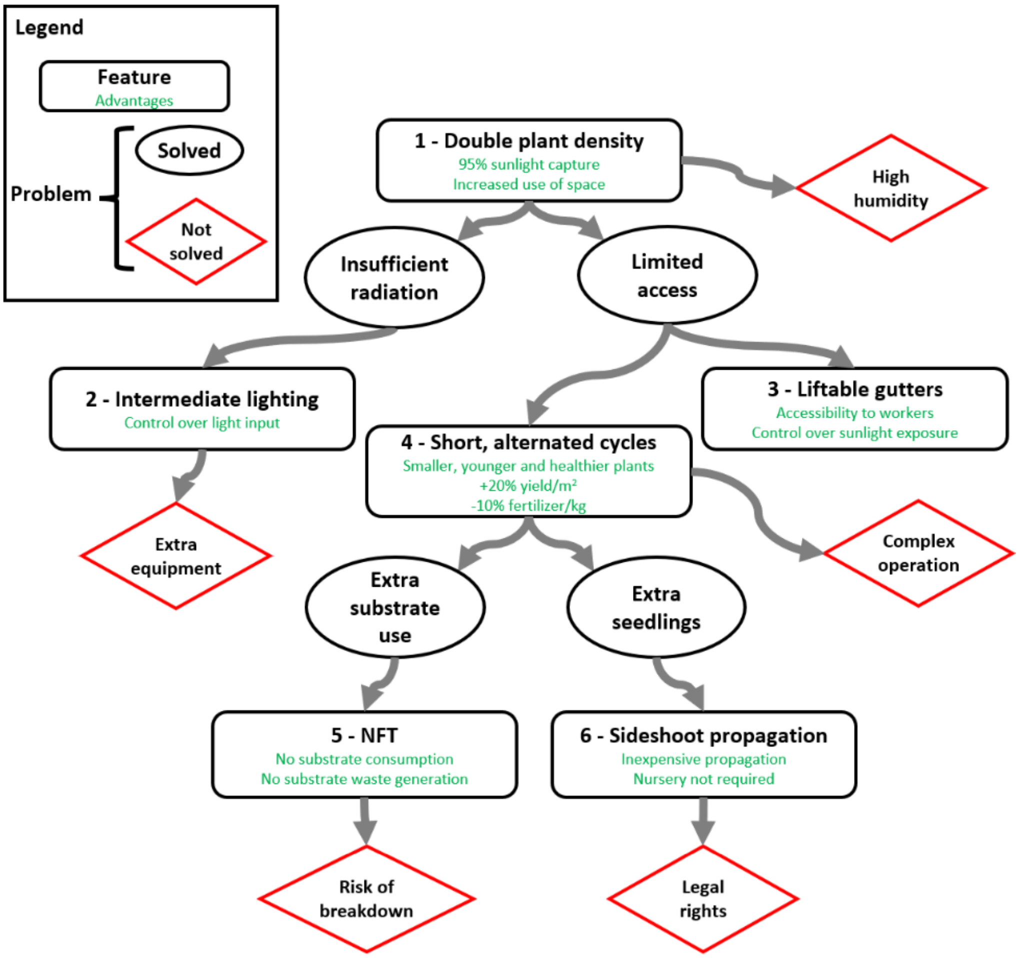


Figure 2 Distinguishing features of Futagrow system.

In Figure 3, a schematic comparison of the schedules of each system is shown. As it can be seen the time and space of the greenhouse is the limiting factor of the production. Both systems use 45 weeks per year (Figure 3). The remaining weeks are used to sanitized the greenhouse and prepared it for the next season. Additional visual content describing the conventional and Futragrow cultivation are included in appendix "A1 - Operational schemes".

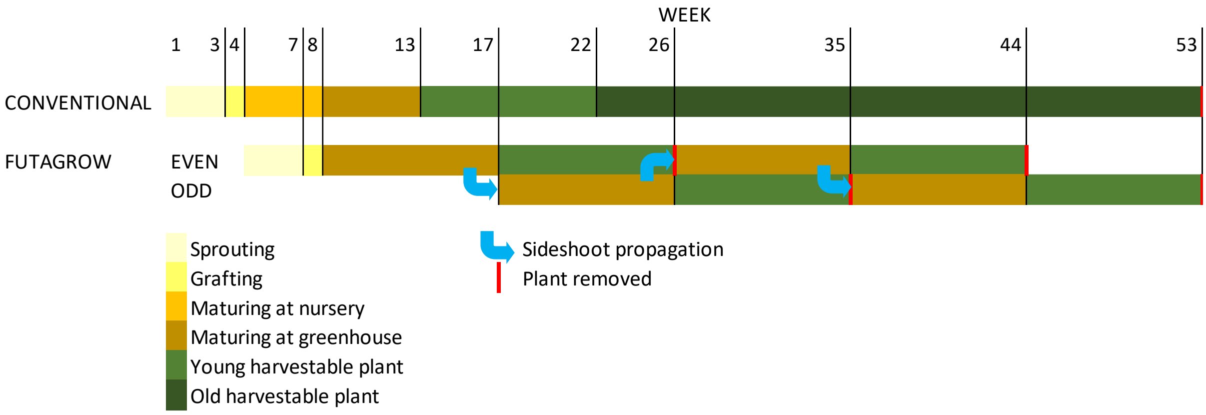


Figure 3 Annual schedules of conventional and Futagrow systems.

3. RESEARCH QUESTIONS

The analysis of the environmental performance of these systems was guided by the following research questions:

Main research question:

Which of the proposed hydroponic farming systems for tomatoes is more environmentally sustainable in the case of Souss-Massa?

Sub-research question 1:

Which processes and interventions are contributing the most to the main environmental issues in the region, namely, water scarcity, water eutrophication, soil pollution and global warming?

Sub-research question 2:

How can the environmental impacts previously identified be diminished while keeping productivity high?

4. METHODS

4.1. Life Cycle Assessment

To answer the previous research questions, this study used Life Cycle Assessment (LCA) as primary tool. According to the norm ISO 14040, LCA is a "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, 2022). This makes LCA an appropriate tool to analyse the environmental performance of production systems like tomato farming since they have a clear function, producing tomatoes. Following the guidelines from the LCA handbook by Guinée (2002), all stages are accounted in the calculation of environmental impacts, including the extraction of all raw materials involved (for cultivation, energy production, greenhouse construction, etc), their transformation into useful inputs, their use, and their final disposal. Only by considering the whole product system can it be judged if a hydroponic farming system is more environmentally friendly than the other (Guinée, 2002).

Furthermore, LCA also helps to identify in which of all processes the main impacts are produced. Knowing this, strategies can be designed to effectively tackle the main environmental hotspots of a product. In this study, this feature of LCA is utilized iteratively to develop improved scenarios, adding each time a new feature that aims to neutralize the biggest impacts, finally creating a new alternative that takes into account all processes and impact categories.

LCA methodology is standardized and structured in four phases as defined by the norm ISO 14040: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results (see Figure 4). The first stage sets the foundations of the analysis by stating its purpose, functional unit, and the target audience. On the inventory analysis, the system is defined in detail and the data is collected. At the end of the second phase, the inventory results show the total interventions (emissions and extractions) between the system and the environment. During the impact assessment, the inventory results are converted into scores of a selection of impact categories such as climate change, soil acidification or marine eutrophication, using characterization factors. It is also possible to compare the gravity of the impacts or even aggregate them by a process called normalisation that, however, adds a high level of uncertainty. Finally, during interpretation, the results are evaluated to identify the main environmental hotspots within the system, followed by the formulation of conclusions and recommendations.

It should be noted that this report is not completely structured in the same way as the LCA framework. The contribution analysis of each scenario is presented right after the characterisation results. This follows the actual order in which the study was performed, an iterative process starting with characterisation results from the baseline scenario followed by contribution analysis, search of potential solutions and modelling new scenarios.

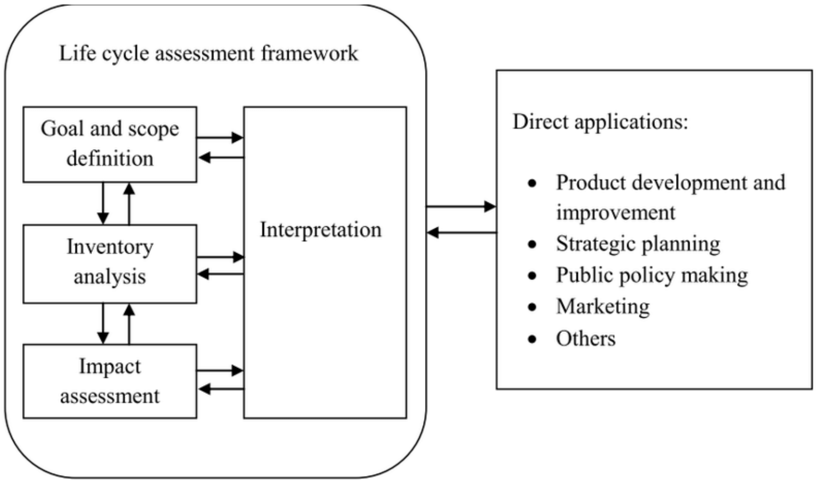


Figure 4 Framework and phases of LCA. (ISO 14040:2006, 2022)

The software Activity-Browser (Steubing et al., 2020) was used to create the LCA model, compute the data, and calculate the results. This software is an open-source tool for advanced LCA based on the framework Brightway2 and widely used among the research community.

4.2. Data requirements

The study relied primarily on the vast literature and datasets from Dutch horticultural experience, and was adapted to Moroccan conditions following the findings of previous works in Souss-Massa (Nederhoff and Stanghellini, 2010; Stanghellini et al., 2017). When available, primary data was used instead of secondary sources.

LCA strives to be predominantly quantitative in nature, aiming to provide a comprehensive understanding of the environmental impacts involved. However, in cases like the present study in Souss-Massa, where quantitative data is not always available due to the early stage of implementation, qualitative aspects can and must be considered additionally. By combining LCA with qualitative aspects, this investigation aims to present as complete a picture as possible of the environmental impacts associated with the system under study. To fill the qualitative data gap, this study was carried out in close contact with professionals of the sector and included a field trip to Agadir and Rabat in which discussions were held with stakeholders such as farmers, government, researchers, and companies connected to Moroccan horticulture to assess the validity of the data as well as the feasibility of the different scenarios.

Furthermore, these qualitative inputs are also valuable to gain insight into the techno-socio-economic-barriers slowing down the transition towards more sustainable agricultural systems in the region. Investigating those pitfalls falls out of the scope of the present study which, as mentioned before, focus exclusively on the environmental implications. However, they are inevitably relevant and thus, are briefly discussed in appendix 10 where the quantitative findings are complemented by the inclusion of qualitative insights to provide recommendations into possible pathways.

The research workflow can be seen in Figure 5.

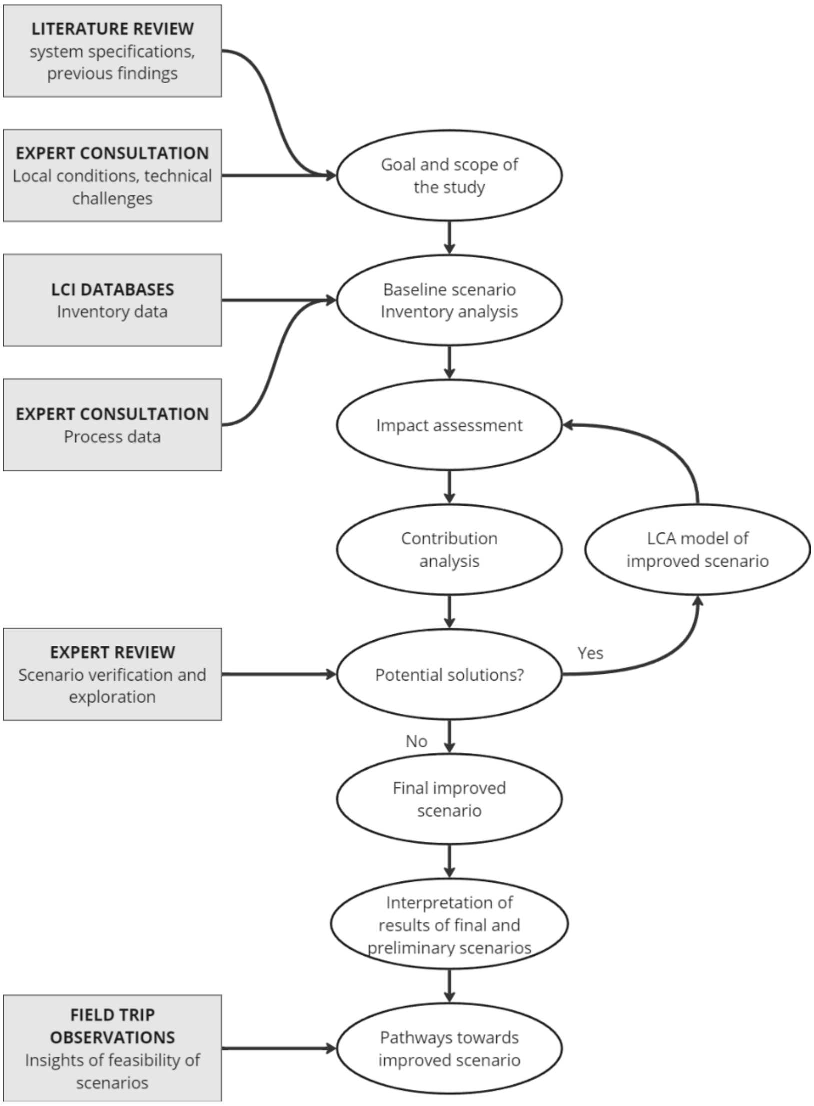


Figure 5 Research plan workflow and data sources.

5. LCA OF GREENHOUSE CULTIVATION IN SOUSS-MASSA

5.1. Goal and scope definition

5.1.1. Goal definition

This study applies Life Cycle Assessment to compare two cultivation methods for tomatoes using hydroponic systems in industrial greenhouses in the geographical context of Souss-Massa region, in Morocco, that have the potential to upgrade the current agricultural practices in terms of productivity, fruit quality and sustainability.

While hydroponic technologies have been developed and become common practice in the Dutch horticultural sector, they have barely been implemented in the Souss-Massa region and therefore have not been adapted to the specific requirements of this area, which differ significantly from those of the European country. The results of this study will allow to predict the environmental hotspots and impacts during cultivation that these techniques would cause if they were directly implemented there. Furthermore, using an iterative approach, the system was adjusted and analysed again in multiple scenarios to optimize its environmental performance before its final deployment.

This study is conducted by a student from TUDelft and Leiden University as his final thesis research project of the Master's Industrial Ecology. Along with the projects from other students, it is part of the Impact Cluster created in Agadir (Morocco) which aims at improving horticultural practices in the region by implementing advanced technologies and knowledge from the Dutch agricultural sector. Therefore, interested parties are the Moroccan government, companies from the horticultural sector and, especially, local farmers seeking to upgrade their productivity while ensuring sustainability in their operations.

Although multiple experts from the field have been consulted during all phases of the study, a further expert review will be required if the results are to be applied to a specific farm since the characteristics of each variety of tomato and the environmental conditions can highly differ from the average values used in this analysis.

5.1.2. Scope definition

This study focused on the cultivation of tomatoes in plastic greenhouses in Souss-Massa using different hydroponic systems. The temporal scope was located at the present 2023, in an hypothetical scenario in which these technologies have already been deployed in the region to simulate the impacts that they would be causing right now. The system included all phases until the harvest of tomatoes excluding the packaging as well as the transportation to the next entity in the supply chain. The analysis included all the environmental emissions found in ecoinvent 3.9.1 datasets.

For a more detailed description of the systems, see chapter 2 and appendix A1. System boundaries will be described in section 5.2.2.

5.1.3. Function, functional unit and reference flows

The function, functional unit, alternatives and reference flows defining the LCA are indicated in Table 1.

Table 1 Function, functional unit, alternatives and reference flows

Function	Production of fresh quality tomatoes in Souss-Massa region (Morocco) in 2023.
Functional unit	1 kilogram of tomatoes in bulk at greenhouse gate
Alternative A	Conventional (Dutch) hydroponic cultivation
Alternative B	Futagrow hydroponic cultivation
Reference flow A	1 kilogram of tomatoes in bulk at greenhouse gate using conventional hydroponic cultivation
Reference flow B	1 kilogram of tomatoes in bulk at greenhouse gate using Futagrow hydroponic cultivation

5.1.4. Scenarios

During the course of the study, several scenarios were created after an iterative process of analysing results and implementing potential solutions to reduce environmental impacts. Scenarios are created based on real and feasible solutions as discussed with professionals from the field. For instance, plastic recycling is very limited in the present, as it is primarily carried out by the independent unofficial workers. However, companies are more and more getting involved, organizing and stimulating the sector as it was explained during a visit to Agrotech in Agadir (Chandarrou et al., 2021).

In Table 2, an overview of the different scenarios is shown.

Table 2 Characteristics of scenarios included in the study.

Scenario	Abbrev. [1]	Characteristics
BASELINE	CB / FB	Direct implementation of Dutch systems. All systems from a high-tech greenhouse are included, except for the cover material which is plastic instead of glass. The inputs are adapted to the Moroccan conditions (sunlight, temperature, waste treatment, energy mix, etc).
ZERO ENERGY	CZ / FZ	Energy inputs are cut out. So, there is no top artificial lighting nor heating. This has a direct impact on yield which is reduced by 30%. In Futagrow, electricity cannot be completely cut out as intermediate artificial lighting needs to remain active to illuminate the shadowed lower branches.
RENEWABLE ENERGY	CRE / FRE	Same as BASELINE scenario but electricity and heat are 100% provided by renewable sources (windmills and solar collector panels)
PLASTIC RECYCLING	CPR / FPR	Same as BASELINE but implementing waste plastic recycling (instead of unsanitary landfilling) as follows: - 100% HDPE and LDPE waste from cover material - 50% of PE harvest operations - 100% of dripping pipes from recycling material
RENEWABLES AND RECYCLING	CRR / FRR	Previous two scenarios combined
RR + HUSK ALLOCATED	CRR-HA / FRR-HA	Previous scenario adding economic allocation to the husk during coconut cultivation.

More detailed information regarding the characteristics of each scenario can be found on the unit process data tables found in appendixes A4.1-6.

[1] "C" for Conventional hydroponic system, "F" for Futagrow hydroponic system

5.2. Inventory analysis

5.2.1. System boundaries

5.2.1.1. Economy-Environment system boundary

The product system includes all foreground and background processes transforming the economic flows that are required to produce the reference flow (1 kilogram of bulk tomatoes at greenhouse gate), i.e., seed production, sprouting, grafting, maturing, and harvesting. The main processes considered in the study are greenhouse construction and demolition, sanitation, climate control, artificial lighting, heating, pest control, pollination, substrate production, irrigation, fertilization, greenhouse operation, transport, and waste management. Environmental extensions are the only flows crossing the system boundaries. Uncontrolled landfilling and dumping are considered within the system boundaries, but their outflows are not treated anymore within the technosphere becoming biosphere flows. Fertilization uses artificial fertilizers. Pest control is considered fully organic and thus chemical pesticides are not included (fungicides, herbicides, or insecticides).

5.2.1.2. Cut-offs

Due to limited access to primary or secondary data, the next processes have not been included in the analysis. However, their impact on the results is expected to be negligible:

- Biological pest control and pollination supply chain (beneficial insects).
- Sticky substance on pest control tape.
- Secondary packaging used only during transport: bags, pallets, wrapping film, etc.
- Commuting to the greenhouse and basic equipment of workers such as uniforms and tools.

5.2.2. Flow chart

Table 3 show an overview of the processes considered into the Life Cycle Inventory (LCI) for the cultivation of plants. Figure 6 shows the process flowchart, the system boundaries and the group classification used during the contribution analysis, which are explained in detail right after.

Table 3 Processes considered in each life stage of tomato plants.

	Sprouting	**Grafting**	**Maturing (nursery)**	**Maturing (greenhouse) + Harvest**
Greenhouse (construction, sanitation and demolition)	YES, materials from Europe.	YES, materials from Europe.	YES, materials from Europe.	YES, materials from Europe.
Auxilliary equipment	YES, propagation trays.	NO	NO	YES, trellis wires, gutters.
Irrigation	YES, drip, open loop.	YES, drip, open loop.	YES, drip, open loop.	YES, drip, closed loop.
Fertilization	NO, prefertilized substrate	NO, prefertilized substrate	NO, prefertilized substrate..	YES, fertigation, inorganic.
Substrate	YES, plugs/bulk coir substrate.	NO	YES, blocks.	YES, slabs.
Pest control	NO	NO	NO	YES, sticky tape.
Pollination	N/A	N/A	N/A	YES, bumblebees.
Electricity	YES, for lighting.	YES, for lighting.	YES, for lighting.	YES, for lighting.
Heating	YES, gas boiler.	YES, gas boiler.	YES, gas boiler.	YES, gas boiler.
Seed production	YES, from NL.	N/A	N/A	N/A
Waste treatment	YES, propagation trays.	YES, plants and substrate.	YES, plants and substrate.	YES, plants. Substrate and auxiliary equipment.

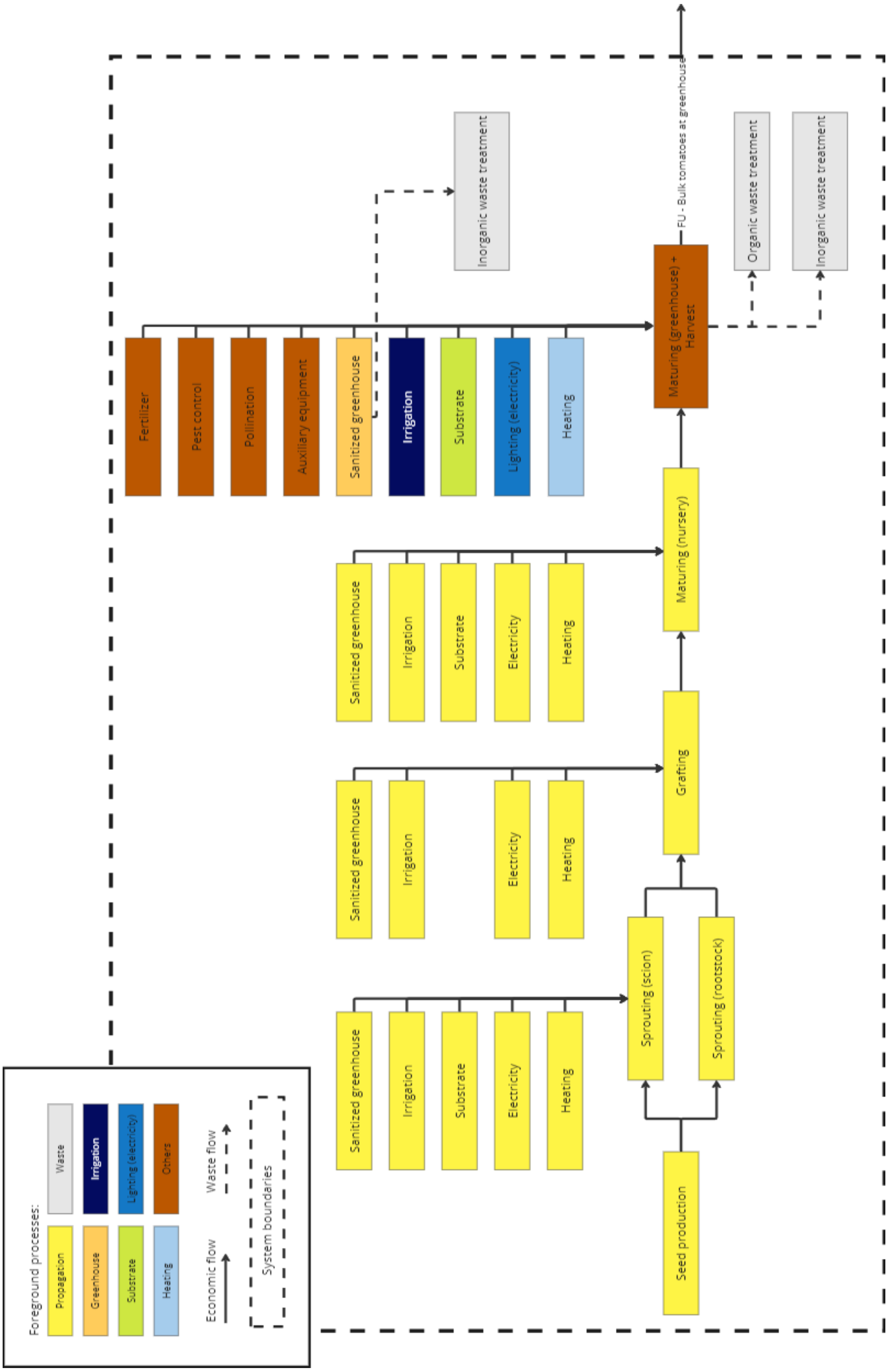


Figure 6 Simplified flowchart of processes considered in the product system. Colors indicate the groups considered during the contribution analysis.

5.2.2.1. Groups for contribution analysis

Lighting

This group comprises all the electricity consumed by artificial lighting, which in the present study is considered to represent 100% of the electricity consumption. In the baseline scenario, electricity is sourced from the grid, fed by the Moroccan energy mix. The group does not include the equipment, e.g,. the lamps or the installation as this is included in the greenhouse group.

Sanitized greenhouse

Construction, maintenance and disassembly of the greenhouse structure. It also includes sanitation to keep the greenhouse interior clean. The greenhouse is considered to be made of plastic and materials that are imported from Europe. All wastes generated during these processes are excluded as they will form a separate group along with other waste flows.

Waste treatment

It includes all the types of waste generated during harvest and construction, including plastics, metals, construction materials and plant waste. In the baseline scenario, all waste flows are considered to be unsanitarily landfilled or dumped to the environment.

Propagation

This group includes all the processes needed to provide a mature seedling. Like harvest, propagation also takes place in a greenhouse with similar processes: lighting, waste treatment, greenhouse, etc. However, since the contribution of seedling production to the environmental profile of tomatoes is relatively small, all these inputs have been combined into one group.

Heating

The artificial heating required to increase the temperature of the greenhouse to reach ideal conditions for tomatoes. It has been adapted from Dutch values to Morocco considering the number of months that the average temperature is under 19 ^{o}C. Like in lighting, the equipment is not included, only the energy.

Substrate

In the conventional system, plants are grown using coir plugs, blocks, and bags. This material is produced from coconut husk coming from Sri Lanka or India. It needs to be treated in order to make it suited for horticulture. The specific flowchart to produce this material is shown in Figure 7.

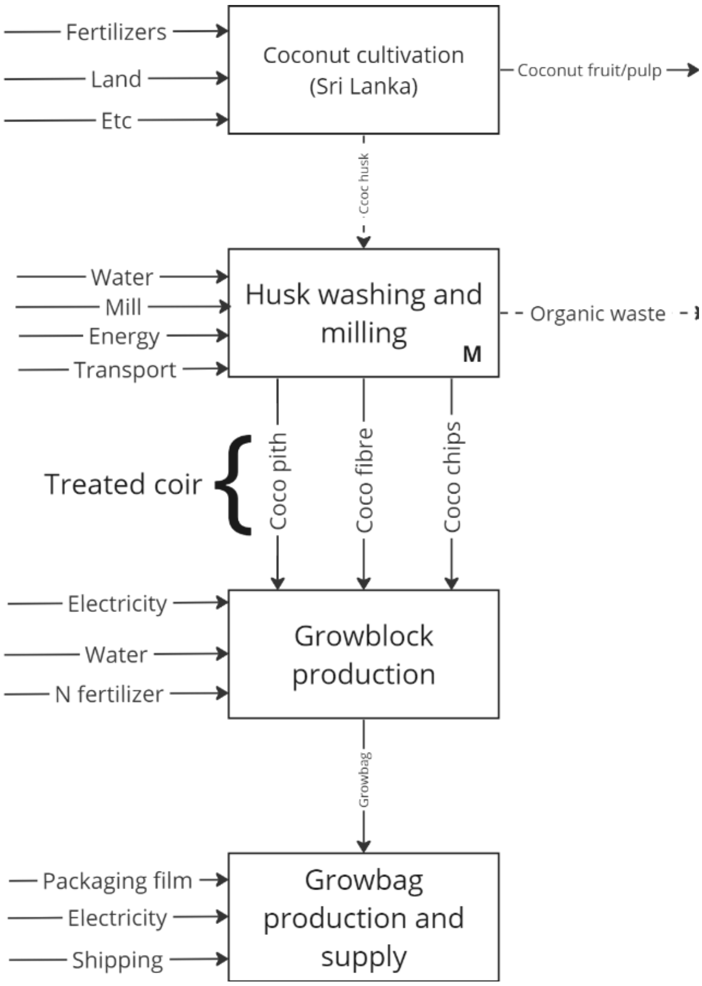


Figure 7 Flowchart of coir substrate bag production. "M" indicates multifunctional process.

Irrigation

The group includes the water and the infrastructure to deliver it from the natural source to the greenhouse. The main sources of water in Morocco are groundwater (64%) and rivers (36%) (Choukr-Allah et al., 2016).

Other

All the other processes with their emissions not included in the previously defined groups. Some examples are the auxiliary materials such as the trellising wire to keep tomato plants straight. These processes have been combined since their impacts were found insignificant or irrelevant for the study. Surprisingly, fertilizers are included in this group since the results (chapter 5.3.3) showed they had little contribution. This unexpected result might be explained by the reduced input and losses of nutrients in closed fertigation systems as those investigated in this study.

5.2.3. Data collection and relating data to unit processes

Data was firstly collected by performing desk research. All LCI data from background processes belongs to ecoinvent 3.9.1 database, with system model "Allocation, cut-off by classification"[2]. Preference was given to datasets from Morocco or, in their absence, to regions with similar conditions. However, data was more often found in European datasets, especially from the Netherlands, so it had to be adapted by making assumptions based on literature. In the case of foreground processes, it is retrieved from different sources as shown in Table 4.

Table 4 Main processes and literature data sources of the study

Process	Source
Coir substrate: processes, inventory and environmental exchanges	Extracted from LCA of coir and rockwool substrates in Sri Lanka commissioned by Jiffy (Chandrasekhar and Vasudeva, 2011; Linh, 2023; Maaoui, 2022)
Transport distances between Sri Lanka- Morocco and Netherlands-Morocco	Estimations on google maps and SeaDistances.org, taking the industrial hubs and ports as reference.
Fertilizer consumption	Adapted from ecoinvent 3.9.1. database, process "tomato production, fresh grade, in heated greenhouse [NL]" and adapted to plant life stages from Fajardo (2018)
Emissions from cultivation (harvest)	Adapted from ecoinvent 3.9.1. database, process "tomato production, fresh grade, in heated greenhouse [NL]" (EcoInvent 3.9.1., n.d.)

[2] Two background processes from the database were updated: "electricity, high voltage [MA]" and "irrigation, surface [MA]". The changes can be seen in Appendix A3.

Process	Source
Electricity consumption	Conventional systems: literature review (Tsafaras et al., 2022) In Futagrow, from the report by van Staalduinen (2015)
Waste treatment in Morocco	Landfilling assumed for all waste streams based on literature review (Dahchour and Hajjaji, 2020)
Propagation (sprouting, grafting and maturing)	Experts from different companies in the sector (Jiffy, HortiTech, Priva, Koppert, Hoogendoorn…) and literature review (Calpas, 2002)

More detailed information about sources and the calculation of inventory data can be found on the appendix A2 of the excel file.

5.2.4. Multifunctionality and allocation

No multifunctional processes were considered within the system boundaries besides the already existing ones in ecoinvent. The only economic flow crossing the system boundaries is the reference flow, tomatoes in bulk, which means there are no co-products.

Nevertheless, there is one process involved in which multifunctionality was assessed, coconut cultivation. Coir substrate is produced using coconut husk as raw material. In previous LCA studies this resource has been considered a waste outflow from coconut cultivation and therefore, it was free of environmental burdens (Chandrasekhar and Vasudeva, 2011). This assumption is, however, controversial as the demand for this material grows, providing a substantial part of the income of coconut farmers, and so, boosting their activity. Therefore, not allocating any impact to the husk is at least questionable as it conflicts with one of the basic principles of LCA, which tells that the final consumption of products happens to be the driving force of the economy and thus can influence the environmental management along the supply chain (Guinée, 2002).

For this reason, 24% of the impacts from coconut cultivation was allocated to the husk according to economic criteria (Table 5). The results were calculated with and without this allocation to assess the influence of these common assumptions.

Table 5 Economic allocation of coconut husk during coconut cultivation.

Mass ratio of production (husk/dehusked fruit)	0.63	
Price of dehusked coconut	0.26 $/kg of fruit (excluding husk)	(commodityonline, 2023)
Price of coco husk	0.13 $/kg of husk → 0.08 $/kg of fruit	(Alibaba, 2023)
Total income	0.34 $/kg of fruit (including husk)	
Husk allocated factor	0.08/0.34 = **0.24**	

5.2.5. Results of inventory analysis

After the modelling of all processes and the collection and entry of data into the Activity-Browser software (Steubing et al., 2020), the inventory results are calculated. These results show all the interactions between the product system and the environment. The complete list can be found in appendix A5.

5.3. Impact assessment

5.3.1. Impact categories and characterisation

This study selected the family of impact categories from ReCiPe 2016 (Huijbregts et al., 2017), a method for Life Cycle Impact Assessment (LCIA) created in the Netherlands in 2008 and reviewed in 2016 to translate emissions and resource extractions into a limited number of environmental impact scores. The present analysis only made use of the 18 mid-point indicators (Table 6), thus focusing on the environmental problems (causes) and less on the impacts (effects), which are calculated by aggregating mid-point indicators into 3 end-point indicators: human health, biodiversity and resources scarcity. End-point indicators can help a non-specialized audience to understand how the 18 environmental problems affect humans and nature but, at the same time, critical information is lost during calculation and uncertainty increases significantly. Therefore, they are less useful for this study.

As explained in the introduction chapter, water scarcity is the main environmental problem, followed by soil and freshwater pollution. Because of this, 3 indicators were analyzed closer: water use, freshwater eutrophication, and terrestrial ecotoxicity. At the same time, global warming was also included in this group, as it is commonly considered the main indicator to compare the environmentally friendliness of any product, although too often ignoring the rest of impacts and leading to deceptive conclusions.

Table 6 Impact categories included in the study, selected from ReCiPe 2016 (H) midpoint indicators. Four relevant indicators highlighted in grey. (Huijbregts et al., 2017)

Midpoint impact category	Indicator	Characterisation factor	Unit	Key references
Climate change (GWP100)	Infrared radiative forcing increase	Global warming potential (GWP)	kg CO2-eq to air	(IPCC, 2014); (Joos et al., 2013)
Ozone depletion (ODinf)	Stratospheric ozone decrease	Ozone depletion potential (ODP)	kg CFC-11-eq to air	(CSL and NOAA, 2010)
Ionising radiation (IR)	Absorbed dose increase	Ionising radiation potential (IRP)	kBq Co-60-eq to air	(Frischknecht et al., 2000)
Fine particulate matter formation (PMF)	PM2.5 population intake increase	Particulate matter formation potential (PMFP)	kg PM2.5-eq to air	(van Zelm et al., 2016)
Photochemical oxidant formation: terrestrial ecosystems (EOF)	Tropospheric ozone increase	Photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-eq to air	(van Zelm et al., 2016)
Photochemical oxidant formation: human health (HOF)	Tropospheric ozone population intake increase	Photochemical oxidant formation potential: humans (HOFP)	kg NOx-eq to air	(van Zelm et al., 2016)
Terrestrial acidification (TA)	Proton increase in natural soils	Terrestrial acidification potential (TAP)	kg SO2-eq to air	(Roy et al., 2014)
Freshwater eutrophication (FE)	Phosphorus increase in freshwater	Freshwater eutrophication potential (FEP)	kg P-eq to freshwater	(Helmes et al., 2012)
Human toxicity: cancer (HTc)	Risk increase of cancer disease incidence	Human toxicity potential (HTPc)	kg 1,4-DCB-eq to urban air	(van Zelm et al., 2009)
Human toxicity: non-cancer (HTnc)	Risk increase of non-cancer disease incidence	Human toxicity potential (HTPnc)	kg 1,4-DCB-eq to urban air	(van Zelm et al., 2009)
Terrestrial ecotoxicity (TET)	Hazard-weighted increase in natural soils	Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-eq to industrial soil	(van Zelm et al., 2009)
Freshwater ecotoxicity (FET)	Hazard-weighted increase in freshwaters	Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-eq to freshwater	(van Zelm et al., 2009)
Marine ecotoxicity (MET)	Hazard-weighted increase in marine water	Marine ecotoxicity potential (METP)	kg 1,4-DCB-eq to marine water	(van Zelm et al., 2009)
Land use (LO)	Occupation and time-integrated land transformation	Agricultural land occupation potential (LOP)	m2 × yr annual cropland-eq	(Curran et al., 2014; de Baan et al., 2013)

Midpoint impact category	Indicator	Characterisation factor	Unit	Key references
Water use (WC)	Increase of water consumed	Water consumption potential (WCP)	m3 water-eq consumed	(Döll and Siebert, 2002; Hoekstra and Mekonnen, 2012)
Mineral resource scarcity (SO)	Increase of ore extracted	Surplus ore potential (SOP)	kg Cu-eq	(Vieira et al., 2017)
Fossil resource scarcity (FF)	Upper heating value	Fossil fuel potential (FFP)	kg oil-eq	(Jungbluth et al., 2010)

Due to inconsistencies in the results of water use during the contribution analysis, another indicator was included to complement the analysis: Use of Net Fresh Water (UNFW), from the European standard EN15804 (BS EN 15804:2012+A2:2019, 2021). This indicator was selected after comparing the results among several water-related impact indicators available in Activity-Browser. Moreover, this indicator has characterization factors for 10 different interventions in contrast to just 4 in the indicator from the ReCiPe family.

5.3.2. Classification

In this mandatory step of LCA, all the interventions from the inventory analysis are assigned to the pre-selected impact categories. This study follows the classification already applied by the standardized ecoinvent database.

5.3.3. Characterisation results and contribution analysis

This step comprises the conversion of the inventory results into the characterisation results by using the characterisation factors. The compilation of all the scores provides the environmental profile of each alternative. This calculation is complemented by a contribution analysis to identify the environmental hotspots in every scenario, leading to the selection and implementation of new potential solutions in the model.

The analysis is started with the baseline scenario and evolves to other scenarios according to the subsequent findings.

Baseline scenario – Characterisation results

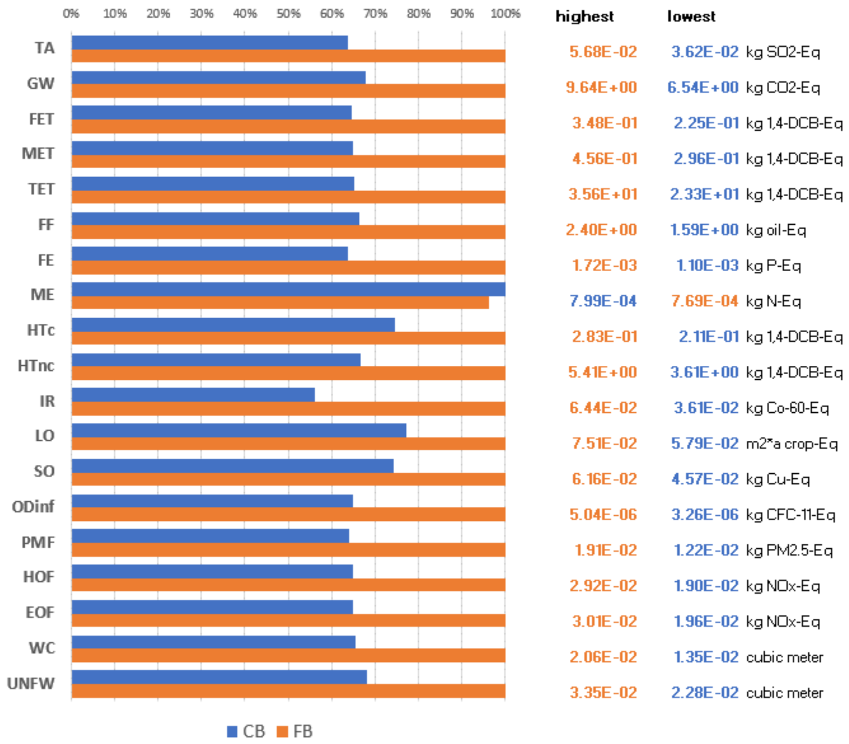


Figure 8 Environmental profiles of Conventional and Futagrow systems in baseline scenario. Adjusted to the highest score.

As it can be seen in Figure 8, the conventional system has a considerably lower environmental profile than the Futagrow system. Across the 18 categories, only marine eutrophication has a slightly higher value (+4%) in the conventional system. In the rest of categories, this system leads to a steady reduction of about 30% to 40% compared to Futagrow. The water footprint of the conventional system according to ReCiPe metrics is 13.5 L per kg of tomatoes against 20.6 L/kg in Futagrow. Using UNFW from EN15804, the relative results are equivalent, but the absolute numbers increase to 22.8 L/kg and 33.5 L/kg respectively. Therefore, in line with the other categories, the conventional system results in savings of around 33% in water consumption. Same applies for the GW indicator which is 32% lower in conventional hydroponics with 6.5 kg CO_2eq/kg compared to 9.6 kg CO_2eq/kg.

Finally, it is also remarkable that Futagrow perfoms worse in terms of land occupation, since the core idea of this system is to increase the space efficiency in the greenhouse. The reason can be found looking at the contribution analysis which is discussed in the next section.

Overall, the results indicate that in the baseline scenario Futagrow is a worse alternative than the conventional system from an environmental perspective.

Baseline scenario – Contribution analysis

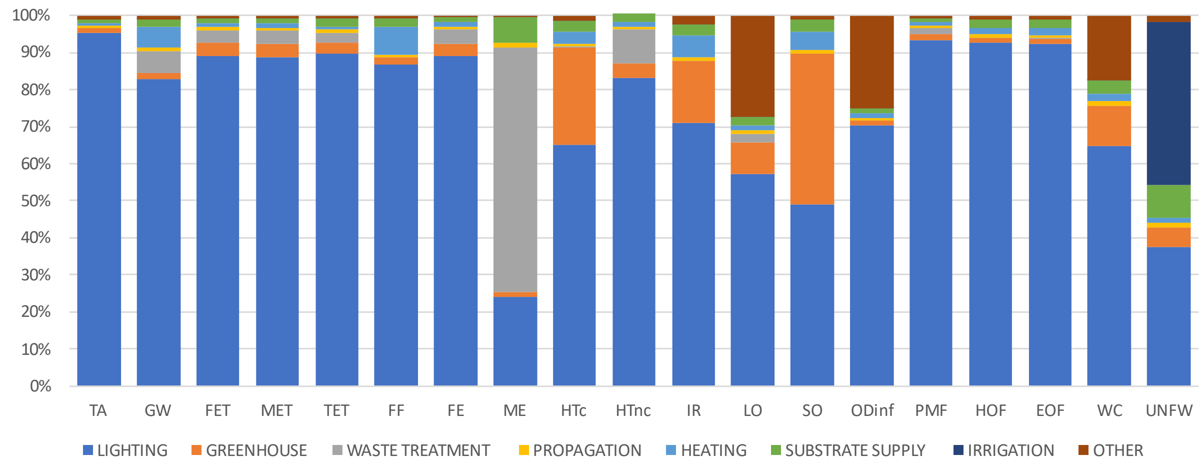


Figure 9 Contribution analysis of CB.

The contribution analysis of the conventional system in the baseline scenario (Figure 9) reveals the enormous contribution of lighting to the environmental profile. Even for UNFW the electricity consumed for lighting is responsible for 38% of the indicator score, similar to irrigation needs (44%). Other important contributors, although in much lesser extent, are waste treatment and greenhouse (construction and maintenance). The reason behind the large contribution of lighting is the composition of the energy mix in Morocco which is monopolized by fossil fuels: oil (55%), coal (32%) and natural gas (3%) combine for 90% of electricity generation according to the International Energy Agency ("IEA-Morocco," 2020). The Sankey diagram in Figure 10 provides a more detailed view of the specific processes that produce the emissions, in this case for GW100. Only the electricity production from oil and coal concentrate 66% of climate change emissions, excluding other activities upstream or downstream.

The contribution analysis of Futagrow (Appendix A7.3) showed similar results, with even higher contribution from electricity production. This explains why Futagrow performs worse in land occupation. In this system, land occupied by the greenhouse only accounts for 17% (0.0126 m^2*a crop-eq) of the total while electricity does for 74% (0.0557 m^2*a crop-eq), very spread along all its supply chain. Therefore, although the direct land occupied during cultivation is larger in the conventional system (0.0151 m^2*a crop-eq), this is compensated by more indirect land occupation due to a higher electricity consumption in Futagrow.

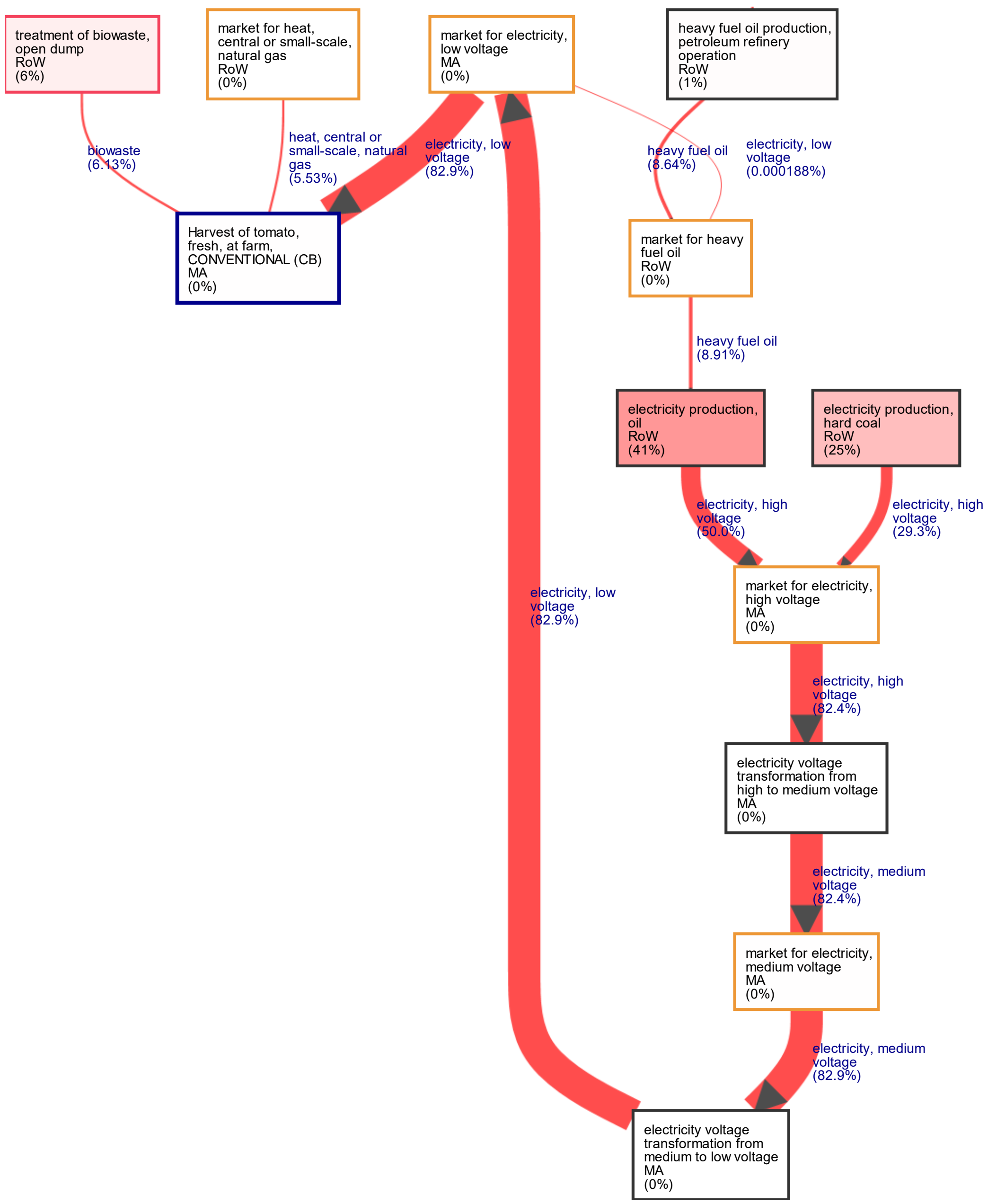
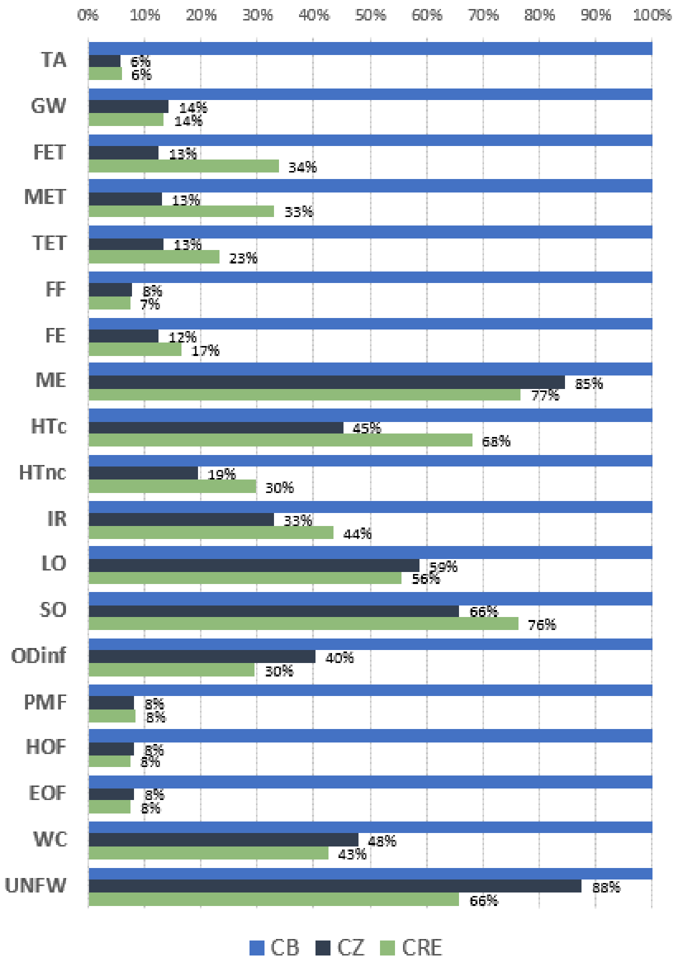


Figure 10 Process contribution Sankey for GW100 in CB scenario.

Energy saving scenarios – Characterisation results

The previous analysis indicated that to reduce impacts is critical to minimize energy generated from fossil-based sources. In the next analysis two scenarios are explored applied to the conventional system. The first one, CZ, does not have artificial lighting and heating and assumes a 30% yield reduction. In the second one, CRE, these energy inputs are generated from renewable sources (electricity from wind and heat from solar collector) without yield reduction.



highest	mid	lowest	
3.62E-02	2.15E-03	2.10E-03	kg SO2-Eq
6.54E+00	9.40E-01	8.85E-01	kg CO2-Eq
2.25E-01	7.61E-02	2.83E-02	kg 1,4-DCB-Eq
2.96E-01	9.81E-02	3.87E-02	kg 1,4-DCB-Eq
2.33E+01	5.41E+00	3.12E+00	kg 1,4-DCB-Eq
1.59E+00	1.26E-01	1.19E-01	kg oil-Eq
1.10E-03	1.81E-04	1.37E-04	kg P-Eq
7.99E-04	6.76E-04	6.13E-04	kg N-Eq
2.11E-01	1.44E-01	9.53E-02	kg 1,4-DCB-Eq
3.61E+00	1.07E+00	7.01E-01	kg 1,4-DCB-Eq
3.61E-02	1.57E-02	1.19E-02	kg Co-60-Eq
5.79E-02	3.40E-02	3.22E-02	m2*a crop-Eq
4.57E-02	3.49E-02	3.01E-02	kg Cu-Eq
3.26E-06	1.32E-06	9.66E-07	kg CFC-11-Eq
1.22E-02	1.04E-03	1.00E-03	kg PM2.5-Eq
1.90E-02	1.55E-03	1.42E-03	kg NOx-Eq
1.96E-02	1.62E-03	1.48E-03	kg NOx-Eq
1.35E-02	6.46E-03	5.76E-03	cubic meter
2.28E-02	2.00E-02	1.51E-02	cubic meter

Figure 11 Environmental profile comparison, CB vs CZ vs CRE. Adjusted to the highest score.

The characterisation results (Figure 11) show that both energy-saving scenarios help to reduce considerably all impacts compared to the baseline scenario. As expected, the reduction is less notably in those categories where lighting was not the main contributor (Figure 9), namely, marine eutrophication or mineral resource scarcity. On the other hand, avoiding fuel-based energy sources can drastically reduce most of impacts at least by 50% and up to 94%. GW100, TET and FE are reduced by around 80%, while freshwater consumption results vary from 12% to 57% reduction depending on the category and the scenario.

Comparing CZ and CRE scenarios, CZ lead in 10 categories while CRE does so in 8 (considering WC and UNFW as only one water-related category). However, the difference is more noticeable in categories where renewable energy has a higher impact. For instance, ecotoxicity in all its variants (FET, MET, TET) is nearly double when using renewable energy. On the other hand, CZ has a significant higher score in only two categories: ODinf and UNFW.

Energy saving scenarios – Contribution analysis

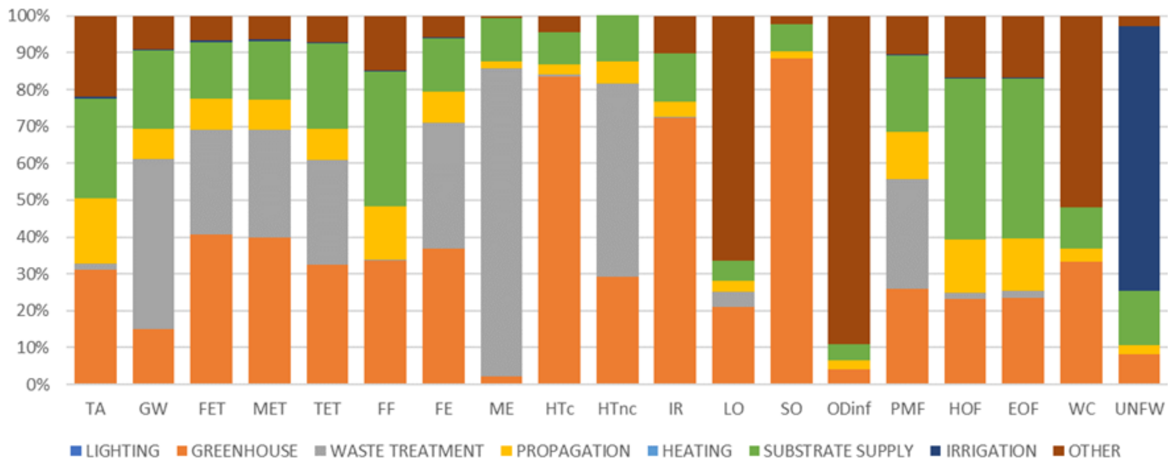


Figure 12 Contribution analysis of CZ

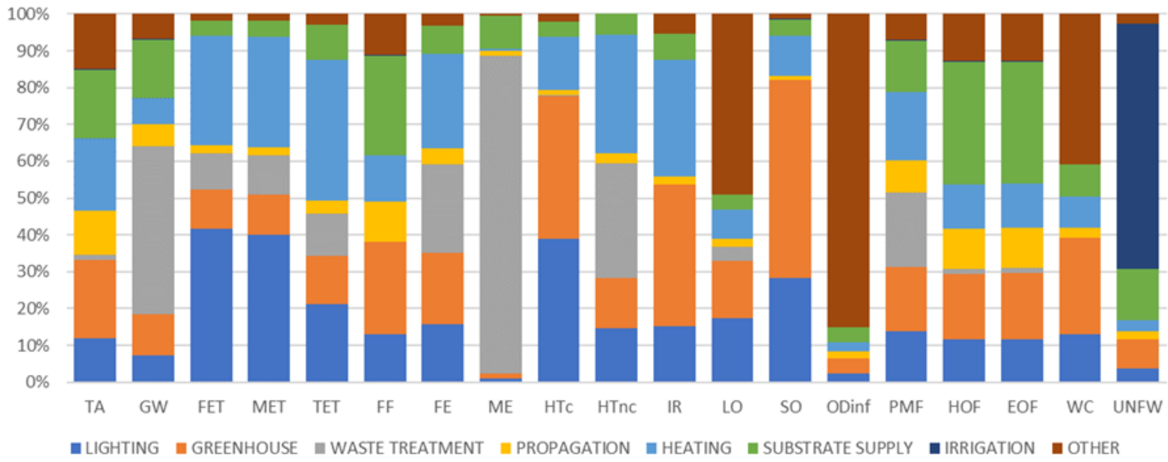


Figure 13 Contribution analysis of CRE.

The contribution analysis of the CZ (Figure 12) scenario confirms that the greatest contributors after lighting are greenhouse construction and waste treatment, while it also reveals the important role of substrate supply. The addition of renewable-sourced heating and lighting in CRE scenario makes the contribution graph more diverse (Figure 13). Heating becomes a relevant factor in this case since the alternative use of solar collectors does not perform better than natural gas, which to a large extent is due to copper production, as the Sankey diagram reveals (Figure 14).

On a sidenote, the shares of the group "OTHER" in ODinf, LO and WC are high due to environmental emissions and economic flows consumed during harvest such as nylon wire for trellising tomatoes that are not included in the rest of groups.

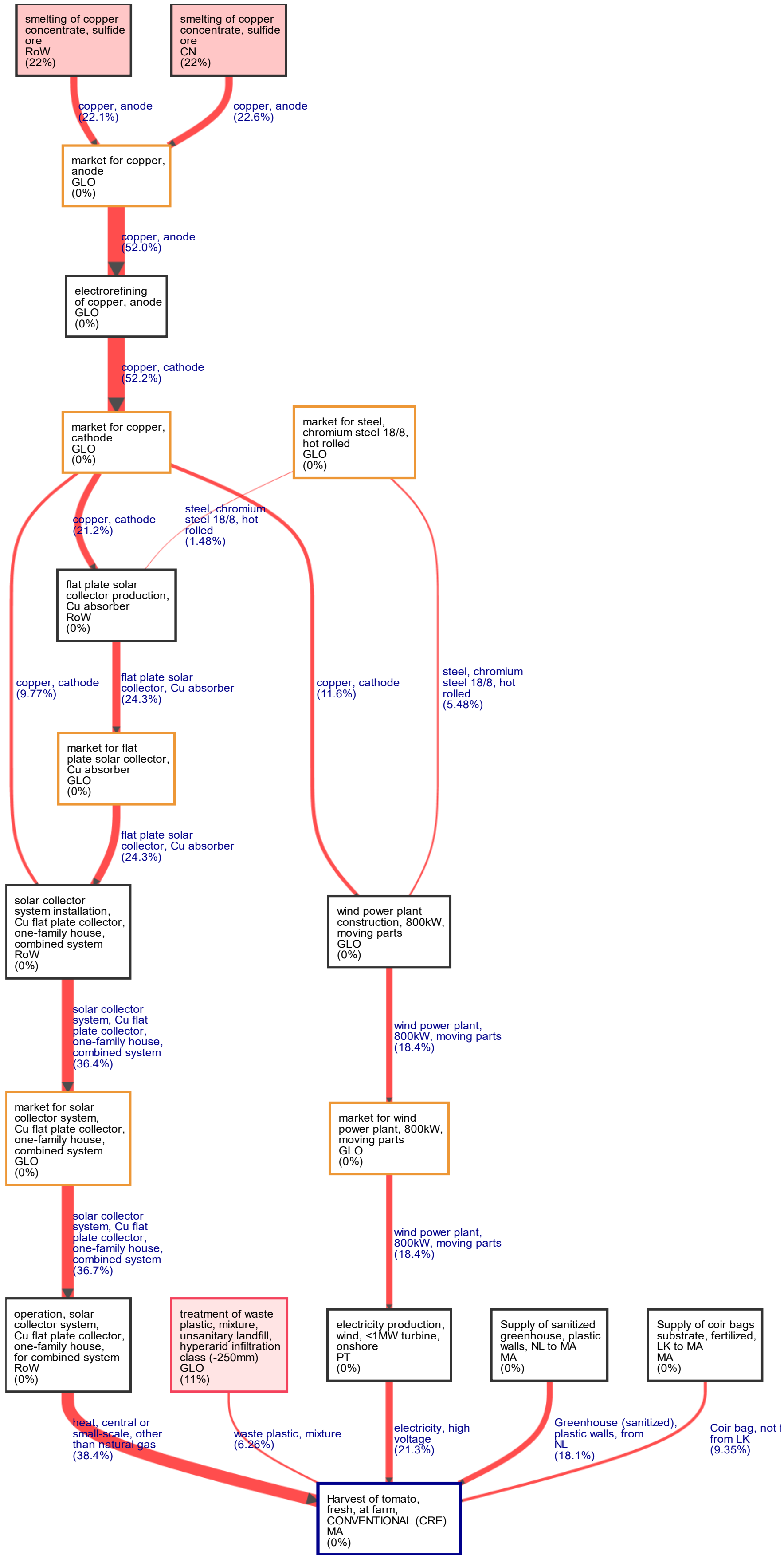


Figure 14 Process contribution Sankey for TET in CRE scenario

Plastic Recycling scenario – Characterisation results

This scenario explores a different hotspot of the product system, waste. Starting from the conventional system in the baseline scenario, this model implements plastic recycling, including the collection of 50% of plastic waste during harvest, 100% of covering plastic film and the use of 100% recycled plastic for irrigation pipes. The system boundaries include the collection and transportation of waste unsorted plastic but not the subsequent processes to transform it into usable material.

The reason to focus on plastic waste, instead of the more abundant organic waste, is that there are some initiatives already ongoing to organize plastic collection and recycling (Chandarrou et al., 2021), while organic waste is still generally dumped in the environment as farmers are too afraid of spreading diseases while recirculating it.

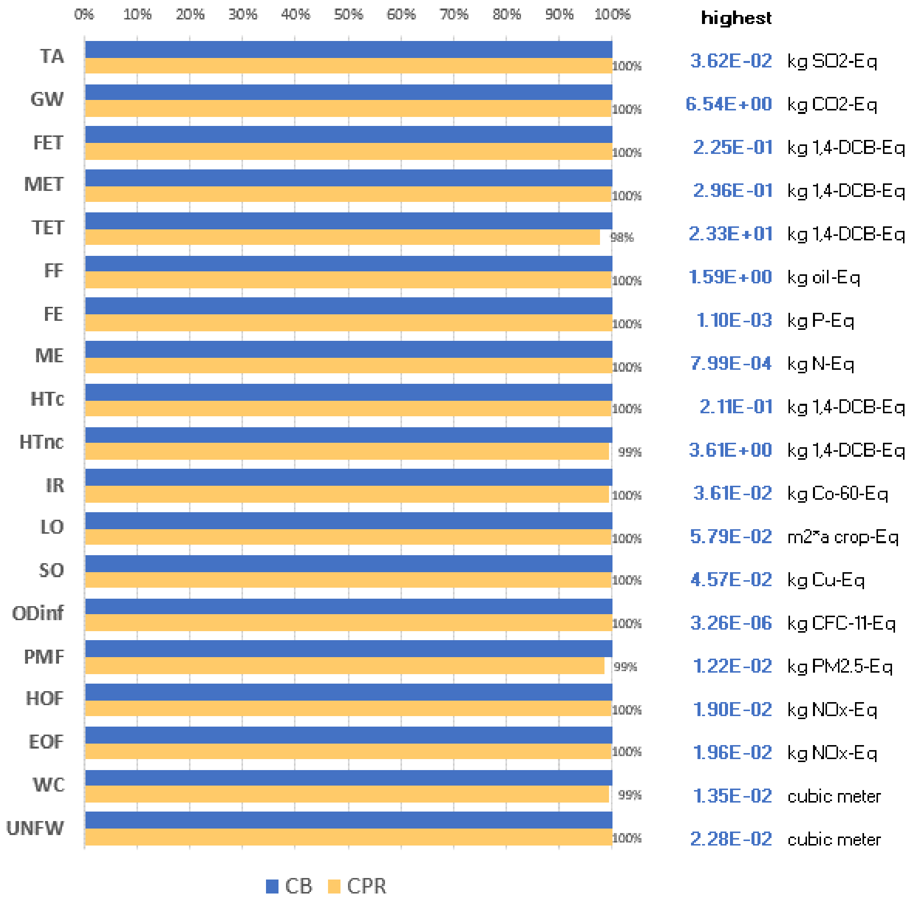


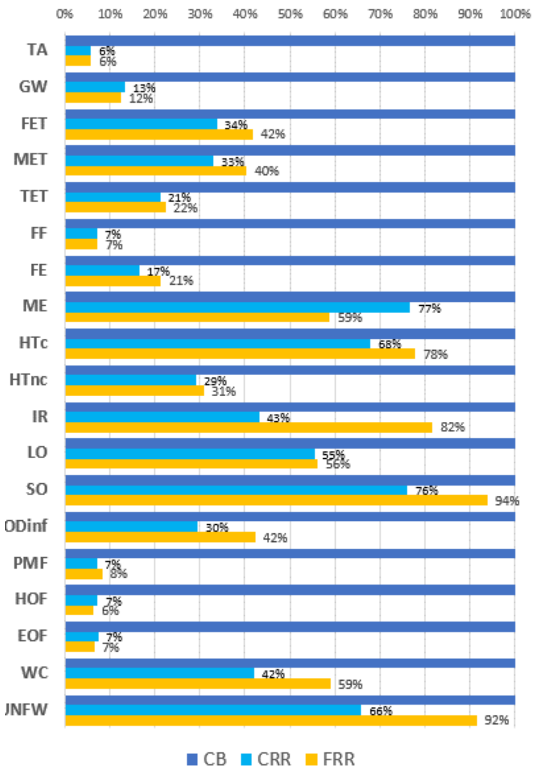
Figure 15 Environmental profile comparison, CB vs CPR. Adjusted to the highest score.

From the characterisation results (Figure 15) it can be concluded that the efforts put on plastic recycling have very little effect on the environmental profile of the conventional system. Besides reductions in PMF, TET, HTnc and WC, the rest of categories remain unaffected. One reason behind these results are the small amount of plastic waste (11 g/kg) compared to organic waste (470 g/kg) whose impacts are more remarkable as seen on the Sankey diagram from Figure 14. Another reasons are the larger impact of other construction materials such as metals, and the limited use of recycled plastic which only includes the pipes. Furthermore, sending waste to recycling does not reduce the burdens allocated to its generation, i.e., only the subsequent consumer of the recycled plastic will benefit from a burden-free raw material. Hence, the impact of recycling is only visible on the results by the avoidance of landfilling which is partially compensated by the additional impacts of collection and transportation.

Since the differences between the environmental profiles of CB and CPR were negligible the contribution analysis became irrelevant and thus, not included in this report.

Renewable + Recycling scenario – Characterisation results

In this scenario, renewable energy and plastic recycling activities are combined and applied to both the conventional and the Futagrow systems, and then compared to the conventional system in the baseline scenario.



highest	mid	lowest	
3.62E-02	2.15E-03	2.13E-03	kg SO2-Eq
6.54E+00	8.77E-01	8.17E-01	kg CO2-Eq
2.25E-01	9.43E-02	7.61E-02	kg 1,4-DCB-Eq
2.96E-01	1.20E-01	9.79E-02	kg 1,4-DCB-Eq
2.33E+01	5.20E+00	4.93E+00	kg 1,4-DCB-Eq
1.59E+00	1.17E-01	1.14E-01	kg oil-Eq
1.10E-03	2.34E-04	1.81E-04	kg P-Eq
7.99E-04	6.13E-04	4.71E-04	kg N-Eq
2.11E-01	1.64E-01	1.43E-01	kg 1,4-DCB-Eq
3.61E+00	1.11E+00	1.05E+00	kg 1,4-DCB-Eq
3.61E-02	2.95E-02	1.56E-02	kg Co-60-Eq
5.79E-02	3.26E-02	3.21E-02	m2*a crop-Eq
4.57E-02	4.29E-02	3.48E-02	kg Cu-Eq
3.26E-06	1.38E-06	9.65E-07	kg CFC-11-Eq
1.22E-02	1.01E-03	8.68E-04	kg PM2.5-Eq
1.90E-02	1.40E-03	1.23E-03	kg NOx-Eq
1.96E-02	1.46E-03	1.28E-03	kg NOx-Eq
1.35E-02	7.97E-03	5.68E-03	cubic meter
2.28E-02	2.09E-02	1.51E-02	cubic meter

Figure 16 Environmental profile comparison, CB vs CRR vs FRR. Adjusted to the highest score.

The implementation of renewable energy and, to a lesser extent, plastic recycling, makes both systems more environmentally friendly than the baseline scenario in all categories (Figure 16).

When comparing CRR to FRR, the conventional system still performed better in most of impact categories, although the difference was not as evident as in the baseline scenario. In fact, in this setup, Futagrow outperformed the conventional system in 4 categories: GW100, ME, HOF, and EOF. The gap between the two in TET and FE also shrinked from 35% and 36% to 5% and 23%, respectively. The difference in water consumption also decreased slightly from 32% to 28%.

Renewable energy + Recycling scenario – Contribution analysis

For this analysis, both scenarios were plotted together and the percentages adjusted to the highest score (Figure 17 and Figure 18). This way it is possible to compare each process individually between the two systems. At the same time, the gap between both environmental profiles is more easily attributed to one or several specific processes.

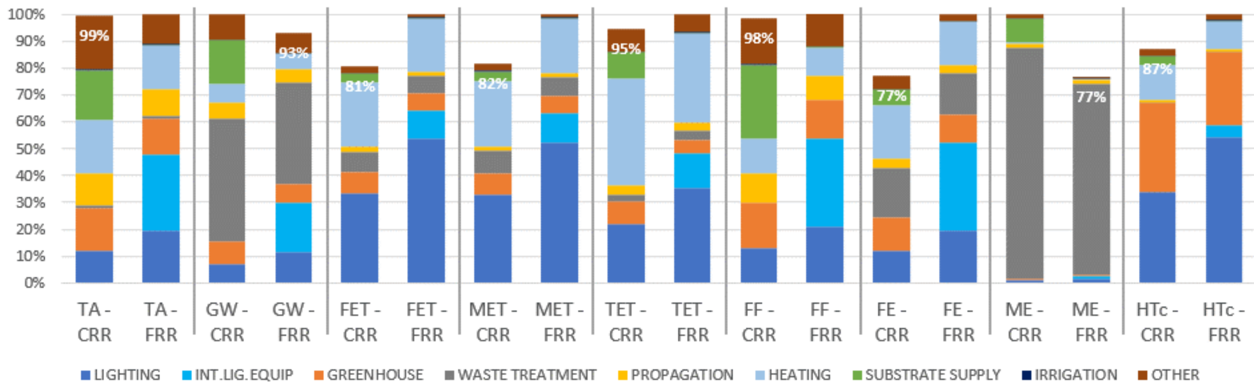


Figure 17 Comparative contribution analysis of CRR and FRR, adjusted to the highest score in each impact category. (1/2)

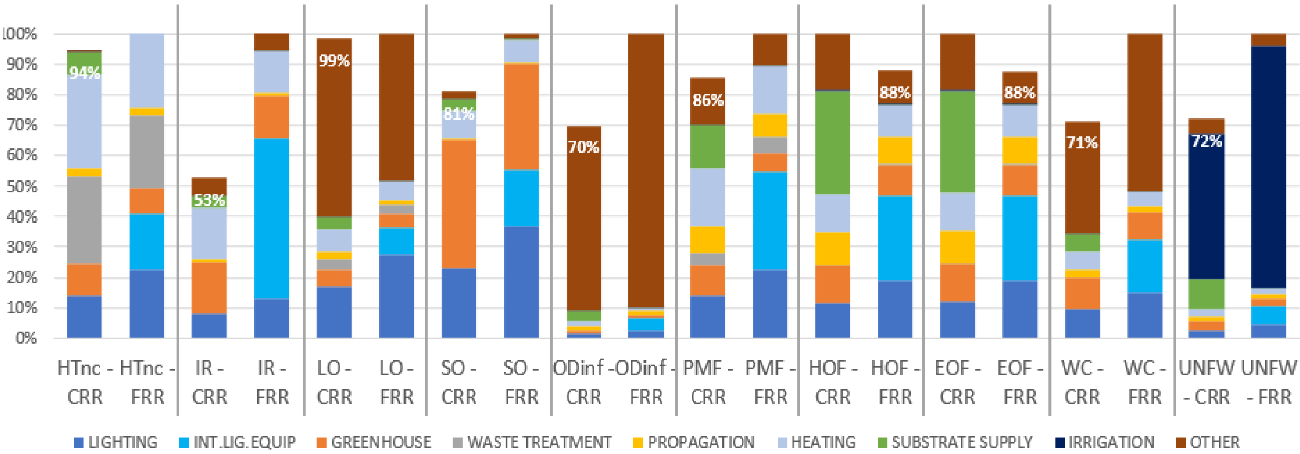


Figure 18 Comparative contribution analysis of CRR and FRR, adjusted to the highest score in each impact category. (2/2)

Husk allocated scenario – Characterisation results

Lastly, the influence of coconut husk allocation was investigated by creating a copy of the CRR scenario and adding the corresponding 24% economic allocation of coconut cultivation.

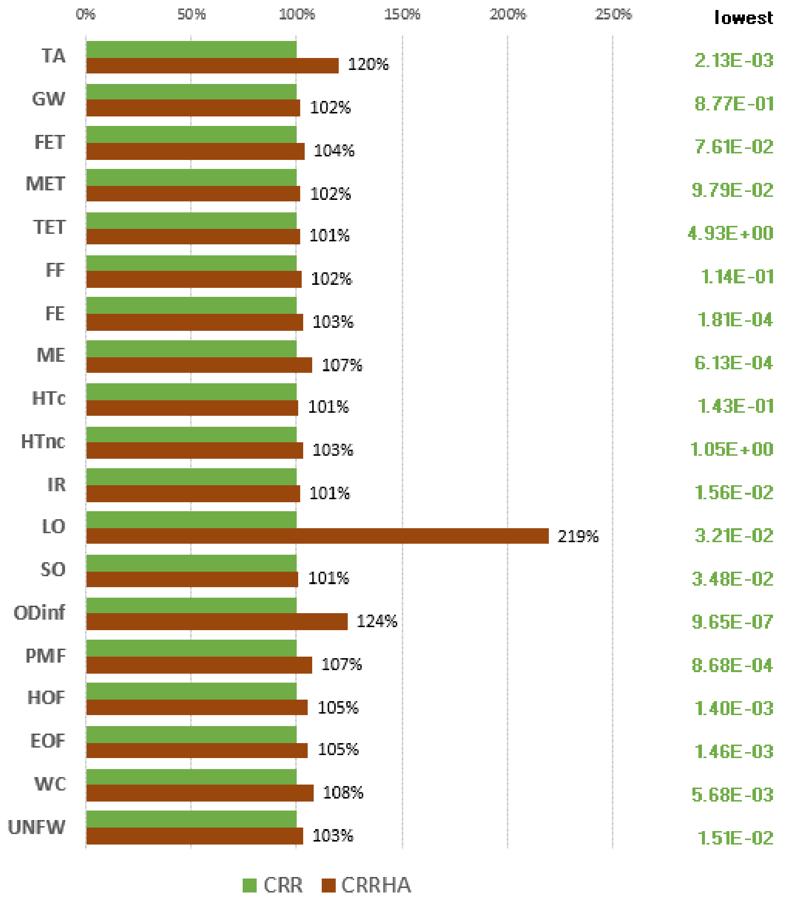


Figure 19 Environmental profile comparison, CRR vs CRR-HA. Adjusted to the minimum score.

The results (Figure 19) showed that including cultivation of coconut as part of the manufacturing process of substrate increases by 1-10% all impacts except TA (+20%), ODinf (+24%) and, most remarkably, LO (+219%). Although none of these additional impacts take place in Morocco, they are an important factor to consider from a global point of view.

In addition, while allocation of impacts from coconut cultivation has an effect on the conventional system results, it does not affect the Futagrow system as it does not use substrate bags. In this scenario, the difference between both systems shrinks even more and Futagrow now performs better in 7 impact categories. (Figure 20)

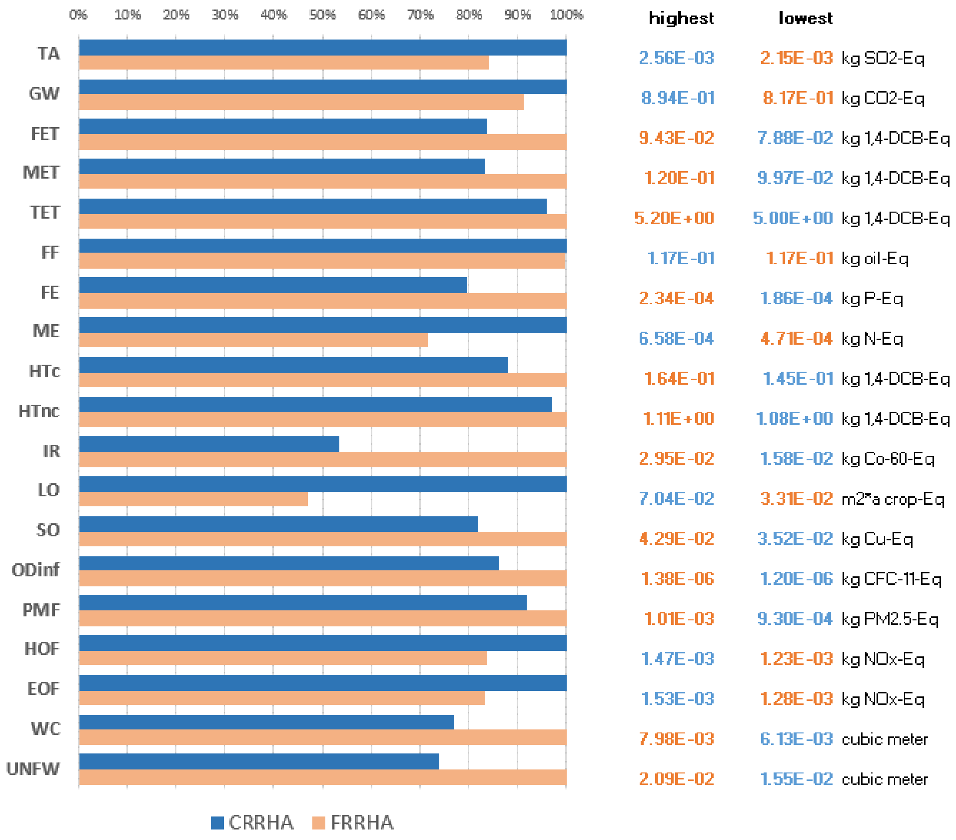


Figure 20 Environmental profile comparison, CRR-HA vs FRR-HA.

5.3.4. Interventions for which characterisation factors are lacking

Interventions that are missing characterisation factors can affect the results and therefore must be considered during interpretation. Here the most relevant examples for the study are discussed. The complete list can be found in appendix A5.

Table 7 Water-related interventions without characterisation factors.

Intervention	Categories	Scenario	Amount	Unit
Water, salt, ocean	('natural resource', 'in water')	CB	0.116	cubic meter
Water	('water', 'ocean')	CB	0.117	cubic meter

Considering the proximity of Souss-Massa to the ocean, it is worth noting that marine water does not have characterisation factors for both extraction and emission (Table 7), despite values above 110 litres per functional unit in the baseline scenario. Nevertheless, the high amount of water does not necessarily mean a high impact as perhaps the extraction and the emission do not negatively affect the ecosystem.

Table 8 Nitrite emissions without characterisation factors.

Intervention	Categories	Scenario	Amount	Unit
Nitrite	('water', 'ground-')	CB	2.91E-05	kilogram
Nitrite	('water', 'ground-, long-term')	CB	1.51E-05	kilogram
Nitrite	('water', 'ocean')	CB	1.52E-09	kilogram
Nitrite	('water', 'surface water')	CB	1.72E-08	kilogram
Nitrite	('water',)	CB	2.05E-08	kilogram

Also remarkable is the lack of characterisation factors for emissions of nitrites to water (Table 8), a common contributor to eutrophication as they oxidize to nitrates (Karydis, 1996). However, these emissions are lower by at least one order of magnitude than nitrate emissions, which do have factors and thus are accounted for on the results. Therefore, the lack of characterisation factors of nitrites does not have a significant impact on the results.

Regarding soil, a total of 218 emission flows without characterisation factors were identified. Although the concentrations were very low (magnitudes around e-10 to e-15), it is worth noting that these amounts are calculated per every kilogram of tomatoes and each hectare produces around 4e5 kilograms per year while the total tomato production in Souss-Massa is 7e8 kilograms. Additionally, every substance has a different toxic threshold. Therefore, an expert review is necessary to assess the risk of toxicity of these emissions.

5.3.5. Economic flows not followed to system boundary

All foreground processes are connected to background processes from ecoinvent 3.9.1. and therefore, the economic flows are followed to the system boundary as far as they are tracked in this database. However, due to time constraints some processes were cut-off as they were not seen relevant enough for the study (See 5.2.1.2). The aspects that were overlooked include the surrounding facilities of the greenhouse which are necessary for its correct operation. Additionally, workers equipment and transportation were disregarded. In terms of shipping, auxiliary materials such as bags, pallets, and wrapping film were not accounted for. Moreover, biological pest control is not accurately modelled as there is limited data available about the supply chain of beneficial insects.

5.4. Interpretation

5.4.1. Consistency check

Data sources are shared among all alternatives providing a firm foundation in which comparisons can be fairly conducted. The geographical scope was placed as close as possible to the target region, Souss-Massa. Alternatively, when data was not found, a region with similar conditions was considered. As an example, electricity production from wind was not available in ecoinvent for the Moroccan region. Instead, Portugal was used as both share comparable wind intensity (globalwindatlas.info, 2023) and location at the Atlantic coast.

Inevitably, since hydroponic systems are not common in areas with similar characteristics to Morocco, these data sources had to be combined with assumptions that enabled to build the LCA model. Adapting the characteristics from the systems in the Netherlands to Moroccan conditions was especially delicate. Variability between different tomato species also difficulted estimations when data for the same species was missing. These assumptions were contrasted with experts to verify their validity. In Table 9, the main assumptions shaping the model are listed.

Table 9 Main assumptions taken during LCA modelling.

Assumption	Source
Artificial lighting required in Morocco compared to the Netherlands (-27%)	Estimated from annual sunshine in the Netherlands (1700 h/yr) and Morocco (3000 h/yr) and considering a requirement of 18h of light exposition per day (6570 h/yr). Irradiation data (globalsolaratlas.info, 2023) of each area (approximately double in Souss-Massa than Westland) were used to validate this assumption.
Artificial heating required in Morocco (-50%)	Estimated from the number of months with average temperatures under 19 ^{o}C: 12 in the Netherlands (worlddata.info, 2023), 6 (Nov-Apr) in Morocco (climatestotravel, 2023)
Yield reduction when removing artificial light and heat (-30%)	From Verheul et al. (2012), discussion with farmers and experts.
Landfilling as the only waste treatment method.	Originally from Dahchour and Hajjaji (2020), verified during field trip, although some minimal recycling and composting operations were also observed.
Economic allocation of coconut husk (24%)	Prices are retrieved from real market sources (Alibaba, 2023; commodityonline, 2023) but it is assumed that all farmers are selling the husk and there is no risk of offer increase and subsequent husk price fall.

5.4.2. Completeness check

To check the completeness of the model the material flow analysis carried out by van Tuyll et al. (2022a) was used (Figure 21). In their work, the authors compiled the inputs and outputs from previous studies and therefore the results are considered a consistent reference. The amounts shown in the figure correspond to the materials used during cultivation only (propagation and harvest), ignoring background processes.

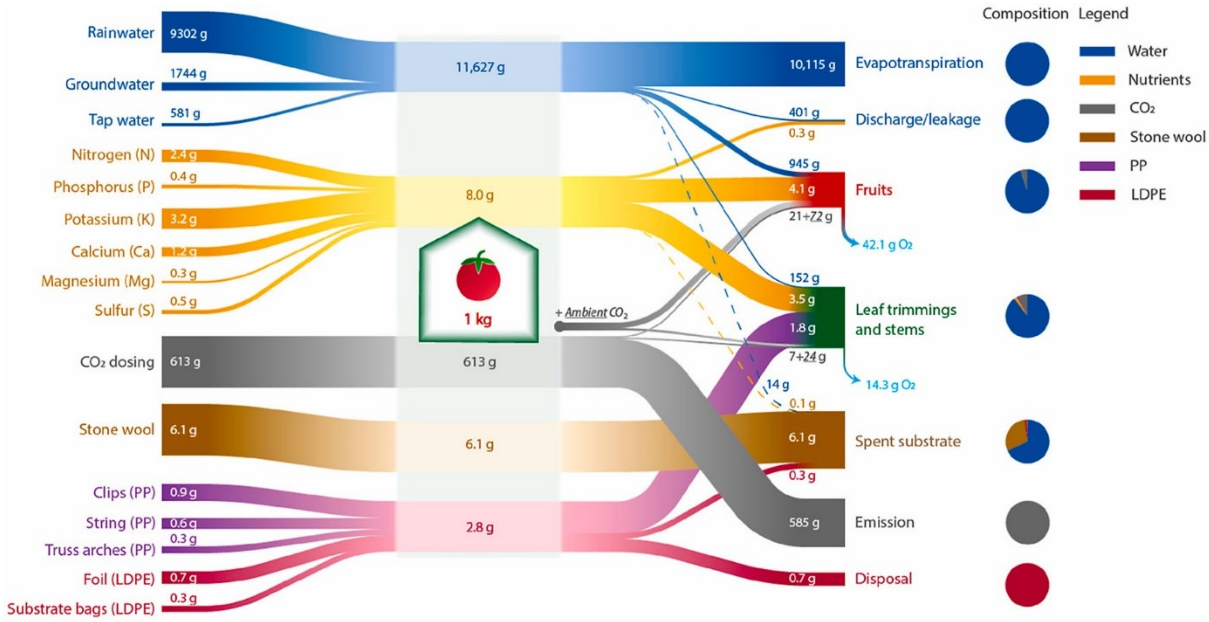


Figure 21 Material flow analysis of tomato production in greenhouses. Extracted from van Tuyll et al. (2022a).

Table 10 Main material flows during cultivation in the present study and van Tuyll et al. (2022a), and deviation.

Material flow	Present study (g)	van Tuyll et al. (2022a) (g)	Deviation
Water	10000	11627	-14%
Nutrients	8.9	8.0	+11%
CO_2	100 (from air) 533 (supplement)	94 (from air) 613 (supplement)	+6% -13%
Substrate	78 (coir)	6.1 (stone wool)	+1279%
Plastics	4.75	2.8	+70%

From the comparison, it can be confirmed that water, nutrients and CO_2, have been considerably well modelled. CO_2 supplement is calculated considering 100% of CO_2 from the boiler injected to the greenhouse and an emission rate of 60g of CO_2 per MJ. Substrate varies greatly due to the physical differences between rockwool and coir that also affect the application method. Rockwool is 6 times lighter, so in volume the difference would be reduced to +205%. The accountability of plastics is complex since it includes many small materials flows (trellis wire, clamps, wrapping film, etc). Furthermore, as it has been seen by the low influence of plastic recycling scenario, these materials do not constitute a hotspot of the product system and, therefore, +70% is considered an acceptable deviation.

5.4.3. Sensitivity analyses

Agricultural systems differ greatly from farm to farm, even when growing the same crop using an equivalent system. Climate conditions, farmer own practices, types of fertilizers, greenhouse characteristics are only some of the factors that hinder the estimation of acceptable values that can be implemented into the LCA model. To solve this problem a sensitivity analysis was conducted to evaluate the variability of LCA results depending on the first three assumptions from Table 9 regarding artificial lighting and heating, and yield reduction when these two are missing. In addition, the characterisation factors were calculated using an alternative family of impact categories, CML V.4.8 2016 to check if the same conclusions can be drawn.

Artificial lighting and heating

Table 11 Sensitivity analysis. Variation of characterisation results after 10% reduction of lighting and heating.

Indicator	CB scenario Light: 4.58 kWh/kg Heat: 4.50 MJ/kg	-10 % light 4.12 kWh/kg	-10% heat 4.05 MJ/kg
TA (kg SO2-Eq)	3.62E-02	3.28E-02 (-9.5%)	3.62E-02 (-0.1%)
GW100 (kg CO2-Eq)	6.54E+00	6.00E+00 (-8.3%)	6.51E+00 (-0.6%)
FET (kg 1,4-DCB-Eq)	2.25E-01	2.05E-01 (-8.9%)	2.25E-01 (-0.1%)
MET (kg 1,4-DCB-Eq)	2.96E-01	2.70E-01 (-8.9%)	2.96E-01 (-0.1%)
TET (kg 1,4-DCB-Eq)	2.33E+01	2.12E+01 (-9.0%)	2.32E+01 (-0.1%)
FF (kg oil-Eq)	1.59E+00	1.46E+00 (-8.7%)	1.58E+00 (-0.8%)
FE (kg P-Eq)	1.10E-03	9.97E-04 (-8.9%)	1.09E-03 (-0.1%)
ME (kg N-Eq)	7.99E-04	7.80E-04 (-2.4%)	7.99E-04 (0.0%)

Indicator	CB scenario Light: 4.58 kWh/kg Heat: 4.50 MJ/kg	-10 % light 4.12 kWh/kg	-10% heat 4.05 MJ/kg
HTc (kg 1,4-DCB-Eq)	2.11E-01	1.97E-01 (-6.5%)	2.10E-01 (-0.3%)
HTnc (kg 1,4-DCB-Eq)	3.61E+00	3.31E+00 (-8.3%)	3.60E+00 (-0.1%)
IR (kg Co-60-Eq)	3.61E-02	3.35E-02 (-7.1%)	3.59E-02 (-0.6%)
LO (m2*a crop-Eq)	5.79E-02	5.46E-02 (-5.7%)	5.79E-02 (-0.1%)
SO (kg Cu-Eq)	4.57E-02	4.35E-02 (-4.9%)	4.55E-02 (-0.5%)
ODinf (kg CFC-11-Eq)	3.26E-06	3.03E-06 (-7.0%)	3.26E-06 (-0.1%)
PMF (kg PM2.5-Eq)	1.22E-02	1.10E-02 (-9.3%)	1.22E-02 (-0.1%)
HOF (kg NOx-Eq)	1.90E-02	1.72E-02 (-9.3%)	1.90E-02 (-0.2%)
EOF (kg NOx-Eq)	1.96E-02	1.77E-02 (-9.2%)	1.95E-02 (-0.2%)
WC (m^3)	1.35E-02	1.26E-02 (-6.5%)	1.35E-02 (-0.2%)
UNFW (m^3)	2.28E-02	2.20E-02 (-3.8%)	2.28E-02 (-0.1%)
	Influence factor	0.75	0.02

As expected, Table 11 indicates that a reduction of lighting has a bigger impact on the results than heating. While a 1% change in lighting produces 0.75% average change on the indicators, heating only causes 0.02%. Categories where the contribution of lighting is higher are more sensible to variations of this value.

Yield reduction in zero energy scenario

This analysis looked into how changing the percentage of yield loss when artificial light and heating are not provided (CZ scenario) affects the results compared to other scenarios (Table 12). In the study it was assumed that yield would be reduced by 30%, making the CZ scenario more environmentally friendly than using renewable energy (CRE scenario) in approximately half of the categories.

However, with 0% yield reduction, CZ performs better in all categories. Considering 30% reduction, CRE outperforms CZ in approximately half of the categories. Finally, if yield was reduced by 80% because of lack of light and heat, CZ would become a worse option in all categories. Therefore, attending to the number of impact categories, scenarios CRE and CZ have similar performances when assuming 30% yield reduction. Should more yield be lost, renewable energy would become a more sustainable alternative.

Table 12 Deviation of results from CZ in comparison to CRE, depending on yield loss percentage.

Green: CR<CRE; Yellow: CRE<CZ<CB; Red: CB<CZ

Yield loss	YIELD (kg/m2)	TA	GW	FET	MET	TET	FF	FE	ME	HTc	HTnc	IR	LO	SO	ODinf	PMF	HOF	EOF	WC	UNFW
-0%	40	-32%	-26%	-74%	-72%	-60%	-26%	-47%	-23%	-54%	-54%	-47%	-26%	-39%	-5%	-32%	-24%	-24%	-21%	-7%
-10%	36	-24%	-17%	-71%	-69%	-55%	-17%	-41%	-14%	-48%	-49%	-41%	-18%	-33%	6%	-25%	-15%	-15%	-13%	3%
-20%	32	-15%	-7%	-68%	-65%	-50%	-7%	-34%	-4%	-42%	-43%	-34%	-8%	-24%	19%	-15%	-5%	-5%	-2%	16%
-30%	**28**	**-3%**	**6%**	**-63%**	**-61%**	**-42%**	**6%**	**-25%**	**10%**	**-34%**	**-35%**	**-24%**	**6%**	**-14%**	**36%**	**-3%**	**9%**	**9%**	**12%**	**33%**
-40%	24	14%	24%	-57%	-54%	-33%	24%	-12%	29%	-23%	-24%	-12%	23%	1%	59%	13%	27%	27%	31%	55%
-50%	20	36%	49%	-48%	-45%	-19%	49%	6%	54%	-7%	-8%	6%	48%	21%	91%	35%	53%	53%	57%	86%
-60%	16	70%	86%	-35%	-31%	1%	86%	32%	93%	16%	15%	32%	85%	51%	139%	69%	91%	91%	96%	132%
-70%	12	127%	148%	-13%	-8%	34%	148%	76%	157%	55%	53%	77%	146%	102%	218%	126%	154%	154%	162%	210%
-80%	8	241%	272%	30%	38%	102%	272%	164%	286%	132%	129%	165%	270%	203%	377%	239%	282%	281%	293%	365%
-90%	4	581%	644%	160%	176%	303%	644%	428%	671%	364%	358%	430%	639%	505%	854%	577%	663%	663%	686%	830%

The comparison between CZ and the baseline scenario (CB) shows that even with 90% yield loss, i.e. producing just 4 kg/m^2, CZ would still be preferable according to 9 impact categories. This reinforces the necessity of avoiding energy generated from fossil fuels.

CML V4.8 2016

Characterisation results from scenarios CRRHA and FRRHA were calculated again using the family of impact categories from the Institute of Environmental Sciences of Leiden University (CML). This family includes ten categories for which 10 equivalent categories from ReCiPe were selected. The ratio between both alternatives in each category was calculated to assess if the same conclusions could be drawn (Table 13). The analysis revealed similar results in 6 out of 11 categories. The other five categories showed discrepancies as CML family gave a lower score to FRRHA than to CRRHA, unlike ReCiPe. The biggest discrepancy was found for terrestial ecotoxicity where ReCiPe assigned a score 6% higher to Futagrow than to the conventional system, while in CML the indicator of Futagrow was 94% lower. In addition, the main contributor according to ReCiPe is copper production (59%) while for CML is coconut cultivation (91%) a process that Futagrow barely uses as it does not require substrate.

A probable reason for this difference is the list of characterisation factors. ReCiPe has a total of 1409 factors for this category compared to 800 from CML.

Table 13 Comparison of characterisation results with ReCiPe (H) 2016 v1.03 and CML 2016 v4.8. Discrepancies in red.

Equivalent category		**FRRHA/CRRHA**	
ReCiPe (H) 2016 v1.03 midpoint	CML 2016 v4.8	ReCiPe (H) 2016 v1.03 midpoint	CML 2016 v4.8
acidification: terrestrial | terrestrial acidification potential (TAP)	acidification | acidification (incl. fate, average Europe total, A&B)	0.84	0.88
climate change | global warming potential (GWP100)	climate change | global warming potential (GWP100)	0.91	0.93
ecotoxicity: freshwater | freshwater ecotoxicity potential (FETP)	ecotoxicity: freshwater | freshwater aquatic ecotoxicity (FAETP inf)	1.20	0.66
ecotoxicity: marine | marine ecotoxicity potential (METP)	ecotoxicity: marine | marine aquatic ecotoxicity (MAETP inf)	1.20	1.35
ecotoxicity: terrestrial | terrestrial ecotoxicity potential (TETP)	ecotoxicity: terrestrial | terrestrial ecotoxicity (TETP inf)	1.04	0.06
energy resources: non-renewable, fossil | fossil fuel potential (FFP)	energy resources: non-renewable | abiotic depletion potential (ADP): fossil fuels	1.00	0.99
eutrophication: freshwater | freshwater eutrophication potential (FEP)	eutrophication | eutrophication (fate not incl.)	1.26	0.79
human toxicity: carcinogenic | human toxicity potential (HTPc)	human toxicity | human toxicity (HTP inf)	1.14	0.89
material resources: metals/minerals | surplus ore potential (SOP)	material resources: metals/minerals | abiotic depletion potential (ADP): elements (ultimate reserves)	1.22	1.20
ozone depletion | ozone depletion potential (ODPinfinite)	ozone depletion | ozone layer depletion (ODP steady state)	1.16	0.94
photochemical oxidant formation: terrestrial ecosystems | photochemical oxidant formation potential: ecosystems (EOFP)	photochemical oxidant formation | photochemical oxidation (high NOx)	0.83	0.91

5.5. Limitations

The results of this study come with some limitations that need no to be acknowledged. First, the author had limited knowledge on horticultural systems before the start of the project and, despite an intense 6-month period of research including discussions with multiple experts and professionals, his experience cannot be equated to that of an agronomy postgraduate. Nevertheless, this is a challenge that LCA practitioners face on a regular basis as they apply their knowledge to a wide variety of fields and it is taken into account in the methodology by implementing consistency, completeness and sensitivity checks.

In terms of data collection, all data was finally collected from secondary sources. Unfortunately, time-constraints during the field trip to Agadir prevented from the collection of good quality primary data from farmers. Nevertheless, research in the area allowed to validate assumptions taken during the modelling phase as well as data collected conducting literature review. A downside of using secondary data is the limited knowledge about the conditions in which it was collected. Regarding ecoinvent database, some processes might not accurately represent the product system modelled in this study. An example is dumping of organic waste from greenhouses in the areas nearby, which has been modelled using the process biowaste landfilling which potentially overestimates the impacts caused by this practice. Nevertheless, ecoinvent remains as one of the most complete sources for LCA analysis and therefore it is assumed that the overall accuracy of the model is enough to obtain valid results.

Additionally, data quality is hindered by several other factors. Above all, hydroponic systems have barely been implemented in Morocco and therefore, there is a significant lack of information that had to be remedied by adapting data via assumptions, from a different geographical or technology scope. In addition, futagrow system has never been scaled up and used commercially increasing the uncertainty of inventory data.

Another limitation that affects interpretation becomes visible from the discrepancies in the characterisation results when switching between (in principle) equivalent impact categories like "Water consumption" from ReCiPe and "Use of net freshwater" from EN15804 ISO21930. Some deviations might be explained by a slightly different scope of the indicator but others are caused by the lack of critical characterisation factors, which require a thorough revision.

Finally, a common step in LCA studies is normalization where the characterisation results are compared to a set of reference information to calculate the magnitude of each impact category. This step was not possible in the present study due to the lack of reference information in the Souss-Massa region. Consequently, this study could not provide priorities between impact categories beyond those previously identified, namely, water scarcity, terrestrial ecotoxicity and freshwater eutrophication.

For these reasons, an expert review is recommended to interpret this study so that the results can be extrapolated to other farms with other characteristics. An expert can additionally adapt the rather general inferences drawn in this study to the singular features of a specific farm and their environmental conditions. Furthermore, some variables such as yield, energy or environmental emissions can be adjusted in the model to reduce the uncertainty of the results.

5.6. Conclusions and recommendations

The results from the analysis allowed to answer the research questions:

Which of the proposed hydroponic farming systems for tomatoes is more environmentally sustainable in the case of Souss-Massa?

In the baseline scenario, the conventional system performs remarkably better than Futagrow, which despite providing higher yield, it is deeply penalized for its high electricity consumption and the extra equipment. This difference shrinks when assessing visions with renewable energy and recycling practices. However, even in the most improved scenario with coconut husk allocated, the conventional system remains preferable in 12 out of 19 categories, including the three main environmental issues of Morocco, namely water consumption, terrestrial ecotoxicity and freshwater eutrophication.

Which processes and interventions are contributing the most to the main environmental issues in the region, namely, water scarcity, water eutrophication, soil pollution and global warming?

Above all, electricity consumed by artificial lighting is the main contributor not only for the categories stated in the question but for 17 out of 18 categories from ReCiPe. This is due to its generation from oil and coal that are powering the Moroccan electricity grid.

After lighting, landfilling of waste is the most polluting activity, contributing the most to global warming, and marine eutrophication, especially due to the abundant supply of organic matter from plants, substrate and unmarketable products.

How can the environmental impacts previously identified be diminished while keeping productivity high?

The answer to this question is the most elaborate as it aims to provide strategies to tackle the issues caused by lighting and waste. The next subsections summarize the conclusions regarding these two aspects and elaborate recommendations for farmers, companies and policymakers seeking to enhance environmental sustainability in Moroccan horticulture. Applying these recommendations, the impacts from transiting to high-tech hydroponic farming systems in Morocco can be drastically reduced by around 80% for categories like global warming, terrestrial ecotoxicity and freshwater eutrophication. Furthermore, freshwater consumption can also be reduced by up to 35% compared to the already very low level achieved in the Netherlands.

In appendix 10, these recommendations are contextualized with the economic and political conditions of Morocco observed during the field trip to Agadir to provide a more complete vision of the transition to more sustainable greenhouse horticulture in this region.

5.6.1. Energy

Electricity can be cut down by supressing artificial lighting completely, additionally avoiding the impacts from equipment production. However, despite the favourable conditions of Souss-Massa, relying on the sun exclusively would negatively impact the yield. Alternatively, electricity for lighting can be generated from renewable sources with a little increase of impacts, especially higher in the case of ecotoxicity. In the model from this study, renewable electricity was coming from windmills. However, each region has different climatic conditions that can affect the selection of the most convenient technology to generate green energy. Solar panels are another viable solution in the usually sunny weather of Morocco.

For heating, thermo-solar panels have not shown much potential to improve the current systems powered by natural gas. However, other technologies can be looked at. For instance, geothermal energy can deliver hot water to maintain the temperature over a threshold in the colder nights of winter. Geothermal sources are not available everywhere but according to the National Office of Petroleum and Mines (ONHYM), a hot point is located around Agadir where the geothermal gradient reaches 30-35 ^{o}C per kilometre of depth, so boiling water can be extracted from under 2500 m deep wells ("Geothermal in Morocco," 2019).

5.6.2. Waste

Waste impact is not as evident in the results compared to electricity. However, once electricity is responsibly managed, it will become the next priority. Plastic recycling scenario did not reveal a significant improvement. However, some observations need to be done. First, in the model recycling rate was limited to 50% considering little plastic pieces that are mixed and lost within other waste streams. This can be increased if new practices are implemented which could include the substitution of plastics with compostable materials. In addition, according to the modelling assumptions used in this LCA, product systems cannot benefit from the after-life use of their residues. Therefore, the benefits of recycling of plastics are only reflected on the results by the avoidance of landfilling (partly compensated by collection) but not on the saving of resources for other products. For these reasons and despite the results, plastic recycling practices are recommended and encouraged.

Nevertheless, plastic waste is only a little fraction of the residues, monopolized by organic matter from substrate, plants and rejected products. These waste streams, also usually dumped in the nearby environment of farms, present a great threat to the local environment as well as the loss of valuable nutrients, while contributing to global warming more than any other process.

To tackle these problems, it is essential to stop the systematic spill of waste and implement revalorization techniques like composting that breaks down solid waste into humus that can be applied to soil-grown crops. Another alternative is using a biodigester to accelerate the decomposition process. These closed systems generate, apart from compost, liquid fertilizer and methane gas that can be used for energy generation[3]. Furthermore, with enough capacity, biodigesters could be fed by organic waste from the surrounding community bringing positive externalities in terms of waste treatment. Lastly, it is also possible to process waste substrate to produce media for mushroom cultivation, opening new business opportunities to farmers (van Tuyll et al., 2022b).

Ultimately, the solution for substrate waste would be to drastically reduce its use by switching to NFT systems. However, this technology is still in development for its application to tomato production and will take time for it to be a viable option in Agadir.

Lastly, the recommendations given in this chapter are purely based on the quantitative results from the LCA study. Nevertheless, such results must not be interpreted isolated from the economic, cultural, and political context. To fill this gap and enrich the outcomes of the study, a field trip to Agadir and Rabat was conducted from May 4th to May 15th 2023 to collect different views on the transition to these technologies from different stakeholders involved. The agenda from this trip can be found on Appendix A9 and the most relevant findings are included in Appendix A10, at the end of this document.

[3] Biodigesters require regular maintenance to avoid methane leaks, which would highly increase the impact in global warming.

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7. APPENDIXES

Appendixes A1 to A9 are included in excel file “Appendixes”. Appendix A10 starts in the next page.

A1	Operational scheme of hydroponic systems under study
A2	Foreground unit process overview
A3	Modified background processes
A4.1	Unit process data (UPD) table Baseline
A4.2	UPD table Zero-Energy
A4.3	UPD table Renewable energy
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A5	Inventory results
A6	Characterisation results
A7.1	Contribution analysis (processes)
A7.2	Process contribution (Sankey diagrams)
A7.3	Contribution analysis (stages)
A8	Sensitivity Analysis
A9	Field trip agenda
A10	Transition to sustainable greenhouse cultivation in Souss-Massa

Appendix 10

Transition to sustainable greenhouse cultivation in Souss-Massa

As a follow-up of the LCA results, this section briefly summarizes the most relevant takeaways from the information collected during numerous interviews and meetings with farmers, companies, researchers, and governmental institutions. The trip also included visits to greenhouses, universities, company incubators, among other key locations. A short overview of the agenda can be found on appendix A9.

This section is included in the report to provide only a short overview of the situation, complementing the LCA conclusions and highlighting the barriers found against the implementation of the suggested changes. In-depth research on these topics fell out of the scope of the study.

Reluctance to the implementation of new technology

Most growers in Morocco do not seem especially interested in upgrading their farms. Historically, increasing production has been achieved by extending croplands rather than investing in more efficient methods. Farmers prefer to rely on their own experience on traditional methods which is hindering the implementation of hydroponic farming. Their complex operation also contributes to this reluctance as many of them do not fully comprehend how they work, negatively affecting their trust. To convince growers of the use of hydroponic systems, it is indispensable to show the technology at work in demonstration setups. Secondly, they will require a thorough explanation of how it works followed by clear instructions of how to replicate it. But for long-term success, the ultimate step is achieving a complete understanding of all the variables influencing the operation, allowing farmers to be autonomous. This 4-step procedure is essential for the successful implementation of hydroponic systems in Souss-Massa.

Another important aspect to consider is the fear to pests and diseases which have forced farmers to dismiss any option involving recirculation of materials. Organic waste is not composted and reapplied to the soil to avoid the spread of nematodes while water is never collected as it might facilitate the replication of viruses. To stimulate farmers to engage in the revalorization of organic waste and recirculation of water, there must be demonstrated evidence that these risks are avoided.

It was also suggested that for the successful implementation of new technologies a first step is to introduce automatic data collection which could monitor the progress of water usage and climate conditions and show farmers the improvement achieved. Additionally, sensors are also a powerful tool for government to control the appropriate management of natural resources and safeguard the effectiveness of policies.

Finally, another concern of complex hydroponic systems is the supply of spare parts for repairs and maintenance, which in Africa is unreliable and with very long shipping times. Even though the network for greenhouse technology supply is already growing in Morocco, with more hubs located in strategic locations, the situation still requires of extra planification and stocking more equipment on-site so, in case of a breakdown, the plants are kept alive and operations can continue as normal. This vulnerability is expected to decrease over time.

Unaffordable investment for new technologies

Despite its economic growth in the last decades, Morocco is still considered a developing country where more than half of rural population consider themselves poor (WorldBank.org, 2018). In this situation, the initial high investment required to build high-tech greenhouses becomes a challenging barrier to overcome. There is a consensus among companies of the sector that the return of investment would be achieved in a few years. However, a more in-depth economic analysis conducted by an independent entity from academic institutes or government is required. In this regard, life cycle costing (LCC) analysis would be recommendable, including external factors such as market trends and quotas that restrict exports to Europe. On the other hand, convincing of potential economic profit is more attractive to farmers, companies and investors than all the environmental benefits achieved by these technologies, so all campaigns addressed to these groups should be framed accordingly.

Unprecedented symbiotic industrial relationships and community projects

Symbiotic industrial relationships where the waste of one company becomes the raw material of other are a common element in circular economies. They are essential to achieve sustainability in production systems and they can bring not only environmental benefits but also economic advantages to their members. An example for Souss-Massa would be the waste biodigester plant proposed previously, fed by several farmers and neighbours to produce substrate, fertilizer and biofuel while eliminating waste. Nevertheless, in the horticultural sector in Morocco this kind of partnerships is rarely seen. Same can be said for community projects that bring together different stakeholders interested in a common goal to collaborate and share resources, for instance, a geothermal energy plant that could power several farms and villages with clean cheap energy and be financed by the whole community.

Cooperatives of farmers already in place could be the start of these initiatives but, so far, collaboration is limited to the share of information and getting an advantageous position in the market. In some cases, this strategy leads to investing in a common packaging station so they can label their products under the same brand.

In order to boost further collaboration with real environmental benefits, there is a need for dedicated entity in charge of connecting potential partners and securing confidence of supply in the network. This will increase trust among farmers on the benefits of a common project enabling an affordable way to deploy the recommended solutions along with more efficient hydroponic systems.