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Life Cycle Assessment of Vertical Farming: a comparative study between Italy and Algeria on aeroponic agriculture

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Abstract

Vertical farming has been increasingly promoted as a sustainable alternative to conventional agriculture, given its capacity to reduce land use, enhance water efficiency, and ensure year-round production. However, its high energy demand, particularly for lighting and climate control, raises concerns regarding its environmental viability. This thesis investigates the life cycle impacts of a vertical farming greenhouse designed by an Italian firm through a Life Cycle Assessment approach implemented in SimaPro. The study compares two geographical contexts, Northern Italy and Algeria, focusing on the embodied impacts of construction materials and electricity consumption, while excluding the cultivation phase. Several assessment perspectives were applied, including characterization, normalization, weighting, and single-score methods. Results reveal that electricity use is the dominant driver of global warming potential, while steel and aluminium production contribute significantly to marine aquatic ecotoxicity and acidification. The comparison highlights the influence of local energy mixes: Italy benefits from a higher renewable share, whereas Algeria shows greater reliance on fossil fuels, resulting in higher cumulative energy demand and emissions. The findings emphasize the role of energy efficiency and renewable integration in mitigating environmental burdens. Limitations of this study include data availability and the exclusion of cultivation processes, suggesting that future research should address crop-level impacts, renewable energy adoption, and circular strategies for material use.

1. Introduction

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In the face of increasing environmental constraints, rapid urbanization, and growing food demand, vertical farming has emerged as a compelling alternative to traditional agricultural practices. By reimagining food production through vertically stacked, climate-controlled environments, this approach offers new opportunities to address sustainability challenges in both urban and rural contexts. Yet, despite its promise, vertical farming remains a subject of debate, particularly when it comes to understanding its true environmental impact across different regions and energy scenarios.

The environmental conversation surrounding vertical farming often centers on its capacity to conserve land and water while enabling year-round cultivation. However, these benefits must be weighed against its substantial energy requirements as will be analysed afterwards, especially for lighting and climate control. As such, evaluating the sustainability of vertical farming cannot rely solely on theoretical advantages or isolated performance metrics; instead, it requires a holistic, data-driven analysis of its lifecycle impacts.

This thesis tries to respond to that need by applying the Life Cycle Assessment methodology to a real-world greenhouse structure from a company near Turin. The study leverages SimaPro software to explore the environmental implications of building and operating such a system in two distinct contexts: northern Italy and Algeria. The comparison is not just geographic, but systemic, considering how energy mixes, the combination of different primary energy sources, such as fossil fuels, nuclear power, and renewables (like solar, wind, and hydro), that a country or region uses to meet its energy needs, and climate influence the sustainability of vertical farming.

Beyond calculating impact metrics, this work seeks to deepen our understanding of how design and location shape the environmental footprint of high-tech farming systems. The intention is to move the conversation from theoretical potential to practical insight, providing an overview to better understand and start developing from.

Structure of the Thesis

The document unfolds as follows:

- Chapter 2 lays the theoretical groundwork by introducing vertical farming and the principles of Life Cycle Assessment. This chapter offers the technical background necessary to understand the systems under study and the methodology used for environmental evaluation.

- Chapter 3 reviews current literature on vertical farming and Life Cycle Assessment, highlighting key trends, methodological approaches, and research gaps. This contextual analysis informs the rationale and positioning of the thesis.

- Chapter 4 presents the proposed framework, describing how SimaPro is used to model the greenhouse structure and assess its environmental performance. It details the case study setup, including material categorization and impact modeling, with a focus on Global Warming Potential.

- Chapter 5 reports the results of the Life Cycle Assessment, offering a comparative analysis of the system’s environmental impact in Italy and Algeria. Findings are discussed in relation to energy profiles and possible optimizations.

- Chapter 6 concludes the thesis with reflections on limitations and potential avenues for future work, including suggestions for improving the sustainability of vertical farming through material choices, energy sourcing, and system design.

By combining rigorous environmental analysis with contextual sensitivity, this thesis aims to contribute meaningfully to the ongoing discourse on sustainable food systems, bonding the promise of vertical farming in empirical evaluation and strategic insight.

2. Theoretical background

2.1 Vertical Farming Overview

Through the years, researchers have advanced myriad methods of urban and vertical farming in the hopes of contributing to sustainable food production. Between these, advanced farming methods could provide greater yields and use far less water than traditional farming [42; 21]. The design, layout, and configuration of these high-tech farms would provide optimal light exposure, along with precisely measured nutrients for each plant and, since these farms are designed to grow in a controlled, closed-loop environment, it will be eliminated the need for harmful herbicides and pesticides, maximizing nutrition, and food value in the process [19].
Researches intend to develop, refine, and adapt these systems so that they can be ultimately deployed anywhere in the world and provide maximum production and minimum environmental impacts. They represent a paradigm shift in farming and food production and scholars view them as suitable for city farming where land availability is limited [42].

Instead of farming vegetables and other foods on a single level, such as in a field or a greenhouse, vertical farming produces foods in vertically stacked layers commonly integrated into other structures like a skyscraper, shipping container or repurposed warehouse, as in *Figure 1*. The artificial control of temperature, light, humidity, and gases makes producing foods and medicine indoor possible. In many ways, vertical farming is similar to greenhouses where metal reflectors and artificial lighting augment natural sunlight. The principal intention of vertical farming is maximizing crops output in a finite space.

Figure 1 – Large-scale example of indoor farm in Singapore

Summarising the data gathered in the research across all these related concepts, it could be argued that there are six main characteristics that influence the different classifications of these types of indoor farming (Size, Density, Controls, Layout, Building type (/form) and Location), but, in order to provide an high level of understanding on this technology there are four key topics which are the main characteristics.

Firstly, Physical layout. Since the goal of vertical farming is producing more food per square meter to accomplish this goal, crops are cultivated in stacked layers in a tower-like structure.

Secondly, Lighting, where the implementation of energy-efficient lighting systems, such as LED technology, allows the reduction of times and the ideal intensity of lights.

Thirdly, Growing medium. Instead of soil, aeroponics (plant cultivation process without root restrictions), hydroponic (a system of growing plants in the water) or aquaponics (hydroponic maintained by products or fish) growing methods are used through the avail of peat moss or coconut husks and similar non-soil mediums which are very common in vertical farming.

Lastly, Sustainability features. As will be seen afterwards, vertical farming method uses various sustainability features to counterbalance the energy cost of farming, trying to focus on the reduction of water usage, decreasing up to 95% [25]. However, this technique implies a high use of electricity, generating, as will be covered later on, other sustainable problems.

As mentioned before, vertical farming often utilizes soilless cultivation methods within controlled environments to optimize plant growth. The three primary techniques employed are hydroponics, aeroponics, and aquaponics, each with its unique approach to delivering water and nutrients to plants.

Hydroponics, as can be seen in *Figure 2* is the most prevalent method in VF, where plants are grown in circulating water that is enriched with precisely measured quantities of nutrients [13]. Various system types exist, such as nutrient film techniques (NFT), deep water culture (DWC), and drip irrigation, each suited to different plant types and scales [15]. This system not only promotes plant health but also improves sustainability as it captures and recirculates nutrient solution over an extended period without the need for drainage, thus exemplifying the circularity of vertical farming.

Aeroponics (*Figure 3*) involves suspending plant roots in the air and misting them with a nutrient-rich solution. This method offers even greater water efficiency and oxygen availability for the roots compared to hydroponics, potentially leading to healthier plants. However, aeroponic systems can be more complex to manage [15].

As illustrated in *Figure 4*, Aquaponics is an integrated system combining hydroponics and aquaculture, creating a symbiotic relationship. Fish waste provides nutrients for the plants, and the plants filter the water for the fish, resulting in a closed-loop, sustainable system that produces both plants and potentially fish, but, while sustainable, aquaponics requires careful balancing of the needs of both the fish and the plants and can have higher initial costs [15].

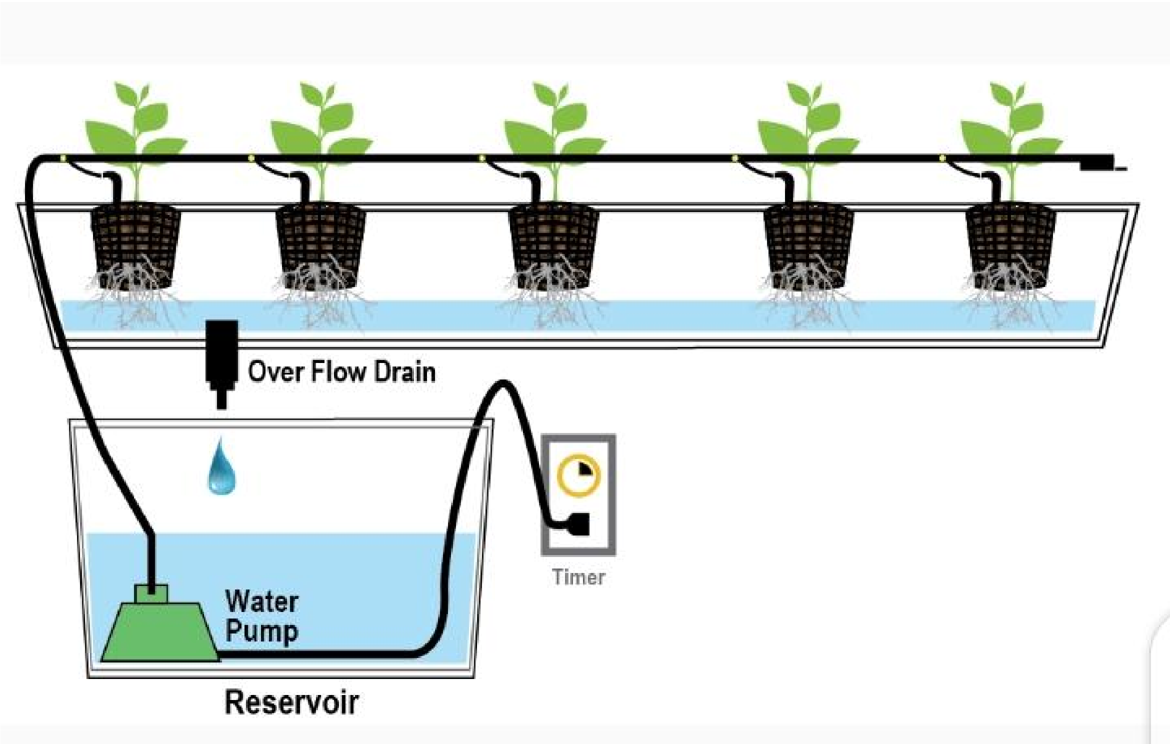

Figure 2 – Hydroponic graphic

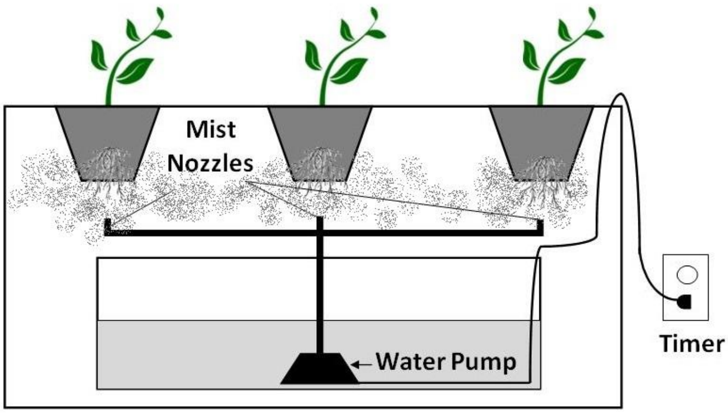

Figure 3 – Aeroponic graphic

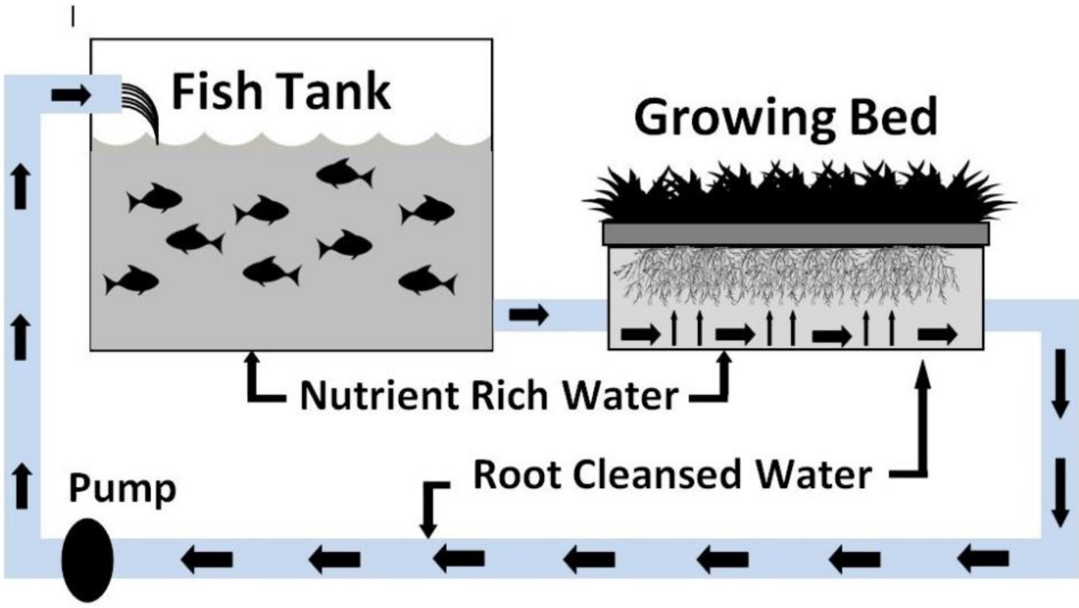

Figure 4 – Acquaponic graphic

2.1.1 Advantages of Vertical Farming

By creating regulated, layered ecosystems, VF has the potential to revolutionize agriculture by increasing sustainability and productivity. It can help reduce dependency on dangerous pesticides, conserve water and land, and produce crops all year round [41; 2; 25, 4] and, thanks to shorter supply chains, lower emissions, and improved local food security, the integration into metropolitan regions is also possible [25; 38; 42]. VF has the potential to revolutionize contemporary farming by tackling climate issues and inventing new uses and the advantages can be categorized in four main categories: Food Security, Yield and production, Resource Management and Environmental benefits [20].

2.1.1.1 Food Security

The highly controlled environment typical of VF systems, allows for extremely precise nutrient management, facilitating targeted fertilization that provides plants with only the strictly necessary amounts and proportions of essential elements, leading to a drastic reduction in fertilizer use, estimated at between 50% and 70% less compared to traditional methods [42]. This precision not only optimizes crop growth but also significantly reduces the risk of nutrient dispersion into the environment, mitigating negative impacts like eutrophication, while supporting the sustainable use of resources [20; 6]. Concurrently, the confined and protected nature of VF installations creates an environment inherently unfavorable to the development of pests, diseases, and weeds that plague open-field crops, enabling cultivation that requires minimal or zero use of pesticides and herbicides, with reductions estimated at 80-90% in the application of plant protection products [20]. This advantage enhances the quality and safety of the final product and reduces the introduction of potentially harmful chemicals into the ecosystem, contributing to overall environmental sustainability [6]. Also crucial is its flexibility in location, permitting direct integration within or near urban centers and densely populated areas [20; 34; 6], an aspect particularly relevant given the pressure on land resources in many regions [16]. The ability to produce locally and year-round, irrespective of external climate conditions [6], increases the resilience of the food system and can improve accessibility to healthy food in urban areas, positioning VF as a valuable tool for enhancing urban food supply security and fresh food availability [9].

2.1.1.2 Yield and Production

One of the main features that VF carries, is the ability to year-round crop production, enabling consistent output regardless of external weather conditions, which is especially beneficial in non-tropical regions [33], allowing increased production number compared to open-field agriculture.

For what concerns the production lettuce, for instance, yields, from vertical farms, can achieve lettuce yields per square meter up to more than 80 times higher than those achieved through open-field agriculture and up to 12 times greater than those from greenhouses over the production time of the vegetable [15; 19; 20; 31].

This impressive productivity means, as studied by Dickson Despommier, microbiologist and ecologist, that a single indoor acre of a vertical farm may produce yield equivalent to more than 30 acres of farmland, when the number of crops produced per season is considered. [33; 14].

Furthermore, VF optimizes land use through multilayered growth systems, which maximize yield per square meter of growing space.

This is particularly advantageous in urban areas, where it has been estimated that a 10-meter-tall vertical farm, producing wheat, could produce up to 600 times more food per land area compared to traditional farming [4].

2.1.1.3 Resource Management

An important asset of VF is the Reduced Water Usage, since VF systems, particularly hydroponics and aeroponics, can reduce water usage by up to 95% compared to traditional agriculture [25]. Closed-loop recycling systems further minimize water consumption [25] and VF's water use per kg of dry lettuce can be up to 18 times lower than open-field agriculture using surface irrigation.

The controlled environment inherent in VF allows for a substantial reduction or even complete elimination of chemical pesticides and herbicides, with some operations employing biological controls, such as ladybugs, to effectively manage pest infestations [33].

2.1.1.4 Environmental Benefits

VF adoption can be seen as “environmental friendly” for the significantly contribution to a reduced carbon footprint related to transportation, by minimizing or eliminating the use of tractors and other large farming equipment, which, automatically, decreases fossil fuel consumption and, thanks to the strategic placement of vertical farms in urban areas, there are also lower farm-to-market transportation costs [20; 34].

VF also plays a climate-friendly role by protecting crops from extreme weather events such as droughts, hail, and floods; indoor growth systems effectively shield plants from the adverse effects of outside weather and climate change. The reduction in transport distances also helps to minimize food waste due to the deterioration of fresh products during transit and ensures the availability of fresh, high-quality food more rapidly [6].

Lastly, VF enhances land conservation by increasing yields per surface area through multilayered growth, thus reducing the need for additional land that can subsequently be returned to its original ecological function.

2.1.1.5 Other Advantages

In addition to the primary categories, VF offers additional benefits, especially in urban areas where market accessibility is essential.

By establishing infrastructure in urban areas, VF not only aligns supply with local demand [4] but also drives job creation across diverse fields such as engineering, construction, biotechnology, biochemistry, and research and development.

In addition, VF improves food security by ensuring a consistent, local supply of fresh produce - a necessity for urban populations, which will be further.

Regarding health and safety, VF reduces typical work-related risks associated with conventional farming, like mishaps with large equipment and exposure to dangerous chemicals.

Lastly, the closed environments utilized in VF could also have implications for space exploration, offering potential solutions for cultivating food in extraterrestrial settings [28].

2.1.2 Disadvantages of Vertical Farming

On the other hand, VF needs to be deeper dived on factors such as economic, logistic and environmental which develop. The last, in particular, has also been mentioned as advantage though its positive outcomes on water and land usage but the same cannot be said about the CO_2 emission, due to the electricity consumption, which generates non-negligible values.

2.1.2.1 Economic Implications

VF has its main problems in the economic considerations, including high initial costs associated with the establishment of infrastructure, technology, and energy systems, particularly in urban locations where real estate can be expensive [33].

The energy consumption required to maintain optimal growing conditions in VF is substantial, which can lead to increased operational costs and environmental concerns.

As a result, VF businesses tend to be economically viable only within specific niche markets or integrated into an added value chain, as they primarily focus on the production of low-calorie plants like lettuce and herbs [13].

Other limitations include market acceptance issues, where some consumers may not understand the potential of VF and may view products as genetic modification, gathering the nickname, as Steven Drings, professor at the University of Chicago, states "Frankenfoods". This misconception could generate a barrier that may effect in the worst way the sales form this method [38].

VF also competes with traditional farming practices, and while it can achieve greater production volumes, this may undermine broad-acre agriculture, risking to instantly paralyze farmers and consequently the core sector for many countries.

2.1.2.2 Environmental Impact

The other notable impact, the Environmental impacts, are another key problem with VF since the latter exhibiting much higher average energy use compared to traditional outdoor farming.

This reliance on intensive lighting, climate control, and air circulation systems contributes to a larger land footprint for electricity production when compared to open-field agriculture and greenhouses, while the overall environmental performance of wheatgrass protein from VF remains uncompetitive with traditional protein sources due to the high environmental impact of the current electricity mix [15].

2.1.2.3 Technical and Logistical Challenges

For what concerns the technical and logistical challenges, these arise from the heavy dependence on technology, which not all farmers may be familiar, with methods such as hydroponics, aeroponics, and aquaponics which need to be studied and trained before being applied.
The limited data and research available on VF further complicate the evaluation of its sustainability and the lack of transparently the data provided by the VF companies makes it difficult to further investigate the sustainability of this technology

2.2 Life Cycle Assessments

Life Cycle Assessment, mostly known as LCA, is an analytical tool used to evaluate the potential environmental, social, and economic impacts of a product, service, or process throughout its entire life cycle [10]. This spans from the extraction of raw materials to the end of the life cycle, such as disposal [41; 28], offering a holistic and complete view of the system [41]

2.2.1 History of LCA

The concept of LCA emerged in the early 1960s, when the global economy began to face the first signs of resource scarcity and growing concern about the environmental consequences of industrial development [22]. During this period, researchers and policymakers increasingly recognized that industrial systems were highly dependent on finite raw materials and fossil energy, prompting efforts to quantify the environmental and energy implications of production processes. One of the earliest documented studies resembling the modern LCA framework was conducted by Harold Smith (1963), who, at the World Energy Conference, presented an analysis of the cumulative energy requirements for various manufacturing and chemical processes [22]. His work represented the first systematic attempt to assess the total energy inputs across a product's production chain, laying the foundations for what would later become known as life cycle energy analysis.

The 1970s were pivotal years for the conceptual development of life cycle thinking. The publication of The Limits to Growth (*Meadows et al., 1972*) (*Figure 5*) and A Blueprint for Survival (*The Ecologist, 1972*) (*Figure 6*) marked a turning point in the scientific community's understanding of the relationship between industrial expansion, demographic growth, and ecological limits [50]. These studies used systems modeling to demonstrate that unchecked economic growth and resource consumption could lead to environmental collapse. In parallel, the first practical applications of life cycle - type analyses appeared. In 1969, the Midwest Research Institute (MRI) in the United States undertook one of the earliest quantitative comparisons of packaging systems, evaluating the resource use and environmental emissions associated with different types of beverage containers. The MRI study quantified inputs such as raw materials, fuels, and emissions throughout the manufacturing and distribution chain—essentially creating the first Life Cycle Inventory (LCI) framework, a cornerstone of today's LCA methodology [22].

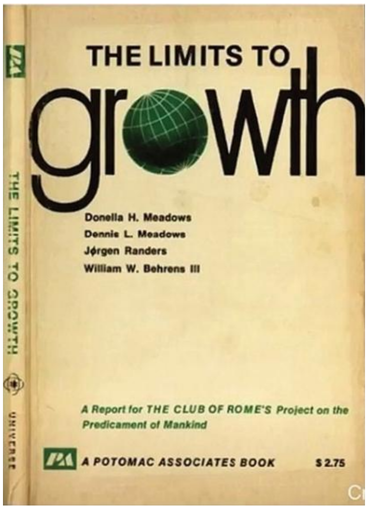

Figure 5 – The limits to Growth by Donella H. Meadows, D.L. Meadows, J. Randers and W.W.Behrens III

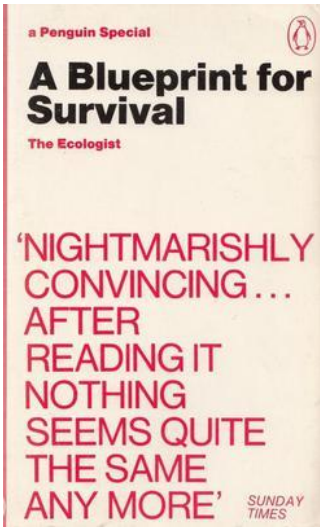

Figure 6 – A Blueprint for Survival by The Ecologist

The energy crises of the 1970s further stimulated the development of environmental and energy accounting tools. The need to optimize fuel efficiency and reduce dependency on fossil energy sources led to the first energy-based environmental assessments of biofuels and industrial processes. In 1979, Chambers introduced one of the first analyses of the fossil energy balance of biofuels, exploring what is now termed the Energy Return on Investment (EROI) for renewable alternatives [User text]. Around the same time, methodological frameworks such as Resource and Environmental Profile Analysis (REPA) in the United States and EcoBalance in Europe began to formalize the idea of evaluating the total environmental implications of products across their life cycle [22, 50]

During the 1980s, methodological refinement accelerated. Researchers began to expand the scope of assessments beyond energy use to include broader environmental impact categories such as air emissions, eutrophication, acidification, and resource depletion. These developments marked the shift from energy analysis to comprehensive environmental life cycle analysis, supported by the emergence of computerized databases and modelling tools [22]. The growing awareness of the need for harmonized methods led to the establishment of international networks and workshops coordinated by the Society of Environmental Toxicology and Chemistry (SETAC). The term "Life Cycle Assessment" was officially adopted in 1993 at the SETAC conference in Smuggler Notch, Vermont (USA), when researchers agreed on a unified terminology and conceptual framework [22].

This consensus paved the way for international standardization. In 1998, the International Organization for Standardization (ISO) published the first formal LCA standards, ISO 14040 and ISO 14044, defining the principles, framework, and requirements for conducting LCA studies [22].

Today, LCA has evolved into a robust scientific tool that supports decision-making in both policy and industry. It enables the quantitative evaluation of environmental burdens associated with products, processes, or services from "cradle to grave", including raw material extraction, production, use, and end-of-life stages [22], while contemporary applications span diverse sectors, from energy systems and transportation to agriculture, construction, and information technology.

Within the LCA framework, the definition of system boundaries determines which life cycle phases are considered and is therefore fundamental to the robustness and interpretability of the results. The cradle-to-grave approach is the most comprehensive, encompassing every stage of a product's life, from raw material extraction ("cradle") to the end-of-life treatment and final disposal ("grave"). It integrates production, distribution, use, and waste management, thus providing a holistic representation of cumulative environmental impacts across the entire life cycle.

Other variants of LCA focus on specific life cycle segments. The cradle-to-gate approach limits the analysis to processes from resource extraction up to the factory gate, excluding the use and end-of-life phases. It is particularly applied in industrial and manufacturing contexts, where downstream impacts depend heavily on user behavior or localized conditions. The gate-to-gate approach, in contrast, isolates a single process or production stage within a broader supply chain, enabling detailed process optimization and benchmarking. A more recent evolution is the cradle-to-cradle perspective, which aligns with circular economy principles by extending traditional boundaries to include material recovery and recycling, ensuring that outputs of one life cycle serve as inputs for another.

In practical applications, such as those modelled through SimaPro for agricultural systems, cradle-to-grave assessments have been used to quantify embodied impacts of materials (e.g., steel, polycarbonate, aluminium), operational energy demand during cultivation, and emissions from end-of-life management. This boundary setting ensures alignment with ISO 14040/44 principles and supports the comparability and transparency of environmental performance across technologies and geographical contexts.

2.2.2 Pros and Cons of LCA

LCA, as we know it today, has developed in many ways, generating a long list of advantages, or pros, which, unlikely, imply as many disadvantages, or cons.

Pros:

- Comprehensive Assessment: LCA provides a holistic, cradle-to-grave perspective, evaluating environmental impacts throughout a product's entire life cycle [36].
- Informed Decision-Making: LCA supports decision-making with scientific data, enabling improvements and strategic decisions.
- Strategic Applications: LCA helps improve processes and make strategic decisions, guiding product development to minimize environmental impacts.

- Hotspot Identification: LCA helps identify 'hot-spots' in the life cycle, enabling targeted improvements.
- Promotes Eco-Efficiency: LCA-based environmental management can become part of good business management, heading towards the eco-efficiency concept of ‘producing more quality with fewer resources.

Cons:

- Subjectivity and Data Gaps: LCA uses subjective judgment extensively, and data may be lacking.
- Time and Resource Intensive: LCA can be time-consuming and expensive, requiring significant resources for data collection and analysis.
- Debates on Methodology: LCA's objectivity, methodological considerations, and completeness have been debated. Allocation and other methodological choices have been subject to extensive scientific discussion in the field.
- Data Availability: Data availability can be a limiting factor, with limited data on specific materials and infrastructural components.
- Misunderstanding: LCA should not be misunderstood as a comprehensive or a complete assessment, but rather as one tool among many.

2.2.3 Importance of LCA

LCA holds significant importance across multiple domains; stakeholders recognize it as an essential component of the environmental management toolkit, and it proves invaluable for strategic planning in new product development and corporate strategy formulation. It facilitates communication through environmental declarations and contributes to initiatives like the EU Ecolabelling Programme [36].

LCA enables the comparison of different products based on their functionality and relates environmental impacts to market changes and technological advancements. Additionally, it promotes green procurement by encouraging the use of resource-efficient and environmentally friendly products and practices across society.

Transparency is crucial in all LCA studies, with careful consideration of the target audience influencing the choice of reporting methods. Finally, LCA can be integrated with social life cycle assessment (S-LCA), broadening the boundaries of sustainability to encompass social dimensions as well. [36]

2.2.4 LCA Methodology

Any LCA study systematically evaluates the environmental impacts of a product, process, or system through four iterative phases, as shown in *Figure 7*. The first step in the process is defining the goal and scope, which sets the objectives, parameters, and functional units of the investigation. The LCI studies and measures waste, emissions, energy consumption, and resource inputs at every stage of the life cycle. Life cycle impact assessment (LCIA), the third stage, converts inventory data into quantifiable environmental effects like resource depletion or climate change. Lastly, the interpretation step addresses uncertainties, synthesizes data, and highlights crucial concerns to aid decision-making.

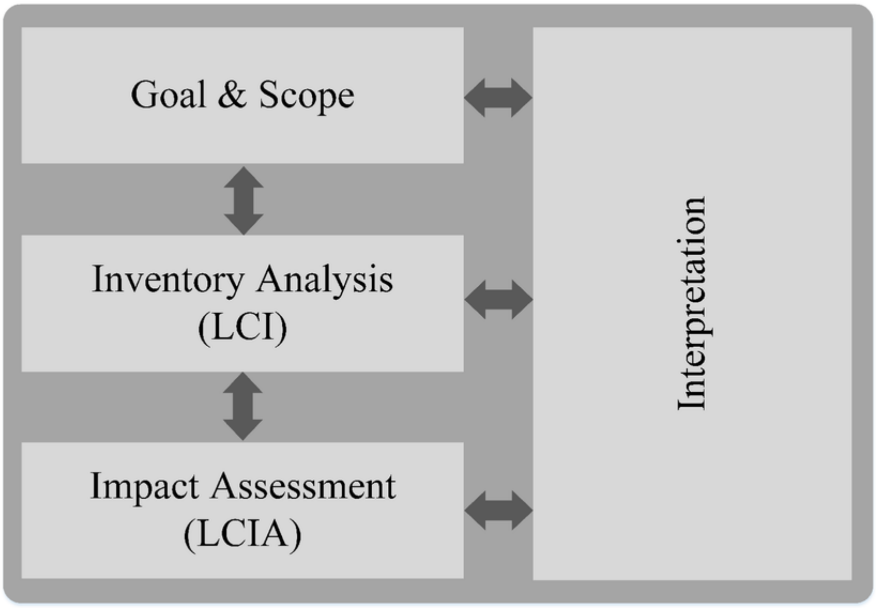

Figure 7 – Steps involved in the LCA Methodology

2.2.4.1 Goal and Scope Definition

The goal and scope definition is a crucial phase in conducting an LCA, as it establishes the intended application, reasons for the study, and the target audience.

This phase outlines the system boundaries, which delineate what will be included in the assessment and the methods to be employed, significantly influencing the results of the LCA.

A functional unit is defined during this stage to specify what is being studied, ensuring comparability between different systems.

Defining system boundaries is imperative to specify which stages and processes are included in the assessment, with significant implications for data collection and analysis. Any omissions must be clearly justified to maintain confidence in the results, ensuring that the study's goals are met without compromising data integrity.

It is important to note that LCA focuses solely on environmental impacts related to ecological systems, human health, and resource depletion, without addressing economic or social effects. Additionally, the boundaries can be expanded to incorporate additional functions or systems for more equitable comparisons.

2.2.4.2 Life Cycle Inventory (LCI)

Following the Goal & Scope definition, the LCI phase focuses on data collection, which is essential for gathering and analysing all relevant input and output data concerning the system under investigation, ultimately leading to the quantification of environmental impacts and damages.
The quality of the data used in the LCI directly affects the final LCA results, necessitating a systematic assessment of data quality to ensure transparency and understanding of these.

2.2.4.3 Life Cycle Impact Assessment (LCIA)

The LCIA employs the Environmental Footprint method developed by the European Commission to robustly evaluate environmental impacts associated with products in the European market.
During characterization, LCI results are translated into contributions across various environmental impact categories, while weighting assigns relative importance to these categories, reflecting societal values or policy goals. The interpretation phase involves assessing consistency, sensitivity, and significant issues within the inventory and impact results, which inform conclusions, recommendations, and limitations of the study. During this phase, it is important to maintain transparency, in order to clarify everything for the reader.

2.2.5 Main LCA Metrics for Vertical Farming

There are many metrics that are being used for the analyse of the LCA, but vertical farming requires a holistic assessment using multiple metrics and indices [9]. As explained before, apart from the environment. the complete sustainability evaluation also entails the economic, social, spatial, and time-related dimensions, so the evaluation of vertical farming employs a mixed set of indices spanning the environmental, economic, and social sustainability dimensions, typically aided by spatial and time-related dimensions [9].

2.2.5.1 Global Warming Potential

The Global Warming Potential (GWP) is among the most widely used midpoint indicators in the LCA, allowing for the quantification of greenhouse gas (GHG) emissions in terms of CO_2 equivalents (CO_2-eq) over a standard 100-year time horizon. It serves as a critical metric for assessing the climate impact of production systems,

In vertical farming, GWP is typically evaluated within cradle-to-gate or cradle-to-grave system boundaries. The main sources contributing to GWP in these systems are electricity consumption (especially for LED lighting and climate control), material inputs (e.g., for infrastructure, packaging), and sometimes supplementary CO_2 injection. Studies have reported a wide range of GWP values for vertically farmed crops, varying from less than 1 kg CO_2-eq/kg product to more than 8 kg CO_2-eq/kg depending on location, system scale, and electricity source [18; 29].

Methodological Considerations in GWP Evaluation

As stated before, several methodological aspects significantly influence GWP results in vertical farming LCA:

- *Electricity Mix*: As VF are highly energy-intensive, the carbon intensity of the electricity mix (e.g., coal-based vs. renewables) is often the dominant factor in determining GWP. For instance, systems operating under coal-heavy grids can show up to tenfold higher emissions compared to those powered by renewable energy.
- *System Boundaries*: The inclusion or exclusion of infrastructure [lighting systems, HVAC (Heating, Ventilation and Air Conditioning) units, racks, etc.] significantly alters GWP outcomes. Cradle-to-grave models that include construction, maintenance, and end-of-life treatment provide a comprehensive picture but increase data requirements and variability.
- *Functional Unit Definition*: The selection of the functional unit (e.g., per kg fresh weight, per m^2 per year, per nutritional content) impacts the interpretation of GWP results. For instance, given the high-water content of leafy vegetables, expressing impact per Kg dry matter or per kcal may offer more balanced comparisons with field-grown alternatives.
- *Allocation and Scaling*: Allocation of impacts among multiple crops or production cycles can skew results. Small-scale experimental setups may not represent commercial-scale efficiencies, leading to either over- or under-estimation of GWP.

- *Technological Assumptions*: Improvements in LED efficiency, climate control, and energy recovery can significantly reduce GWP over time. Therefore, dynamic LCAs or prospective scenarios are increasingly relevant in capturing the evolving nature of vertical farming technologies.

2.2.5.2 Energy Consumption

Vertical farming systems, especially plant factories with artificial lighting (PFAL), demand significantly more energy than traditional agriculture, mostly due to LED-based photosynthesis, HVAC, pumps, and control systems. As estimated that PFAL energy consumption can exceed that of open-field or greenhouse systems by several times and suggest optimization of spectral lighting, HVAC coupling, and renewable energy integration as key mitigation strategies [29]. Hallikainen's LCA of vertical lettuce in Sweden have moreover revealed that energy usage patterns are heavily influenced by grid mix and operational design [28], highlighting the importance of the latter. Energy is typically characterized by using cumulative energy demand (CED) metrics ($\frac{\text{MJ}}{Kg}$), with some studies also presenting kWh per functional unit and conducting sensitivity analyses across regional energy mixes. These studies consistently identify energy use as the primary environmental burden and advocate integration of renewables and efficiency improvements in lighting and HVAC systems [39].

2.2.5.3 Water Usage

Vertical farming demonstrates exceptional water-use efficiency, as stated in the previous chapter achieved through closed-loop hydroponic and aeroponic systems combined with controlled irrigation, which led to reported water savings of up to 95% compared to greenhouses, attributing this to recirculation and transpired water recovery [15]. Quantification typically uses $\frac{m^3}{Kg}$ yield for blue water, with some LCAs also incorporating green and grey water via broader Water Footprint Assessments. True accuracy rests on detailed modelling of local water availability, recirculation losses, and system closeness.

2.2.5.4 Land Usage

As shown previously, VF offers significant reductions in land occupation, versus traditional agriculture [15, 29]. LCIA models implement land occupation (LO) and land transformation (LT) indices to account for both direct and indirect land use and these are evaluated through the square meter per year per kilograms ($\frac{m^2}{Kg \times Year}$). For comprehensive assessment, Embodied land use was included in materials production to properly weigh the trade-off between operational efficiency and structural demand.

2.2.5.5 Ozone Depletion Potential

Ozone Depletion Potential (ODP) is the environmental impact that represents the reduction of the ozone layer in the atmosphere. This layer is reduced with the concentration of halocarbons in the atmosphere as these gases dissociate the ozone molecules presented, reducing this layer. The depletion of the stratospheric ozone layer increases the radiation that can reach the Earth's surface, such as the ultraviolet radiation, which results in several climate changes that can affect the ecosystems and human health. ODP is evaluated by a kilogram of CFC-11 (Trichlorofluoromethane) equivalent. [18]

2.2.5.6 Acidification Potential

Acidification Potential (AP) quantifies the emissions of acidifying substances such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3), expressed in kilograms of SO_2 equivalents. In vertical farming systems, these emissions mainly originate from electricity generation, particularly when derived from coal or natural gas, combustion processes within HVAC systems, fertilizer and nutrient production, and the manufacture of infrastructure materials. To assess these impacts LCA models such as CML, ReCiPe, and TRACI are commonly applied. Each method provides specific characterization factors that convert the emitted substances into an overall AP score, reflecting regional environmental conditions (e.g., those of the USA for TRACI). Furthermore, embodied emissions associated with materials like steel and concrete contribute significantly during the construction phase, underscoring the importance of a cradle-to-grave approach in environmental modelling [39].

3. State of Art

3.1 Literature Review Methodology

To build a solid foundation for this thesis, a systematic literature review was conducted to identify the most relevant studies addressing vertical farming and LCA. The search strategy focused on combining keywords that describe different forms of controlled environment agriculture. The query used was developed using different words: vertical farming, CEA (Controlled Environmental Agriculture), combined with the keyword LCA with searches limited to article title, abstract, and keywords. In addition, it was also added the term "**ponic*", which gives in return all the words that end with ponic (i.e. Hydroponic, aquaponic, aeroponic etc.) *[figure 8]*

Figure 8 - Research query used on Scopus

This query was applied across Scopus, Google Scholar , and Google engine (using prompts such as "Vertical Farming LCA", "Aeroponic VF", etc.) filtering for PDF files.

The initial research has yielded a total of 254 papers: 152 from Scopus, 81 from Google Scholar, and 21 from Google engine.

Following the removal of 95 duplicates, 163 unique papers remained for an initial screening. In this first step, titles, abstracts, and keywords were reviewed to exclude studies not directly related to the research scope. As a result, 83 papers were excluded. The second screening step involved a full-text review of the remaining 80 papers, where another 41 were discarded due to misalignment with the topic or methodological limitations, giving a total of 39 papers. In addition, four more articles emerged during the drafting of the thesis. The results, with the correct divisions, can be seen in *Figure 9* and in *Figure 10*.

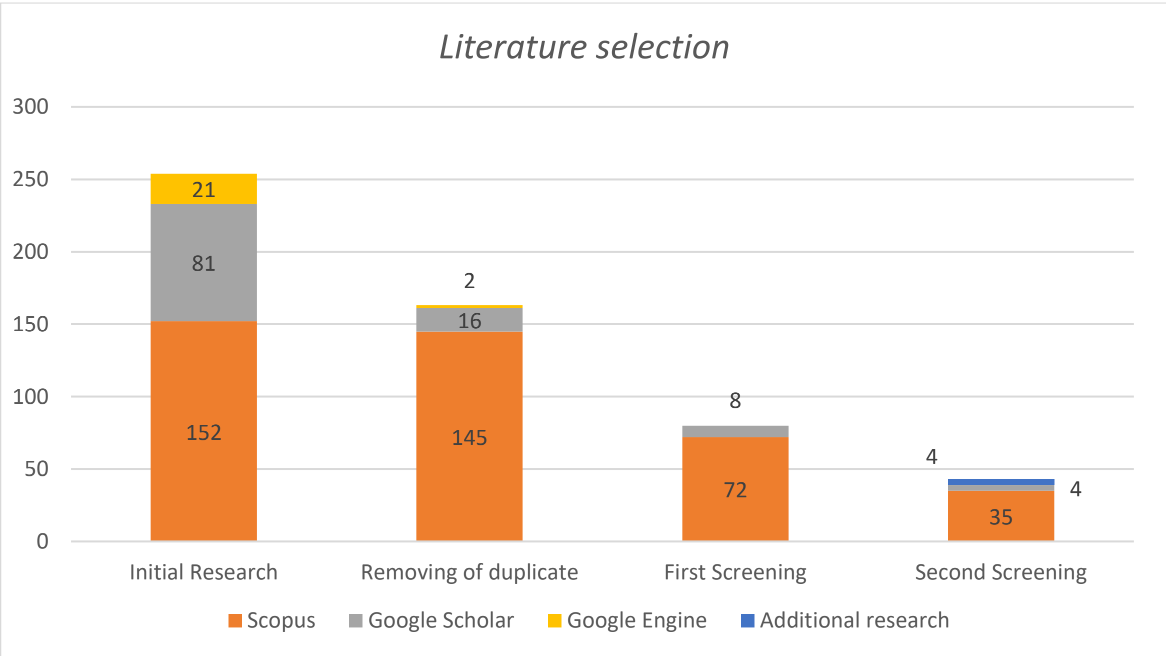

Figure 9 - Literature selection and screening process.

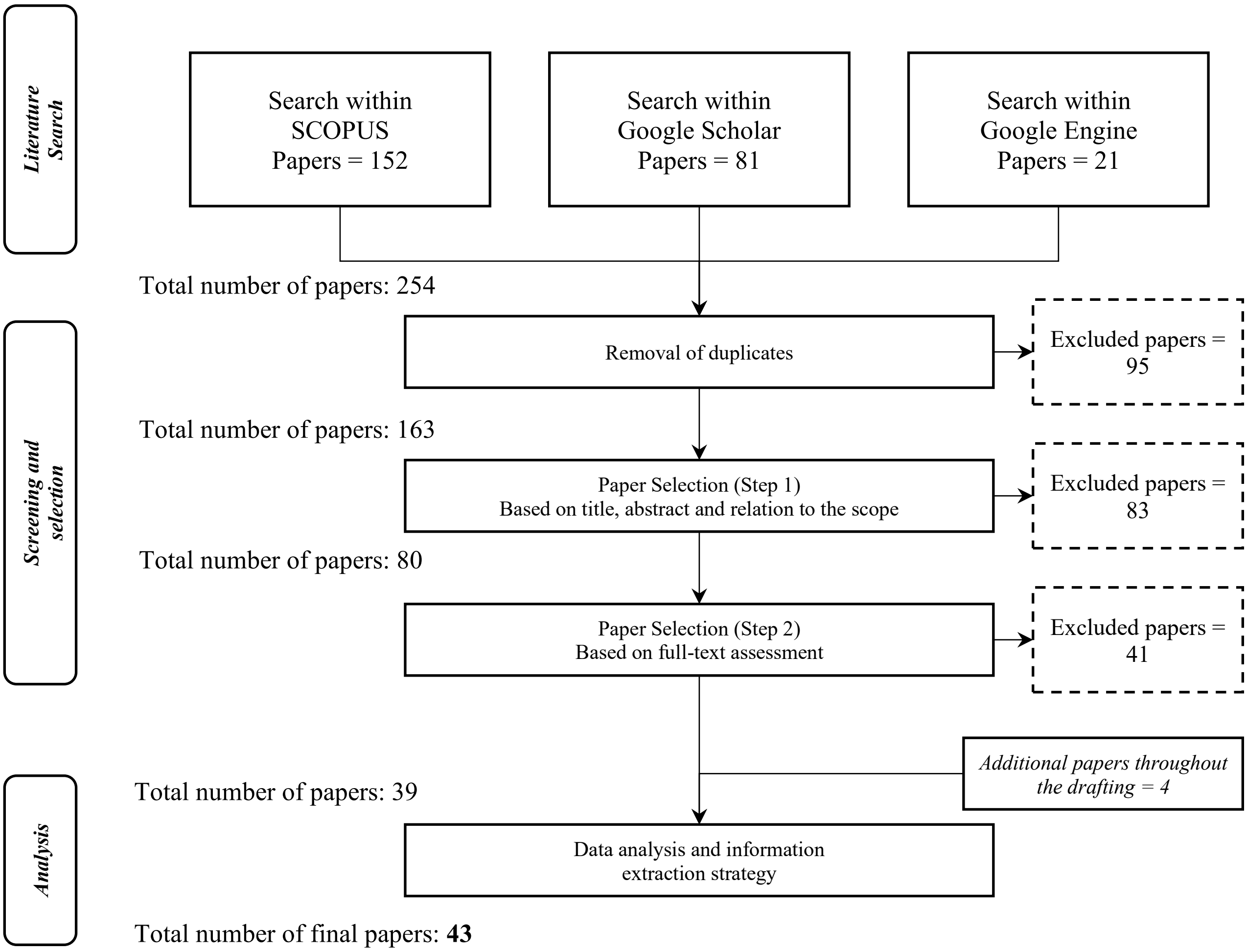

Figure 10 - Literature review methodology

The reviewed literature was carefully examined and organized to highlight its primary focus, methodology, and key insights. *Table 1* provides a structured overview of the selected studies, reporting the reference number, year of publication, main topic, and the most relevant findings of the research. To better capture their contribution, the papers were also grouped into broader categories: Energy and Lighting Optimization, focusing on the critical role of HVAC systems, artificial lighting, and renewable energy strategies; LCA-Oriented Studies, which directly apply or review life cycle assessment methods; Comparative Assessments, which evaluate vertical farming against alternative agricultural systems or scenarios; and Broader Sustainability Frameworks, which extend the analysis to include social and economic perspectives alongside environmental ones. Lastly, a small number of studies that did not clearly fit these areas were collected under a unified category called "Others".

Citation	***Year***	***Title***	***Main Topic***	***Key Observation***	***Category***
[1]	2023	A critical review on efficient thermal environment controls in indoor vertical farming	Thermal/HVAC control on the vertical faming agricolture	HVAC and humidity control dominate energy demand; integrated management is crucial.	Energy and Lighting Optimization
[2]	2024	Feasibility of using vertical farming in northern Iran: A multiple necessity	Regional feasibility	Highlights VF as a necessity in arid Iran, but with socio-economic and energy barriers.	Broader Sustainability Frameworks
[3]	2024	Towards global food security: Vertical farming as an innovative solution	Food security	Frames VF as a contributor to global food resilience, with energy as main limitation.	Broader Sustainability Frameworks
[4]	2023	Urban vertical farming with a large wind power share and optimised electricity costs	Energy systems	Coupling VF with wind power reduces electricity costs and improves sustainability.	Energy and Lighting Optimization
[5]	2023	Assessment of the energy consumption of indoor farming for different climates and lighting system intensity	Energy vs climate	Shows how climate and lighting intensity strongly affect kWh/kg of produce.	Energy and Lighting Optimization
[6]	2023	Urban vertical farming: Innovation for food security	Social impact	VF fosters food access and social inclusion in cities.	Broader Sustainability Frameworks

		and social impact			
[7]	2023	How energy innovation in indoor vertical farming can improve food security	Energy innovation	Energy technologies (LEDs, recovery systems) enhance VF scalability and reduce impact.	Energy and Lighting Optimization
[8]	2024	Energy-saving effect assessment of various factors in container plant factories (random forest)	Data-driven optimization	Machine learning identifies critical factors for energy reduction in container VF.	Energy and Lighting Optimization
[9]	2024	Sustainability assessment for novel approaches in the agri-food industry: Vertical farming	Sustainability frameworks	Proposes a multidimensional framework integrating environmental, social, and economic aspects.	Broader Sustainability Frameworks
[10]	2024	Life cycle assessment of food catering menus in a university canteen (Southern Italy)	Food service LCA	LCA approach useful as a methodological benchmark for VF comparisons.	LCA-Oriented Studies
[11]	2021	An economic model of sustainable development in the Russian Arctic: The idea of building vertical farms	Arctic economy	Explores economic feasibility of VF in extreme climates.	Comparative Assessments
[12]	2021	Eco-efficient Rendering Mortars (chapter)	Construction materials	Provides insights into eco-efficient construction, relevant for VF building context.	Comparative Assessments
[13]	2024	A cradle-to-customer life cycle assessment case study of UK vertical farming	LCA case study	Identifies hotspots in energy and packaging for VF produce.	LCA-Oriented Studies

[14]	2016	Farming up the city: The rise of urban vertical farms	Urban planning	Shows the spatial and planning implications of VF growth.	Comparative Assessments
[15]	2022	Vertical Farming: The only way is up?	Review	Broad review on VF challenges and opportunities, energy as bottleneck.	Others
[16]	2025	Enhancing efficiency through integration of geothermal and photovoltaic heating systems	Renewable integration	Geothermal + PV reduces energy demand in controlled environments.	Energy and Lighting Optimization
[17]	2025	Lighting strategies in vertical urban farming	Lighting strategies	Dynamic lighting improves yield per kWh.	Energy and Lighting Optimization
[18]	2018	Life Cycle Assessment on Vertical Farming (Master's thesis)	LCA study	Early LCA on VF, confirming electricity as main impact driver.	LCA-Oriented Studies
[19]	2023	Plant factory versus greenhouses: Comparison of resource use efficiency	Efficiency comparison	Shows PFs improve land and water use but demand more energy.	Comparative Assessments
[20]	2024	Environmental and resource use analysis of plant factories (Japan case)	Tech scenarios	Examines energy options to improve PF sustainability.	Comparative Assessments
[21]	2022	Text highlighting as a way of measuring consumers' attitudes: VF case	Consumer perception	Proposes novel methods to assess public attitudes towards VF.	Others
[22]	1997	LCA: A guide to approaches, experiences, and sources (EEA)	LCA methodology	Methodological guidance for conducting LCAs.	LCA-Oriented Studies

[23]	2024	Climate change impact and resource-use efficiency of lettuce in VF vs greenhouse (Finland)	Comparative LCA	Shows trade-offs: VF has higher energy but lower water/land impacts.	LCA-Oriented Studies
[24]	2024	The dark side of lighting: Critical analysis of VF impact	Lighting impacts	Demonstrates artificial lighting as key hotspot for VF impacts.	Energy and Lighting Optimization
[25]	2023	CSP technologies for VF in arid regions (Western Iraq)	Renewable energy	CSP can power VF in deserts, reducing grid dependency.	Energy and Lighting Optimization
[26]	2022	VF: Trade-off between crop land and renewable energy land	Land-energy trade-off	Saving cropland may require additional land for energy generation.	Comparative Assessments
[27]	2024	Business model configurations for successful vertical farming	Business models	Shows how different models can make VF more viable.	Others
[28]	2022	LCA of indoor vertical farms: A systematic review	LCA review	Confirms LEDs + HVAC as main impact hotspots.	LCA-Oriented Studies
[29]	2024	Environmental LCA of an on-site modular cabinet VF	LCA case study	Small modular VF can outperform conventional sourcing.	LCA-Oriented Studies
[30]	2025	CO_2 enrichment in protected agriculture (VF, CEA, greenhouses)	CO_2 agronomy	CO_2 enrichment boosts yield but increases energy trade-offs.	Broader Sustainability Frameworks
[31]	2023	VF and cultured meat: Immature technologies	Perspective	Discusses VF as promising but immature technology.	Others
[32]	2023	LCA of microgreen production in indoor VF	Microgreen LCA	Management practices influence yield and environmental efficiency.	LCA-Oriented Studies

[33]	2022	VF in urban areas: Systematic review	Urban review	Synthesizes VF research for cities and citizens.	Comparative Assessments
[34]	2023	The impact of VF on urban planning (system dynamics)	Urban planning	Shows VF affects land use and planning decisions.	Comparative Assessments
[35]	2024	Techno-economic-environmental analysis of solar-hybrid-storage VF (Malaysia)	Hybrid energy	Hybrid PV + storage reduces costs/impacts in tropical climates.	Energy and Lighting Optimization
[36]	2010	ILCD Handbook – EU LCIA methods	LCIA methodology	Provides EU guidelines for environmental indicators.	LCA-Oriented Studies
[37]	2017	LCA summary sheet (TIESS)	LCA primer	Practical sheet for structuring LCAs.	LCA-Oriented Studies
[38]	2017	Future food-production systems: VF & CEA	Overview	Introduces VF & CEA as responses to food demand, but energy-intensive.	Comparative Assessments
[39]	2025	Comparative LCA of HVAC for poultry houses	HVAC LCA	Lessons transferable to VF: HVAC strongly drives impacts.	Energy and Lighting Optimization
[40]	2018	Energy and environmental performance of vertical hydroponic farming (Stockholm)	VF LCA case	Energy use and substrate materials dominate impacts.	LCA-Oriented Studies
[41]	2024	LCA of protein production from wheatgrass in VF	Wheatgrass LCA	Hotspots in LEDs and HVAC, with optimization potential.	LCA-Oriented Studies
[42]	2022	Advances in vertical farming: Opportunities and challenges	Review	Overview of trends, automation, opportunities, and challenges.	Others

[43]	2024	Energy optimisation of plant factories and greenhouses under climates	Energy optimization	Compares PFs and greenhouses, showing climate-dependent energy efficiency.	Energy and Lighting Optimization

Table 1- Article summary

3.3 Thematic Categorization and Key Insights

The selected literature covers a wide spectrum of topics related to vertical farming, but four primary categories emerged from the analysis: Energy and Lighting Optimization, LCA-Oriented Studies, Comparative Assessments, and Broader Sustainability Frameworks. Each group captures a specific dimension of how vertical farming has been studied and provides unique insights for this thesis.

A substantial portion of the papers concentrated on energy and lighting optimization, reflecting the fact that artificial lighting and HVAC systems are the main drivers of environmental performance in vertical farms. Studies in this category illustrate different ways to reduce these burdens: [1] highlighted that thermal and humidity control dominate energy use, while [4] demonstrated that coupling vertical farms with wind power can lower both costs and emissions. Similar concerns were raised by [5], who showed how climate and lighting intensity strongly affect energy consumption, and [7], who pointed to technological innovation in LEDs and recovery systems as key to making vertical farming scalable. Other contributions include [8], which applied a machine learning approach to identify energy-saving factors, [16] and [17], which explored renewable integration and dynamic lighting strategies, and [19] and [20], which compared plant factories across technological options. The critical role of lighting was reinforced by [24], which described it as the main environmental burden of VF, while [25] and [35] investigated renewable solutions such as concentrating solar power and solar-hybrid storage systems. Transferable lessons for HVAC design were provided by [39], and [43] emphasized the influence of climate on the relative energy efficiency of plant factories and greenhouses. Collectively, these works confirm that energy management remains the most pressing issue for vertical farming, while also outlining possible strategies for improvement.

A second group of studies focused on LCA-oriented research, which provides the methodological foundation of this thesis. These contributions assess vertical farming through established environmental metrics such as global warming potential, cumulative energy demand, and water use, often applying professional LCA tools. For example, [13], [18], and [23] used SimaPro to analyse vertical farming systems, confirming that electricity consumption and system boundaries strongly influence results. Similarly, [29] employed OpenLCA for a modular cabinet farm, while [32] relied again on SimaPro for microgreen production. Other relevant case studies include [10], [40], and [41], with the latter specifically adopting GaBi, a software tool for LCA, to assess protein production from wheatgrass. Broader methodological contributions such as [22], [36], and [37] provided reference guidelines and frameworks for structuring LCA studies, and [28] synthesized the state of the art through a systematic review. Together, these works underline that methodological choices, such as the selected tool, system boundaries, and electricity mix, significantly affect outcomes, but consistently point to energy and lighting as the dominant hotspots.

The third category, comparative assessments, grouped works that explicitly benchmarked vertical farming against other agricultural systems or urban planning scenarios. For instance, [11] assessed the feasibility of vertical farms in the Arctic, while [12] analysed eco-efficient construction materials relevant to controlled-environment structures. Urban implications were captured in [14], [33], and [34], which examined the rise of vertical farming in cities and its role in urban planning. Direct comparisons between vertical farms, greenhouses, and alternative energy setups were explored by [19], [20], and [26], while [38] contextualized vertical farming and controlled-environment agriculture as energy-intensive but innovative alternatives to traditional agriculture. Collectively, these studies highlight both the strengths of vertical farming, particularly in water and land efficiency, and its persistent challenges linked to high energy demand.

Finally, broader sustainability frameworks emerged from a smaller set of studies that moved beyond environmental metrics to include social and economic aspects. For example, [2] assessed vertical farming as a socio-economic necessity in northern Iran, while [3] framed it as a potential contribution to global food security. [6] focused on the social benefits of vertical farms in cities, especially regarding food access and inclusion, while [9] proposed a multidimensional framework integrating environmental, social, and economic aspects. In a complementary way, [30] investigated CO_2 enrichment in controlled environments, discussing the tension between higher yields and increased energy requirements. These contributions broaden the discussion, showing that vertical farming cannot be evaluated solely in environmental terms, but must also be considered in relation to its social acceptance, economic feasibility, and role in food systems.

Across the reviewed literature, some common themes clearly emerge. Energy use remains the dominant issue, particularly for artificial lighting and climate control, while the electricity mix, whether based on renewable or fossil sources, proves decisive in shaping environmental outcomes. At the same time, important gaps persist. Many studies lack transparency in reporting data, especially regarding infrastructure requirements and long-term emissions, and only a limited number provide full cradle-to-grave assessments. Furthermore, integrated sustainability analyses that also consider economic and social dimensions remain scarce, and most of those available are based on small-scale or experimental case studies, which may not fully capture the conditions of commercial-scale vertical farming.

3.4 Relevance of the Thesis

Several of the analysed works provided valuable reference points for the approach taken in this thesis. For instance:

- [1] explored a vertical wheatgrass system, emphasizing the importance of optimizing both energy and protein yield, relevant to the multifunctionality of controlled systems (CEA).
- [3] conducted a full LCA from cradle-to-customer in the UK, offering a similar structure but different contextual assumptions.
- [23] presented a comprehensive literature review of vertical farming LCAs, helping to benchmark common practices and methodological challenges.
- [7] provided a critical view of the environmental cost of artificial lighting, reinforcing the importance of including long-term energy impacts, as done in this work.

4. Method and Frameworks

4.1 General introduction

The aim of this thesis is to contribute to the growing body of research on sustainable agriculture, by addressing the feasibility of deploying systems such Vertical Farming in regions where the environmental cost is lower. Indeed, the majority of the reported studies analyse the environmental impact of vertical farming systems regardless of the geographical constraints.

The main objective of this thesis is to evaluate whether vertical farming can be viably adopted in locations with cleaner or more favourable energy profiles, using a rigorous LCA approach. Specifically, the study compares the environmental performance of a vertical farming greenhouse structure when operated in Carignano (North of Italy), a region with a relatively balanced energy mix with low temperature during the winter and mild climate during summer, versus Algeria, where the energy mix is more carbon-intensive but with higher potential in terms of solar sustainable energy. By analysing the same structure across these different contexts, the thesis assesses how location-based energy factors influence the overall sustainability of vertical farming. Ultimately, this work offers practical insights for decision-makers and developers interested in strategically locating vertical farms where the environmental impact, especially related to energy use, can be minimized. It also contributes to broader discussions around sustainable urban food production in both Southern Europe and North Africa, supporting efforts toward more climate-conscious agricultural innovation.

LCA analysis was computed with SimaPro, one of the most widely used and accredited software for LCA. SimaPro has been created with the aim of enabling the practitioner to model product systems and calculate their environmental effects for their entire life cycle. Its point of technical superiority lies in the standardized methodologies and rich, good-quality databases, and thus also ensures results which are methodologically robust from the scientific standpoint and compatible with international formats, e.g., ISO 14040/44. Because of its modular structure and transparent modelling method. With SimaPro, it is possible to analyse complex systems with a considerable amount of details, with a consequent ability of being adapted for comparative analyses or for screening studies. For these reasons, it is a reliable tool for the evaluation of the environmental performance of products and processes.

4.2 SimaPro Overview: Methodologies, Libraries and Database

SimaPro includes a comprehensive set of methodological procedures for LCIA, developed in alignment with ISO 14040/44 standards. These methods are structured into four main stages: characterization, damage assessment, normalization, and weighting. In the first stage, emissions and resource uses are converted into impact category indicators using characterization factors (for example, Global Warming Potential expressed in kg CO_2-eq). Methane, for instance, receives a higher weighting than carbon dioxide due to its greater contribution to climate change. The second stage, damage assessment, aggregates midpoint results into broader areas of protection, such as human health, ecosystem quality, and resource availability. Normalization then enables comparisons across categories by relating results to a reference baseline, such as the average annual environmental impact per capita for a defined region. Finally, weighting applies value-based preferences to derive a single score indicator, facilitating interpretation, communication, and decision-making.

SimaPro includes numerous impact assessment methods developed by international organisations and research groups. Some of the best-known are CML-IA *(Center of Environmental Science Leiden University*) (midpoint-based, which translates to focus on environmental mechanisms, European standards), ILCD 2011 Midpoint+ (developed under the European Joint Research Centre), ReCiPe 2016 (generating midpoint and endpoint indicators), and lastly, EF method 3.0, in line with the EU Product Environmental Footprint methodology [44,45].
Others focus on application fields. For instance, the EDIP 2003 (Danish method with geographical differentiation) which focus on product eco-design and industrial optimization, or Impact 2002+, bridging scientific detail with decision usability, and EPS 2015d/x, damage-oriented, based on the monetization.
Regionalised methods are represented, for North America and for building products, with BEES (Building for Environmental and Economic Sustainability) and with TRACI 2.1; while, for the single issue methods, represent specific areas of impact such as IPCC 2013 for climate change and Cumulative Energy Demand, or AWARE, for water scarcity. These method differences allow the user choices for methodological options compatible with the scope and purpose of their study: detailed environmental footprint or simplified screening level analysis [44,45,46].

As part of its diversification of methods, SimaPro also makes use of extensive libraries of life cycle inventories, which form the quantitative basis for modelling product systems. For instance, Ecoinvent v3 is a library containing over 15,000 datasets covering sectors such as agriculture, transport, chemicals, metals, construction materials, packaging, and waste treatment and it is the most widely used database in LCA studies. This library differs from its competitors with its provision of different system models, such as allocation at point of substitution (APOS) [which combines the impacts of both the initial production and the treatment of the by-product and then allocates these combined impacts to both the main product and the recycled material], cut-off and consequential, each with differing modelling philosophies. Users also have the option of unit process datasets with detailed transparency and potential for uncertainty analysis, and system process datasets, which aggregate results for computational efficiency [47,48].

In addition to Ecoinvent, SimaPro integrates specialized databases tailored to sector-specific needs. The Agri-footprint database supports agricultural and bio-based LCAs, covering crops, animal products, feed, and fertilizers. USLCI, developed by NREL [44,48], provides datasets specific to U.S. production systems, while Industry Data 2.0 includes sector-specific inventories from PlasticsEurope, WorldSteel, and ERASM. These industry datasets are typically aggregated but highly relevant for downstream applications where sector-specific accuracy is critical. Furthermore, input–output databases such as the EU & DK I/O database allow practitioners to estimate impacts at the level of economic sectors, making them particularly valuable for screening studies or filling data gaps in supply chains.

On the online platform, the functionality of these libraries is extended through Flow, Collect, and Explore modules. Flow is used for modelling process networks, collect enables structured data gathering via surveys and explore allows scenario analysis

and collaborative comparison across stakeholders. This modular architecture not only facilitates transparency and consistency but also supports iterative data refinement and stakeholder engagement throughout the LCA process [44,49].
To carry out the LCA of the vertical farming system, SimaPro has been used as main tool to organize the life cycle data and calculate the environmental impacts of the greenhouse structure. I worked within a dedicated project in the software, titled “Life Cycle Assessment Basil_Boretto”, firstly focusing on the impact on the construction of the greenhouse. Afterwards, the environmental costs of basil production in the greenhouse were computed, comparing two different geographical locations: Europe (Italy in particular) and North Africa (Algeria). The production part was developed under the product system “Serra_TOT_Prod_Pre_prod” within the Assembly\Serra_TOT category. For the impact assessment, I selected the CML-IA baseline V3.10 / EU25 method. This method is well-established and follows a midpoint approach, which. I chose it because it offers transparency and detailed results, which are ideal when trying to identify which materials or components are responsible for the most significant impacts. The indicator I focused on was Global Warming Potential (GWP100a), normalized over a 100-year time horizon, in cumulated indicator mode. This gives a clear picture of how much each component contributes to greenhouse gas emissions over the long term.

One specific choice made was to include long-term emissions in the calculations. It was believed that to fully understand the environmental footprint of a structure like this, it’s important not to leave out emissions that may occur decades after the initial construction. These long-term impacts are often overlooked, but they can play a meaningful role, especially in materials that degrade or continue emitting greenhouse gases over time.

In defining the model, particular attention was given to the selection of materials, assemblies, and processes in SimaPro. This stage is fundamental to ensure that the modelled system accurately represents the real-life configuration of the greenhouse and its production processes. Each assembly, such as the structural frame, panels, or energy systems, was associated with specific datasets from the ecoinvent v3 database, chosen for their technological relevance and geographical compatibility with the study region (i.e. World). The datasets were carefully screened to reflect production conditions, resource inputs, and emission profiles for each material.
By structuring the greenhouse as an assembly composed of interconnected processes, SimaPro enables a transparent mapping of material flows from raw material extraction to end-of-life treatment. This systematic organization allows the tracing of environmental burdens across the full life cycle, making it possible to identify the stages with the highest contribution to overall impacts. The careful alignment between modelled assemblies and actual design specifications reduces methodological uncertainty and strengthens the interpretability of the results.

4.3 Methodology applied

The analysis was performed using SimaPro 9.6, with the CML-IA baseline method (V3.10/EU25) and the Cumulative Energy Demand (CED) approach as the main methodological pillars. This chapter will not only present the numerical outcomes but contextualizes them within the broader debates on vertical farming sustainability, with the addition of touch point on the efficiency of the machine used for heating the greenhouses.

The current analysis expands on a prior study conducted at the Polytechnic of Turin that found that greenhouse gas emissions from VF were substantially higher than those from a conventional greenhouse. Therefore, the main objective of this thesis is to find out if moving such a system to a different location, Algeri (Algeria), which has a warmer climate and higher average temperatures, could have different environmental effects than running the same structure in northern Italy. The research aims to demonstrate how location-specific factors, both in terms of climatic constraints and in terms of the available energy mix, impact the overall environmental performance of vertical Because the software libraries frequently rely on global average datasets, it was decided to take extra care in the alignment of the modelled materials with realistic construction inputs. This ensured that the structure used as a reference in Algeria accurately mirrored the Italian case. The analysis focuses on the environmental impacts associated with the greenhouse infrastructure's production phase.

The environmental costs associated with plant development had previously been thoroughly examined in the earlier studies, but the effects of transportation would need a different, specialized, evaluation that is outside the view of this work.

In order to be in line with ISO 14040/44 standards, the system boundaries are defined as cradle-to-gate for the infrastructure, which means that it starts from raw material extraction and processing, up to the assembly of the greenhouse structure. End-of-life processes, maintenance activities and downstream operations were excluded to keep the scope consistent and focused.

The functional unit adopted is the plants produced in a year by one greenhouse infrastructure produced by Agricooltur, (*Figure 11*) an Italian firm from the north of Italy.

The greenhouse total dimension is approximately 496 square meters (sixty-two meters in length, eight in width and four in height) and structurally it uses a thermally insulated shell ("Aeroshell") and is fitted with advanced environmental-control systems (air-conditioning, de-humidification, CO_2 and climate regulation) to maintain optimal growth conditions year-round. The entire system is designed for Industry 4.0 integration, with sensor arrays, data-logging, and automation for irrigation, fertigation, lighting and harvesting and inside, the system accommodates two stacked cultivation levels (hence "800+800"), each configured for high-density growth, leading to a production capacity of roughly 24,000 plants per cycle.

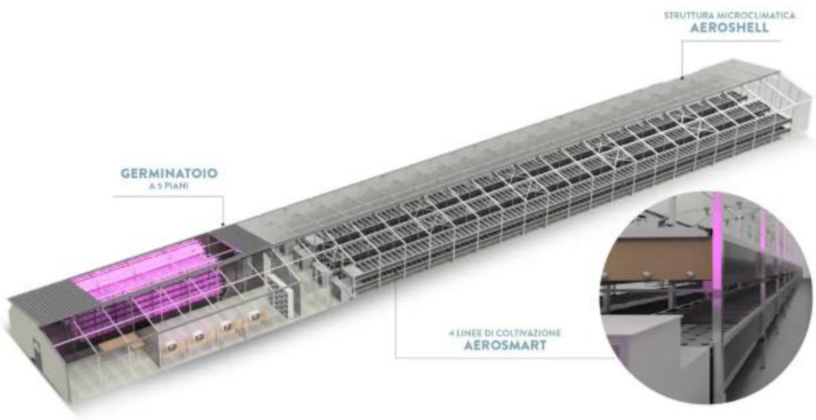

Figure 11 – Agricooltur Plant 800+800

To make the analysis more meaningful and easier to interpret, I divided the Bill of Materials (BOM) into clear material groups. Initially, the list of components was long and included items like aluminium channels, insulating panels, polycarbonate sheets, screws and bolts, and stainless steel and polycarbonate drainage elements. To make sense of all this, I organized them into broader categories, such as flashings in different materials, polycarbonate panels (roof and side), steel brackets, structural frames, and fastening elements. Each group included specific measurements and material types, which helped me compare their relative impacts more directly.

This breakdown was incredibly helpful in understanding where the environmental "hotspots" were. By grouping the materials this way, I could visualize and compare their contributions more clearly, which also made it easier to think about possible design optimizations or material substitutions. In the context of vertical farming, where sustainability is a central goal, this kind of clarity is essential. It allows decisions to be based on real data, rather than assumptions, and supports more informed conversations with designers, suppliers, and other stakeholders.

In order to insert the right data to enter I started from the dimensions (length, width and height) and the quantity of each material, so to have the total volume covered by each object. This was necessary every time the weight of a component was not provided, but the dimensions were. To this aim, tools that were not parallelepiped or spherical in shape, but were divided into smaller pieces and then the total size was calculated (e.g. brackets, screws and bolts).

After that, the volume generated was multiplied by the density of the considered material, obtaining the weight of each component based on their composition and divided, for the uploading on SimPro, in the subsequent categories:

- Canalina Pavimento *(Floor channel)*
- Faldali tamponamento TOT
    - Faldali in acciaio inox *(Stainless steel flaps)*
    - Faldali in policarbonato *(Polycarbonate flaps)*
    - Faldali tetto coibentanti *(Roof polycarbonate panels)*
- Pannello scheletro TOT
    - Pannelli coibentatnti *(Insulated panels)*
        - Pannelli coibentanti frontali
        - Pannelli coibentanti laterali
        - Pannelli coibentanti parte superiore
    - Pannelli in policarbonato *(Polycarbonate panels)*
        - Pannelli policarbonato retro
        - Pannelli policarbonato laterali
        - Pannelli policarbonato tetto
- Porta di accesso *(Access door)*
- Presssori di tamponamento in alluminio *(Aluminium infill spacers)*
- Staffe in acciaio *(Steel brackets)*
- Travi in alluminio quadrate *(Square aluminium beams)*
- Rondelle, dadi e viti *(Washers, nuts and screws)*

The materials used for the construction of the greenhouse are a total of four (Steel, Aluminium, Polycarbonate and Polyester) and each of them had its own Material/Assemblies and Processes, as show in the *Table 2*

Material	**Material / Assemblies**	**Processes**
Aluminium	Aluminium, primary, ingot (CA)| aluminium production, primary, ingot | Cut-off, U	Metal working, average for aluminium product manufacturing (GLO]
Steel	Steel, chromium steel 18/8 (GLO| market for steel, chromium steel 18/8 | Cut-off, U	Metal working machine, unspecified (RER)
Polycarbonate	Polyester-complexed starch biopolymer (GLO) market for polyester-complexed starch	Extrusion of plastic sheets and thermoforming, inline (FR}
Polyester	Polycarbonate {RoW| market for polycarbonate | Cut-off, U	Thermoforming, with calendering (RER)| thermoforming

Table 2 – Assemblies and Processes for each material

To quantify the energy requirements associated with basil cultivation in a controlled greenhouse environment, the analysis considered both heating and artificial lighting as the primary contributors to overall energy demand. The methodological framework followed a process-based approach integrating climatic data, technical system specifications and operational assumptions, provided by the technical basics of the Agricooltur employees, of the cultivation cycle.

The heating demand was determined from the nominal characteristics of the installed heating system and combined with meteorological datasets for the site of Carignano (Turin). These data allowed for the identification of average monthly temperature profiles, as can be seen by *Table 3,* and the subsequent estimation of thermal energy needs as a function of outdoor temperature and the machine's absorbed power. The operational time of the heating unit was defined based on the cultivation cycle, assumed to last six weeks, with the system functioning approximately 12 hours per day, seven days per week. The total operational hours were then multiplied by the sum of the power absorbed (derived from the temperature–power correlation) and the base power supply of the heating machine. This value was scaled to the total number of heating units installed within the greenhouse, following the ratio of one machine per 400 cultivation plates.

Artificial lighting requirements were evaluated independently, assuming the use of LED lamps operating 14 hours per day across the same six-week cultivation period. The corresponding energy consumption was estimated for the full set of 1,600 cultivation plates and later integrated with the heating demand to determine the total energy input per production cycle.

To extrapolate the annual energy demand, the per-cycle energy consumption was multiplied by the number of production cycles per year, assuming eight consecutive six-week cycles.

		Min [°C]	Max [°C]	Median [°C]	Average Temperature per Cycle [°C]	Consumo per ciclo
gen-24	Week 1	-1,5	6	0,8	1,57	42134
	Week 2			0,8		
	Week 3			0,8		
	Week 4			0,8		
feb-24	Week 5	-1,1	7,8	3,1		
	Week 6			3,1		
	Week 7			3,1	5,90	42269
	Week 8			3,1		
mar-24	Week 9	2,2	12,4	7,3		
	Week 10			7,3		
	Week 11			7,3		
	Week 12			7,3		
apr-24	Week 13	6,2	15,7	11,1	12,57	42538
	Week 14			11,1		
	Week 15			11,1		
	Week 16			11,1		
mag-24	Week 17	10,4	19,9	15,5		
	Week 18			15,5		
	Week 19			15,5	18,57	48182
	Week 20			15,5		
giu-24	Week 21	14,8	24,7	20,1		
	Week 22			20,1		
	Week 23			20,1		
	Week 24			20,1		
lug-24	Week 25	17	27,3	22,5	22,33	51005
	Week 26			22,5		
	Week 27			22,5		
	Week 28			22,5		
ago-24	Week 29	16,9	26,7	22		
	Week 30			22		
	Week 31			22	19,13	45360
	Week 32			22		
set-24	Week 33	13,3	22	17,7		
	Week 34			17,7		
	Week 35			17,7		
	Week 36			17,7		
ott-24	Week 37	9,2	16,2	12,7	10,77	42470
	Week 38			12,7		
	Week 39			12,7		
	Week 40			12,7		
nov-24	Week 41	3,7	10,4	6,9		
	Week 42			6,9		

	Week 43			***6,9***	***3,97***	***42202***
	Week 44			***6,9***		
dic-24	*Week 45*	***-0,6***	***6,4***	***2,5***		
	Week 46			***2,5***		
	Week 47			***2,5***		
	Week 48			***2,5***		

Table 3 – Calculation of average temperature and subsequent energy consumption

5. Results of the Case Study

The case study results are presented in this chapter, with the aim of providing a detailed environmental evaluation of the greenhouse structure under two different geographical contexts: Carignano (Italy), where, during the winter, the medium temperature is between 0.8° C and 3.6 °C, and Algeria, where the heat arrives at a medium of 13.7°C.

5.1 Analysis results

The first analysis conducted was on the greenhouse structure, which is composed of a diverse set of materials, including steel, aluminium, polycarbonate, and fastening elements such as screws and bolts and all the data were gathered form the Bill of Material of a Agricooltur’s greenhouse (*Figure 11*), which was, as mention before, an eight hundred plus eight hundred platform, with plant growth developed on two floor, for a total of one thousand six hundred plates.

During this analysis, the division used was the one presented previously, and, through a Characterization, it was possible to assess which where the contribution of the different part involved on metrics such as Global warming (GWP100a), ODP, Fresh water aquatic ecotox., Marine aquatic ecotoxicity and Acidification.

A specific focus was developed in the GWP, developing a Normalization as GWP100a, as in *Figure 12* (and in *Table 4*), where it was possible to notice that steel is the primary contributor to the greenhouse gas's potential to cause global warming, mostly due to the high mass percentage (>4,400 kg), but also because of the energy-intensive production methods (smelting, alloying, and refining) and extensive use in structural components. Although stainless steel has a high embodied carbon footprint, its usage is technically justified since it guarantees corrosion resistance, durability, and load-bearing capacity, all of which are critical for the structure's long-term stability.

It is important to mention that the results delivered by SimaPro take into account also the impact of materials different from the ones uploaded, which are used indirectly (for instance the materials utilised in the Casting of the steel or the Thermoforming).

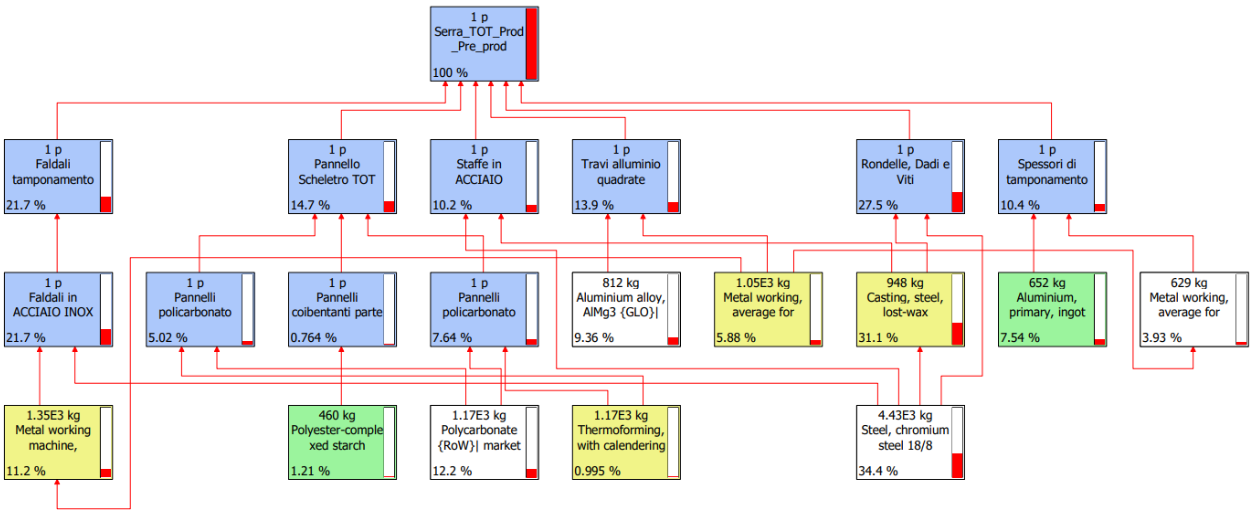

Figure 12 – Material, and components, percentage contribution on GWP

Contributor	**Percentage**
Polycarbonate	*12,20%*
Steel, chromium steel 18/8	*34,40%*

Aluminium alloy, AlMg3	*9,36%*
Aluminium, primary, ingot	*7,54%*
Polyester-complexed starch	*1,21%*
Metal working (aluminium)	*5,88%*
Metal working (aluminium)	*3,93%*
Thermoforming with calendering	*1,00%*
Casting, steel, lost-wax	*31,10%*
Metal working machine	*11,20%*
Thermoforming with calendering	*1,00%*
Casting, steel, lost-wax	*31,10%*
Metal working machine	*11,20%*
Pannelli coibentanti parte	*0,76%*
Pannelli policarbonato	*7,64%*
Pannelli policarbonato	*5,02%*
Travi alluminio quadrate	*13,90%*
Faldali in ACCIAIO INOX	*21,70%*
Staffe in ACCIAIO	*10,20%*
Rondelle, Dadi e Viti	*27,50%*
Spessori di tamponamento	*10,40%*
Faldali tamponamento	*21,70%*
Pannello Scheletro TOT	*14,70%*
Serra_TOT_Prod_Pre_prod	*100,00%*

Table 4 – Results of the contribution on GWP

After the first analysis it was crucial to access the impact of the electricity on the greenhouse, starting from the heating machine used to heat and cool the temperature, up to the lighting LED system, which functioning is important in both the lighting and heating provision.

To understand the impact of the heating machine it has been used the technical data sheet provided by the greenhouse builder (*Table 5*) as a starting point and, after the detection of the average data of each month of 2024 in Carignano (TO) it was possible to calculate the amount of energy used for heating the greenhouse. It has been assumed a utilization of the machine of circa twelve hours per day, for seven days and multiplied for the life cycle of the basil, which is circa six weeks.

Applying this methodology to the specific basil production case, the total operational hours for each heating unit were calculated based on a six-week cultivation cycle with 12 hours of daily operation. The resulting total energy consumption reflected both the absorbed and base power contributions, scaled to four heating units corresponding to the full greenhouse setup.

When combined with the lighting energy demand, derived from continuous LED operation of 14 hours per day for six weeks, the total energy input per cultivation cycle was determined. This comprehensive value provided the foundation for estimating the annual energy demand, obtained by multiplying the per-cycle requirement by the eight annual production cycles [*Table 6*].

MEVO AIR 118T			
TECHNICAL CHARACTERISTICS			
Heating	Termic Power (kW)	Absorbed Power (kW)	COP* *(Coefficient of Performance)*
Outdoor Temp. 12°C - Indoor Temp. 20°C	21,2	4,8	4,42
Outdoor Temp. 7°C Um. 90%U.R. Indoor Temp. 20°C Um. 60% U.R.	19	4,7	4,04
Outdoor Temp. 2°C - Indoor Temp. 20°C	17,1	4,6	3,72
Outdoor Temp. -7°C - Indoor Temp. 20°C	14,1	4,3	3,28
Outdoor Temp. -15°C - Indoor Temp. 20°C	11,1	4,1	2,71
Cooling	Refrigerant Power (kW)	Absorbed Power (kW)	EER* *Energy Efficiency Ratio*
Outdoor Temp. 35°C Um. 45%U.R. Indoor Temp. 27°C Um. 50% U.R.	18,1	4,7	3,85
Supply	V/np/Hz	Max Absorbed Power (KW)	Maximum Electric Current (A)
	400/3ph+N+PE	5,8	12
External Air temperature Limit	Min ~ Max °C	-20°C ~ 35°C	
Internal Air temperature Limit	Min ~ Max °C	10°C ~ 40°C	
Compressor	n.	Absorbed Power kW	Refrigerant
Inverter	1	4,3	R290
Source Fan (outdoor)	n.	Nominal air flow rate m3/h	
Inverter	2	7000	
User-side Fan (indoor)	n.	Nominal air flow rate (m3/h)	Useful Prevalence (Pa)
Inverter	4	2500	150
Dimension	Width (mm)	Height (mm)	Depth (mm)
	1816	1575	760

Table 5 – Technical data sheet on Heating machine

** COP and EER are indicator of performance and are calculated as subsequent:*

$$COP = \frac{Heating\ output}{Electrical\ input} \quad and \quad EER = \frac{Cooling\ capacity}{Electrical\ input}$$

Machine usage	12	*Hours/day*
Life Cycle	6	*Weeks*
Days in a week	7	*Day*
Lights usage	14	*Hours/day*
Consumption LED	22,5	*Watt per plates*
Plant per plate	15	
N° plates	1600	
Tot plants per cycle	24000	
N° heating machines	4	

Table 6 – Overview of the data used for the energy calculation

The calculation of the operational energy demand resulted in a total of approximately 356,160 MWh per year for the eight production cycles considered, which correspond to one year of basil cultivation in Italy under the assumed scheduling (six-week life cycles, repeated eight times annually). When normalized by the total number of plants cultivated (24,000 units), this translates to an average of 1,855 kWh per plant per life cycle. This value aligns closely with findings reported in the literature, where specific energy consumption for similar controlled-environment systems is typically positioned between 21,8 kWh/kg [29] and 24,58 kWh/kg [17]. Considering the average fresh weight of a basil plant at harvest, estimated between 70 and 80 g, this range corresponds to 1,526 – 1,966 kWh per plant, which validates the coherence and reliability of the results obtained in this study.

Following the calculation, the derived energy consumption data were implemented into the SimaPro software under the "Life Cycle" operational phase. Within the model, electricity use was introduced as a proxy for the intensive resource demand associated with artificial lighting and climate control, which, as stated in the literature, represent the primary energy burdens in vertical farming. The subsequent

LCIA confirmed a strong dominance of electricity use in the greenhouse's overall environmental profile, with results revealing a clear hierarchy of contributions to the GWP. As illustrated in *Figure 13*, lighting and heating processes accounted for the largest share of emissions, further emphasizing the centrality of operational energy efficiency in shaping the sustainability performance of the system.

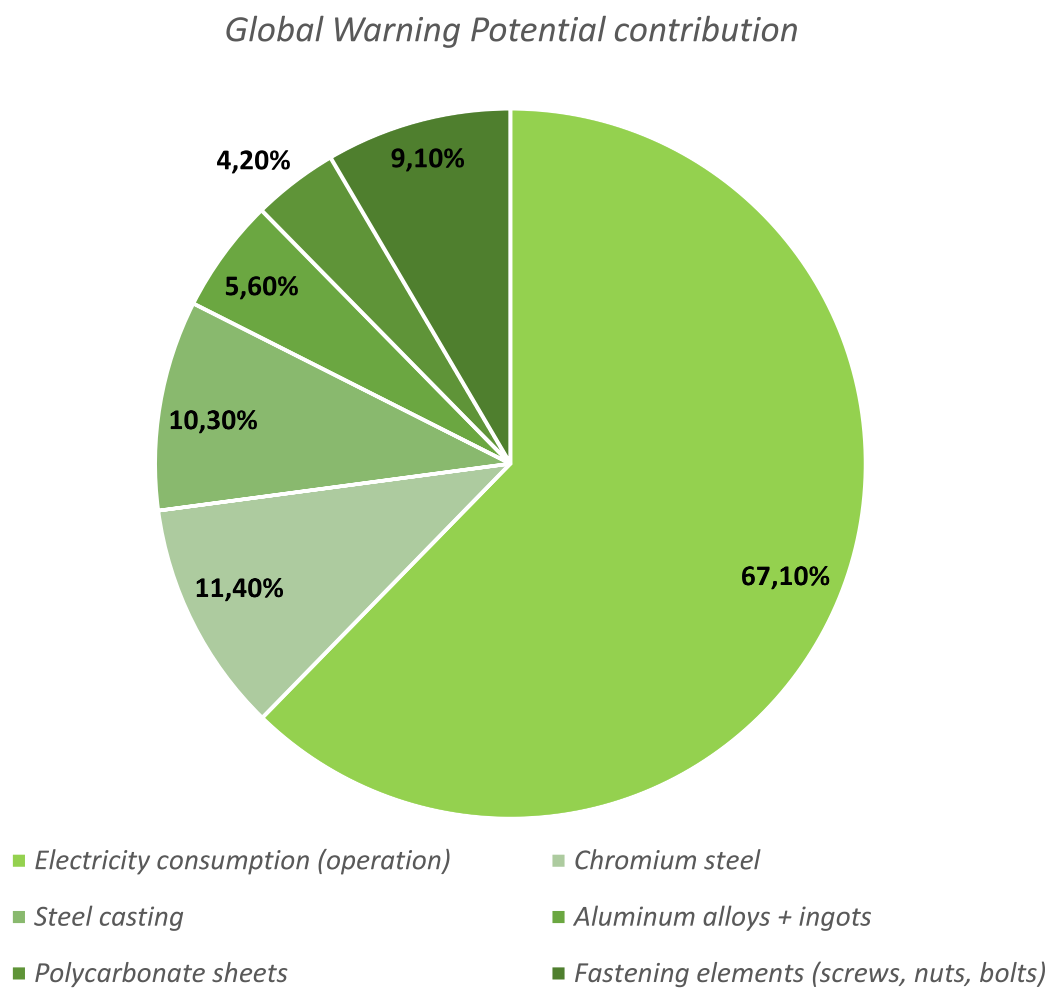

Figure 13 – Contribution of Materials and Electricity to Total GWP (Italy)

5.2 LCA Metrics evaluation

The first evaluation that is done is about the GWP, where the greenhouse gas emissions were assessed using the CML-IA baseline method (V3.10) under both characterization and normalization approaches.

The normalization step allowed also to compare Italy and Algeria on a common scale. In the *Table 7*, is possible to see how the GWP in Algeria is nearly double that of Italy reflecting the different carbon intensities of the two national grids.

Impact category	*Life Cycle Algeria*	*Life Cycle Italy*
Abiotic depletion	2,42E-08	2,34E-08
Abiotic depletion (fossil fuels)	1,64E-07	8,42E-08
Global warming (GWP100a)	6,71E-08	3,94E-08
Ozone layer depletion (ODP)	6,74E-11	3,35E-11
Human toxicity	1,86E-07	1,78E-07
Fresh water aquatic ecotox.	5,44E-07	5,45E-07
Marine aquatic ecotoxicity	4,51E-06	4,60E-06
Terrestrial ecotoxicity	4,27E-07	4,21E-07
Photochemical oxidation	5,63E-09	5,59E-09
Acidification	2,02E-08	2,56E-08
Eutrophication	1,45E-08	1,76E-08

Table 7 – CML-IA baseline comparison - Normalization

This combination of methods shows both the absolute contribution of each process (characterization) and the relative severity of the impact compared to a reference situation (normalization).

Energy Consumption

Energy demand was evaluated with the Cumulative Energy Demand (CED) method V1.12, using both characterization and single score results.

As it possible to see, in the characterization outputs, Algeria is highly dependent on fossil fuels (more than 5,68 million MJ per unit) while Italy uses less than half (2,9 million MJ). Accordingly, Italy shows higher reliance on nuclear and renewable sources such as wind, solar and hydro; this is partly made by the internal production of energy and what comes from other countries (i.e. nuclear energy), as can be seen in *Figure 14* or in *Figure 15* through a direct comparison of each typology of energy between the Italian and the Algerinian greenhouse.

The single score representation aggregates these categories into a total energy footprint: 5,99 TJ in Algeria versus 4,22 TJ in Italy.

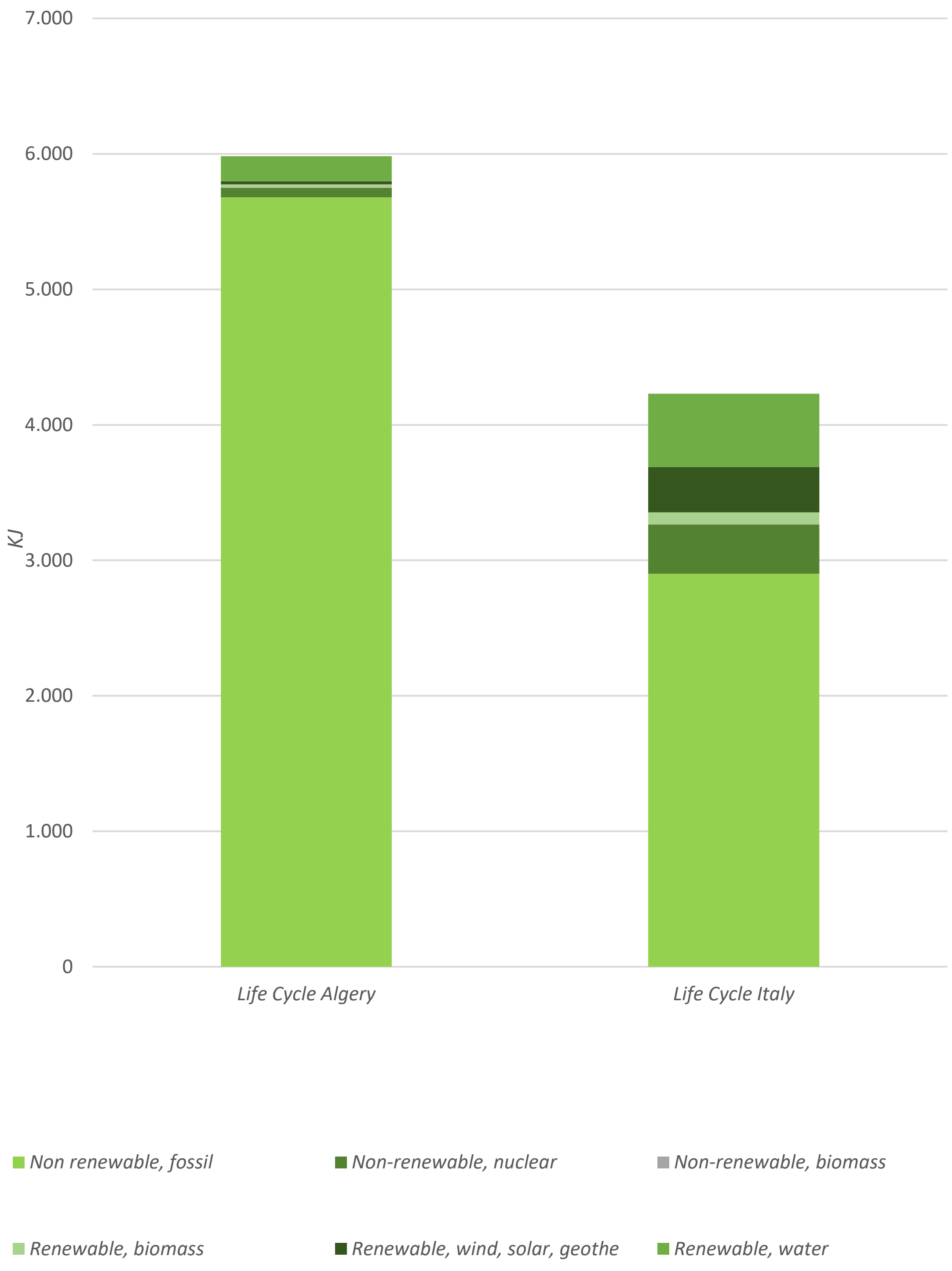

Figure 14 – Cumulative Energy Demand Algeria versus Italy

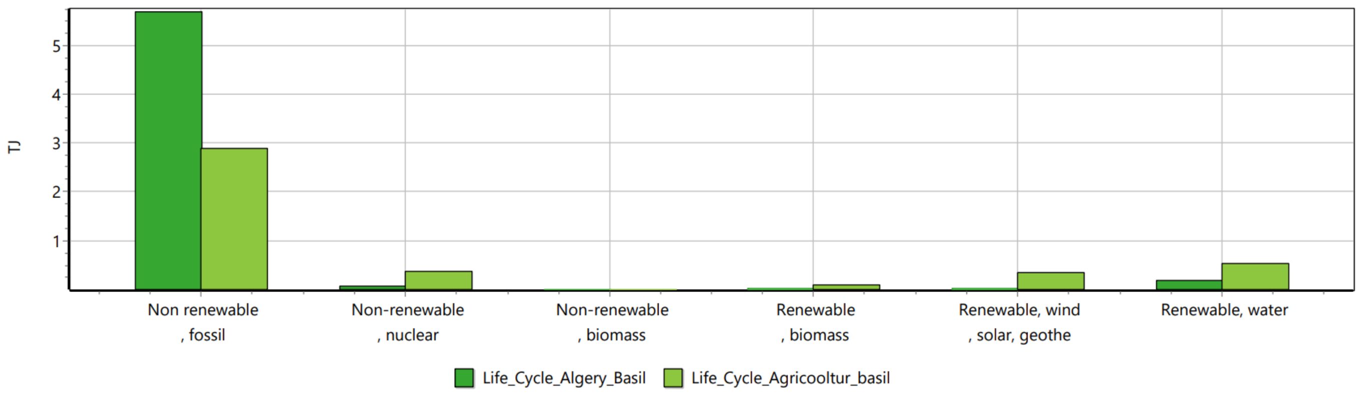

Figure 15 – CED weighting between Algeria and Italy

Water Usage

Although direct irrigation water use in vertical farming is almost negligible, the normalization results reveal a significant indirect water footprint once electricity generation is considered. In fact, in Italy the contribution of hydroelectricity leads to a renewable water use equivalent of 0,539 TJ, compared to only 0,186 TJ in Algeria. This corresponds to 12,72% of the total energy mix in Italy, versus just 3,11% in Algeria (*Table 8*). Such figures do not imply higher irrigation requirements or local water scarcity; rather, they highlight the dependence of the Italian electricity grid on hydropower, a water-intensive process. This underlines the importance of including indirect water use in LCA studies of controlled environment agriculture, since limiting the analysis to direct irrigation would result in a clear underestimation of the actual burden.

Impact category	*Life Cycle Algery [MJ]*	*Percentage*	*Life Cycle Italy [MJ]*	*Percentage*
Non renewable, fossil	5680000	94,92%	2900000	68,57%
Non-renewable, nuclear	71100	1,19%	364000	8,61%
Non-renewable, biomass	172	0,00%	171	0,00%
Renewable, biomass	24700	0,41%	89900	2,13%
Renewable, wind, solar, geothermal	22000	0,37%	336000	7,95%
Renewable, water	186000	3,11%	539000	12,75%

Table 8 – Comparison through Characterization

Equally relevant is the impact of Marine Aquatic Ecotoxicity Potential (MEP), which accounts for more than three quarters of the total normalized score (*Table 9*). This elevated contribution is explained not only by the water dependency of electricity generation but also by the material profile of the infrastructure itself. In particular, the life cycles of steel and aluminium are associated with significant ecotoxic emissions: during the mining, refining, and smelting stages, waste streams often contain heavy metals such as arsenic, cadmium, and lead. When these substances are released into wastewater or tailings, they accumulate in marine ecosystems, generating long-lasting toxic effects on aquatic organisms.

Impact category	*Life Cycle Algery*	*Percentage*	*Life Cycle Italy*	*Percentage*
Abiotic depletion	2,42E-08	0,41%	2,34E-08	0,39%
Abiotic depletion (fossil fuels)	1,64E-07	2,75%	8,42E-08	1,42%
Global warming (GWP100a)	6,71E-08	1,13%	3,94E-08	0,66%
Ozone layer depletion (ODP)	6,74E-11	0,00%	3,35E-11	0,00%
Human toxicity	1,86E-07	3,12%	1,78E-07	3,00%
Fresh water aquatic ecotox.	5,44E-07	9,12%	5,45E-07	9,18%
Marine aquatic ecotoxicity	4,51E-06	75,64%	4,60E-06	77,44%
Terrestrial ecotoxicity	4,27E-07	7,16%	4,21E-07	7,09%
Photochemical oxidation	5,63E-09	0,09%	5,59E-09	0,09%
Acidification	2,02E-08	0,34%	2,56E-08	0,43%
Eutrophication	1,45E-08	0,24%	1,76E-08	0,30%

Table 9 – CML-IA baseline comparison – Normalization - Percentage

Land Usage

Land occupation is captured indirectly through the normalization of abiotic depletion categories. Here, vertical farming has very low direct land use, but the upstream extraction of minerals (steel, aluminium, polycarbonate) introduces indirect land burdens. However, the method used has not provide direct hectares, but it has expressed the relative contribution compared to a regional reference, highlighting again that most land impacts come from material supply chains rather than cultivation.

Ozone Depletion Potential (ODP)

The normalization analysis, present in *Table 5,* indicates that ODP is systematically higher in Algeria (6,74E-11) than in Italy (3, 35E-11). These results are driven primarily from background energy processes in the grid mix and, although the absolute values are small, as is possible to see from the percentage in *Table 7*, the procedure shows how even minor emissions become relevant when compared to reference world averages.

Acidification Potential

Acidification was also calculated with the CML-IA normalization method and, interestingly, Italy presents higher normalized values (2,56E-8) than Algeria (2,02E-8). This suggests that Italy's cleaner electricity mix still involves processes emitting SO_2 and NOx, possibly linked to biomass and industrial combustion. The normalization results are key here, as they reveal trade-offs that characterization alone would not highlight.

6. Conclusion

The comparative LCA demonstrated that electricity consumption represents the predominant source of environmental impact in vertical farming systems for both Italy and Algeria. However, the magnitude of this contribution differs substantially between the two contexts, primarily due to the composition of national energy mixes. Algeria, whose electricity generation relies heavily on fossil fuels, showed overall higher environmental burdens, while Italy benefited from a cleaner mix that includes hydroelectric and nuclear power. This finding confirms the strong dependency of controlled-environment agriculture on local energy systems, highlighting that the sustainability of vertical farming is intrinsically contextual rather than universal.

In both countries, the operational phase overwhelmingly dominated total impacts. In Italy, electricity use accounted for approximately 67% of the total GWP, whereas in Algeria it reached almost 81%, as shown in *Figure 16*. Always in Algeria, the contribution of construction materials, particularly steel and aluminium, remained significant (10–11%), underlining that embodied emissions from infrastructure cannot be neglected. The notable 9.1% contribution of fastening elements, despite their minimal mass, further emphasizes the disproportionate effect of highly energy-intensive manufacturing processes. Collectively, these results confirm that vertical farming's environmental profile is shaped by both energy consumption during operation and the material intensity of its physical structure.

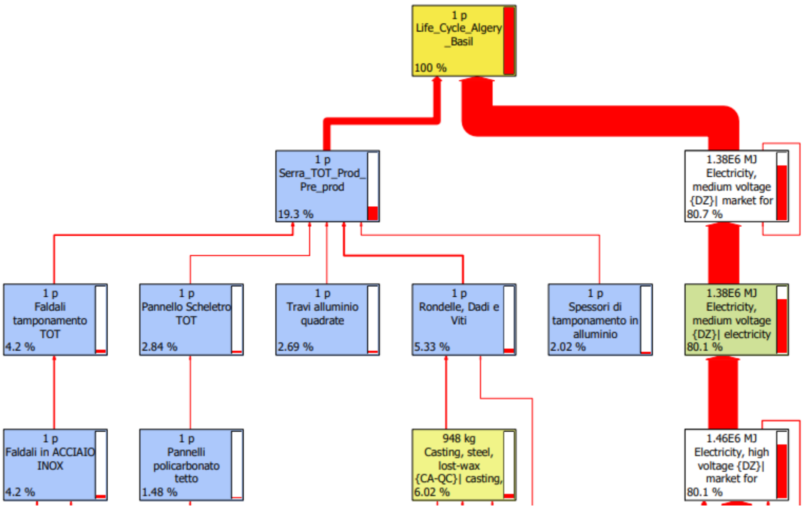

Figure 16 – CML-IA baseline Characterization, Global warming for Algeria

Electricity consumption was also the dominant driver in cumulative energy demand and across most other impact categories. Italy's lower results are largely attributable to its lower fossil energy dependence, while Algeria's grid, where more than 90% of energy still derives from non-renewable sources, exacerbates impacts in almost every category. Additionally, the performance of HVAC systems was found to be crucial. Higher coefficient of performance (COP) and energy efficiency ratio (EER) values in Italy, supported by better maintenance and advanced technologies, significantly reduced electricity needs for thermal comfort. In Algeria, conversely, older and less efficient systems, with COP values closer to three, increased energy consumption even under less extreme temperature differences. This efficiency gap explains why Algerian facilities exhibit higher energy demand despite operating in milder climates.

Beyond global warming, toxicity-related categories such as marine aquatic ecotoxicity also revealed substantial contributions, mainly linked to the extraction and processing of metals like steel and aluminium. These life cycle stages release toxic substances, including arsenic, cadmium, and lead, which strongly influence ecotoxicity and acidification indicators. Similarly, indirect water consumption associated with hydropower in Italy contributes to freshwater depletion, demonstrating how vertical farming remains entangled with energy and material supply chains that extend beyond its immediate boundaries.

Limitations

While the results provide a coherent picture of environmental performance, several limitations must be acknowledged.

First, the cultivation and transportation phases were excluded from the present system boundaries, which limits the completeness of the life cycle perspective. Moreover, many LCA studies on vertical farming, including this one, depend on small-scale, company-provided, or modelled datasets, which may not fully capture the operational dynamics of large-scale commercial facilities. Larger installations, typically characterized by automation, continuous production, and more complex logistics, could exhibit different energy profiles and material efficiencies.

Another source of uncertainty arises from the reliance on average national electricity mixes, which are subject to temporal and geographical variation. The simplified treatment of HVAC system performance, where COP and EER were not dynamically modelled, introduces further uncertainty. Lastly, the use of structural-based functional units (per greenhouse rather than per kilogram of product) restricts direct comparison with literature benchmarks.

Future Perspectives

Despite these constraints, and using them as starting point, the analysis offers several promising directions for future work.

A first step involves extending the assessment to include the cultivation and post-harvest stages, which would connect the environmental impacts of infrastructure and energy use with actual crop productivity. Integrating energy simulation tools such as TRNSYS or EnergyPlus with LCA models would allow dynamic representation of HVAC performance under varying climatic and operational conditions.

Future studies should also evaluate the potential of renewable-powered vertical farming, particularly solar-based systems in Algeria, where high solar irradiance could offset the country's fossil dependency.

At the same time, broader sustainability dimensions, including economic feasibility and social perception, should be incorporated. Assessing the public image and acceptance of vertical farming among consumers would help bridge the gap between environmental optimization and real-world adoption. Furthermore, scenario analyses involving circular material design, recycling of metals, and hybrid renewable integration (e.g., geothermal–solar systems) could reveal pathways to minimize carbon intensity and operational costs simultaneously.

Finally, reframing the functional unit toward product-based metrics, such as environmental impact per kilogram of basil or lettuce, would enhance comparability with existing studies and provide more policy-relevant insights.

In summary, this work demonstrates that the environmental promise of vertical farming is highly context-dependent, governed by energy origin, technological efficiency, and material choices. Italy emerges as relatively more sustainable than Algeria, owing to its cleaner energy mix and higher HVAC performance, yet both contexts expose the structural vulnerabilities of vertical farming: its dependence on energy-intensive operations and globally sourced materials.

To align with the objectives of the energy transition and circular economy, future systems must integrate renewable energy, optimize energy efficiency and adopt circular design principles. Only through such integrative and multidisciplinary strategies can vertical farming evolve from an innovative but resource-intensive model into a truly sustainable and resilient food production system capable of supporting urban food security with minimal environmental burden.

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