

LIFE-CYCLE RESOURCE CONSUMPTION OF HYDROPONIC GREEN ROOF SYSTEMS

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ABSTRACT

The research focuses on assessing the circularity, in terms of life-cycle resources embodied, of a hydroponic system installed on a building roof in Southern Italy, used for producing food in soilless conditions. The analysis of the entire system is performed by applying the Life Cycle Assessment methodology and adopting a “from cradle to gate” approach, which includes all the life-cycle steps from the raw materials supply to the system assembly. The selected categories to quantify the impact on circularity are: land use, water use, use of minerals and metals resources, use of non-renewable energy sources, and use of renewable energy sources. The results reveal the materials and components of examined system that are mainly responsible for these impacts. In particular, for almost all the impacts water tank and platform are the main hot-spots influencing the results and should be further investigated to improve the circularity of the hydroponic system.

1. INTRODUCTION

Promoting sustainable food production and resilient agricultural practices are the main goals of the Sustainable Development Goal 2 – Target 2.4 of the Agenda 2030 for Sustainable Development (United Nations, 2015). To date, food production processes are neither resilient nor sustainable at global level. The effects due to climate change, including extreme weather, drought and flooding, make agri-food production vulnerable by disrupting crop yields, reducing water and soil availability, and increasing the frequency of supply chain disruptions. Furthermore, the food sector contributes significantly to environmental degradation, biodiversity loss, greenhouse gas emissions, and resource consumption (Food and Agriculture Organization of the United Nations, 2021). Together with housing, it accounts for about 72% of the European material footprint, which represents the materials extracted from nature to manufacture or provide goods and services for European citizens. Specifically, these two sectors are responsible for consuming approximately 80% of non-metallic minerals and biomass, 50% of fossil energy materials, and 44% of metal ores (European Environment Agency, 2024).

Thus, identifying new practices to ensure food security, environmental protection and a transition towards circular, resource efficient and less resource intensive processes is fundamental.

Producing food with soilless systems can be considered a potential innovative solution to current agricultural processes, to be applied especially in the urban context, for facing challenges related to food supply such as increasing population, climate change and extreme events, reduced availability of soil for agriculture, etc. (Rapisarda et al., 2024). This new strategy for urban food production has to be efficient concerning the food yield and it needs to be performed in a sustainable way, with a reduced environmental and energy footprint, low costs, and social benefits.

In this context, the present study develops a Life Cycle Assessment (LCA) study to quantify the circularity of hydroponic systems by assessing the resources embodied throughout their entire life cycle.

Circularity is considered from an environmental resource-efficiency perspective, focusing on the extent to which the hydroponic system relies on the consumption and depletion of natural resources throughout its life cycle. Although circularity is a multidimensional concept



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encompassing material flows, resource efficiency, waste prevention, reuse, recycling, and the extension of product and material lifetimes, reducing the demand for primary and non-renewable resources represents a relevant environmental dimension of circular systems.

The innovative contribution of this paper with respect to the state-of-the-art is double:

- Existing LCA studies of hydroponic systems have mainly focused on the production in greenhouses (Mofatteh et al., 2024; Nadeem et al., 2024; Srinivasan and Yadav, 2024; Paturu and Varadarajan, 2024; Martínez et al., 2024) or commercial and large-scale vertical farming systems (Gargaro et al., 2024; Martin et al., 2023; Casey et al., 2022; Martin et al., 2019a; Romeo et al., 2018). Other studies have examined plant factories and combinations of greenhouse and vertical farming systems (Maynard et al., 2023; Blom et al., 2022), while rooftop hydroponic applications have been considered at large scales (Rufi-Salís et al., 2020; Sanyé-Mengual et al., 2015). In addition, some studies have addressed theoretical or human-powered hydroponic configurations (Grigas et al., 2023; Casamayor et al., 2024). The innovative aspect of the present study is that it investigates a small-scale hydroponic system specifically designed for installation on flat residential rooftops and intended to support food production for household consumption. To the authors' knowledge, among the studies identified in the literature, Sanyé-Mengual et al. (2015) represent the closest reference to the present work, as they assessed hydroponic cultivation in a rooftop farming context focusing on a community rooftop garden of 250 m². The small scale of the system examined in this paper and intended application for individual households or small residential buildings represent a key novelty of the present work.
- Previous LCA studies have generally considered a limited selection of resource consumption indicators. Several studies have focused primarily on fossil-resource or abiotic-resource depletion (Mofatteh et al., 2024; Gargaro et al., 2024; Nadeem et al., 2024; Paturu and Varadarajan, 2024; D'Amico et al., 2023; Grigas et al., 2023; Chen et al., 2020; Rufi-Salís et al., 2020; Martin et al., 2019a; Romeo et al., 2018), while others have focused mainly on water use (Maynard et al., 2023; Sanyé-Mengual et al., 2015) or cumulative energy demand (Sanyé-Mengual et al., 2015). The present study provides a broader resource consumption assessment by simultaneously considering land use, water use, mineral and metal resource depletion, and cumulative energy demand (renewable and non-renewable). This allows the resource profile of a household-scale rooftop hydroponic system to be characterized across a wider range of dimensions than those commonly reported in previous studies.

2. CASE STUDY

The case study is a Hydroponic Green Roof System (HGRS) (Figure 1), involving an alternative cultivation tech-

nique that does not use soil.

In detail, in a HGRS system the plant roots are immersed in a well-oxygenated and nutrient-rich water, through a substrate of expanded clay. In this system, the plants do not need to extend their roots much because they do not need to consume energy in search of nutrients as it is normally done on land.

The advantage of HGRSs is that vegetables grow in a controlled environment and the possibility to be exposed to pests or weed species is reduced. As a result, there is less or no use of pesticides and harmful chemicals, helping to produce healthier and safer food for human consumption. Furthermore, the installation of hydroponic systems on building rooftops offer numerous benefits, such as thermal insulation, reduction of urban heat islands, and stormwater management. This system can improve the efficiency of urban space use, contribute to environmental sustainability, and provide fresh food in urban settings. The most important characteristics of the system are the following:

- Water: the roots are immersed in water, allowing the plants to constantly absorb the nutrients and water they need;
- Oxygenation: since the roots are immersed in water, it is essential that the solution is well-oxygenated to prevent the plants from suffocating. This is achieved using an air pump and a porous stone that create air bubbles in the solution;
- Nutrients: the solution contains all the necessary nutrients for plant growth, replacing soil;
- The system includes rapid plant growth and relatively low maintenance once set up.

The examined HGRS is installed on the roof of the building housing the Department of Engineering of the Universi-



FIGURE 1: The examined hydroponic green roof system.

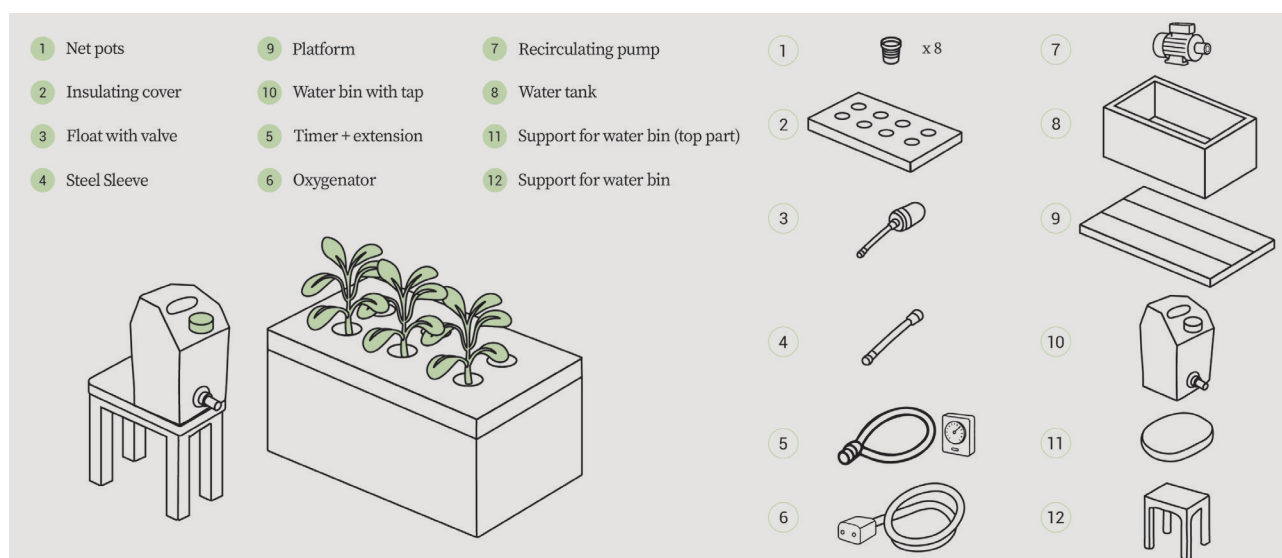


FIGURE 2: System components.

ty of Palermo. At the core of the hydroponic system (Figure 2) is a polyethylene cultivation tank that provides an efficient growing environment. This tank, with a capacity of 200 litres, is covered by an external polystyrene shell, which serves as thermal insulation to maintain stable water temperature and minimize fluctuations that could affect plant development. The dimensions of the tank (104.5 cm in length, 69.5 cm in width, and 34.5 cm in height) allow adequate space to accommodate a variety of plants while ensuring ease of maintenance and monitoring. Supporting the cultivation tank is a robust platform made from a combination of wood and extruded polystyrene, which provides stability and ensures the tank remains securely positioned.

An insulating cover made of extruded polystyrene is placed on the top, featuring eight circular openings, designed to hold the polyethylene terephthalate net pots, allowing the plants to be suspended in the nutrient-rich water while ensuring proper aeration and roots support. Within the tank, a floating valve mechanism ensures a consistent water level is maintained. This float is hydraulically connected via a durable steel sleeve to a 20-liter plastic water bin equipped with a tap, which facilitates easy refilling of water as needed. The container itself is supported by a sturdy aluminium table, whose top surface is also made of extruded polystyrene, further contributing to the insulation and structural integrity of the system. To support an optimal growth environment, the system incorporates both a 10 W recirculation pump and a 6 W oxygenator, powered by electric current and housed respectively in protective cases, made of mixed materials for the pump and ABS for the oxygenator. The oxygenator plays a crucial role in preventing root rot by continuously enriching water with oxygen, thereby enhancing nutrient absorption and promoting healthy plant growth. These components are automated via a timer, which activates the system for 10 minutes every hour, ensuring a balanced and efficient water circulation cycle. The crops to be introduced in the system are cultivated in PET net pots. Before being trans-

ferred to these pots, the young plants undergo an initial growth phase in small polypropylene trays, which are later discarded as waste. Each net pot is equipped with a specialized strap that functions as a wicking material, drawing water and nutrients from the tank to the plant roots. This capillary action ensures that the plants remain consistently hydrated and well-nourished. To provide additional support, expanded clay is used as the growing substrate within the net pots, offering both anchorage and aeration to the developing roots.

3. MATERIALS AND METHODS

The circularity of the hydroponic system was evaluated from a resource-efficiency perspective, by assessing the following life-cycle resources consumption indexes (Damiani et al., 2022; Frischknecht et al., 2015):

- Land use (unit of measure “pt”): it is a soil quality index describing the transformation and use of soil for human activities (e.g. agriculture, roads, etc.). It is calculated as an aggregated impact taking into consideration loss of species, organic matter, soil, filtration capacity, permeability;
- Water use (unit of measure “m3 worldeq”): it represents the depletion of available water calculated with the use of weights that consider the local water scarcity and the water needs for humans and ecosystems;
- Use of minerals and metals resources (unit of measure “kg Sbeq”): referred to the abiotic resources –ultimate reserves, it takes into account the non-renewable resource depletion and the deprivation for future generations;
- Use of non-renewable energy sources (unit of measure “MJeq”): this index includes the use of fossil fuels (such as coal, oil, and natural gas), nuclear energy and non-renewable biomass sources, which are organic materials that can be used as fuel but are not sustainably replenished;

- Use of renewable energy sources (unit of measure “MJeq”): including the consumption of biomass sources (such as sustainably harvested wood or agricultural residues), wind, solar, and geothermal, energy from hydropower.

The above indexes provide information on the depletion of key natural resources associated with the system over its life cycle. Such information support a circularity-oriented assessment because minimizing the use of virgin, non-renewable, and scarce resources and improving resource efficiency are key environmental objectives associated with circular systems.

The calculation of the above resource consumption indexes was made by applying the LCA methodology, developed according to the international standards of the ISO 14040 series (ISO 14040, 2021; ISO 14044, 2022). In general, this approach enables the evaluation of circular aspects in terms of resource consumption throughout the life cycle of a product or service.

The study aims at assessing the resource consumption associated with the manufacturing of the hydroponic green roof system, with particular emphasis on identifying the main components and materials contributing to the overall resource demand. The assessment focused on the environmental burdens associated with the production and assembly of the system, in order to identify the environmental hot-spots and suggest some qualitative eco-design strategies.

The hydroponic system, including all its components and materials, was selected as reference for the indexes evaluation, thus it represents the functional unit of the study that is the quantified performance of the product system to which the input and output flows must be linked (ISO 14040, 2021). This choice is consistent with the goal of the study, which was to quantify the resource consumption associated with the realization of the hydroponic system, rather than the vegetable production. Therefore, the results were expressed per complete hydroponic system. A production-based FU (e.g., kg of vegetables produced) would be more suitable for assessing the environmental performance of the agricultural production phase; however, this was outside the scope of the present study.

A “from cradle to gate” approach was adopted, including the following steps:

- Extraction and processing of raw materials;
- Transport of the raw materials from the site of extraction to the site where the system components are produced;
- Manufacturing of the system components, including energy consumption and ancillaries;
- Manual assembly of the hydroponic system: step directly examined during the installation process.

The end-of-life phase was excluded from the study, based on the material composition of the hydroponic system and the approach adopted for recycling processes. Specifically, the recyclability was estimated by analysing the mass composition of all system components and classifying the materials according to their potential for mate-

rial recovery. Metals, wood, most of the plastic materials and electrical cables were considered recyclable, whereas materials for which material separation and recovery are particularly challenging, such as XPS/polystyrene, PVC, silicone, mixed materials and air stones, were not conservatively considered recyclable and are potentially destined for landfill or incineration.

Based on this material-by-material assessment, the mass of potentially recyclable materials was estimated at about 20 kg, corresponding to about 87% of the total mass of the system. An alternative, less conservative classification, in which XPS/polystyrene, PVC and silicone were also considered potentially recoverable, would result in a recovery rate of 98.89%. The conservative value of 87% was adopted in the present study.

The recycling process was subsequently excluded by adopting a cut-off approach, that is the assumption that the benefits and burdens of recycling are attributed to the new product system that will use the recovered materials.

Since most of the materials are modelled with a cut-off approach, it is assumed that the remaining 13% that is landfilled or incinerated as a negligible impact with respect to the other examined life-cycle stages.

Transport-related impacts from the manufactory site to the installation site were excluded from this analysis, in order to obtain results that are not affected from the distance between the sellers of the hydroponic system and the installation site.

The analysis started with the collection of primary and secondary data. In particular, primary data related to the components of the hydroponic system (materials used and masses) were collected during the assembly step through a weighting process and using the datasheets of these components (Table 1). Then, for each input, secondary data were selected in the environmental database Ecoinvent (Wernet et al., 2016), in order to describe the inputs supply chains in a life-cycle perspective. The application of LCA allowed calculating a list of environmental indicators related to raw materials consumption. These indicators were grouped into the resource consumption indexes listed above. In detail, the grouping method applied for the consumption of energy sources was the Cumulative Energy Demand (Frischknecht et al., 2015), while the other indexes were assessed by applying the Environmental Footprint method (European Commission, 2021). All the calculations were performed by using the LCA software Simapro (Prè, 2024).

Primary data were collected with direct measurements (Figure 3) and analysis of datasheets related to system components.

4. RESULTS AND DISCUSSION

The results of the analysis, related to the calculation of the resource consumption indexes, are reported in Table 2.

Focusing on the contribution of the different inputs of hydroponic systems, previous LCA studies have highlighted the importance of energy and material requirements as key contributors to environmental impacts, although the dominant processes vary substantially depending on

TABLE 1: Collected primary data.

Component	Material	Mass (kg)	Length (m)
Water tank - Inner part	Polyethylene	10.90	
Water tank - Outer Part	Polystyrene	0.84	
Insulating cover	Polystyrene	0.65	
Platform	Wood	4.70	
	Polystyrene	0.70	
Water bin	HDPE	0.90	
Tap	Brass	0.10	
Pump	Mixed materials	0.20	
Pump (electric cable)			1.45
Oxygenator	ABS	0.05	
	Copper	0.08	
	Steel	0.08	
	PVC	0.04	
	Air stones	0.06	
	Silicone	0.03	
Oxygenator (electric cable)			1.37
Timer	Polycarbonate	0.03	
	ABS	0.16	
Timer (electric cable)			2.93
Water bin support	Aluminium	2.05	
	Polystyrene	0.20	
Float	HDPE	0.03	
Valve	Stainless steel	0.17	
Net Pots	PET	0.15	
Steel sleeve	Stainless steel	0.20	
Substrate	Expanded clay	0.15	

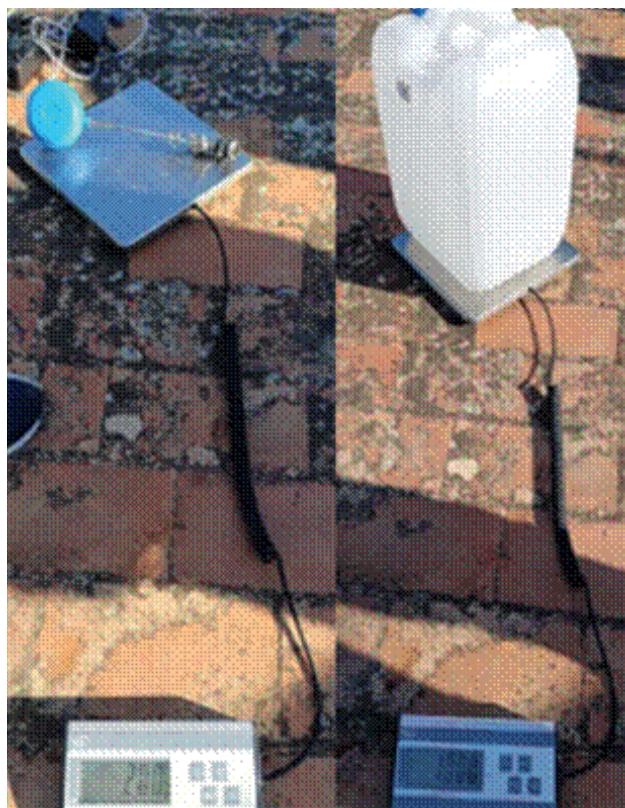


FIGURE 3: Weighting process of the system components..

TABLE 2: Results of the analysis.

Resource consumption index	Unit of measure	Quantity
Land use	pt	8.66E+02
Water use	m3 worldeq	4.58E+01
Use of minerals and metals resources	kg Sbeq	2.93E-03
Non-renewable, fossil	MJeq	1.66E+03
Non-renewable, nuclear	MJeq	1.57E+02
Non-renewable, biomass	MJeq	3.17E-02
Renewable, biomass	MJeq	1.30E+02
Renewable, wind, solar, geothermal	MJeq	3.17E+01
Renewable, water	MJeq	5.75E+01

system configuration, scale, and technology. In particular, studies on vertical farming and plant-factory systems have frequently identified energy demand associated with controlled cultivation conditions as a major environmental hotspot, whereas studies on greenhouse and rooftop hydroponic systems have reported a greater relevance of cultivation infrastructure, water management, and pumping requirements (Romeo et al., 2018; Martin et al., 2019a; Casey et al., 2022; Gargaro et al., 2024; Sanyé-Mengual et al., 2015).

A dominance analysis of the environmental impact assessment obtained in this study (Figure 4) identified some critical hotspots across the examined impact categories. In detail:

- Land use: the platform had a substantial impact on land use (62.78%), with a value of 5.43E+02 pt, indicating significant land occupation and transformation. Water tank also contributed to the land use impact, accounting for 17.74% of the total. Sustainable land use practices and minimizing land disturbance during production are critical. Implementing land restoration projects and optimizing land use efficiency can help mitigate these impacts.
- Water use: the production of the water tank required a relevant amount of water, resulting in significant water scarcity impact, with a total water deprivation value of about 20.97 m³eq, corresponding to 45.76% of the overall water use impact. Additionally, the water directly used within the system for the initial filling also contributed notably, accounting for 20.67% of the total. These findings underscore the need for water-efficient manufacturing processes and the adoption of sustainable water management practices to mitigate resource depletion and reduce pressure on freshwater availability.
- Use of minerals and metals resources: the timer, water bin, and oxygenator demonstrated a significant contribution to resource use related to minerals and metals. Among these, the timer (and in particular cables) was the most impactful component, with a quantified value of 6.13E-04 kg Sbeq, representing 25.62% of the total impact. The water bin and oxygenator followed closely, contributing 25.07% and 17.40%, respectively. The critical inputs of water bin emerging as significant hotspot for this impact category, is brass, while for oxygenator

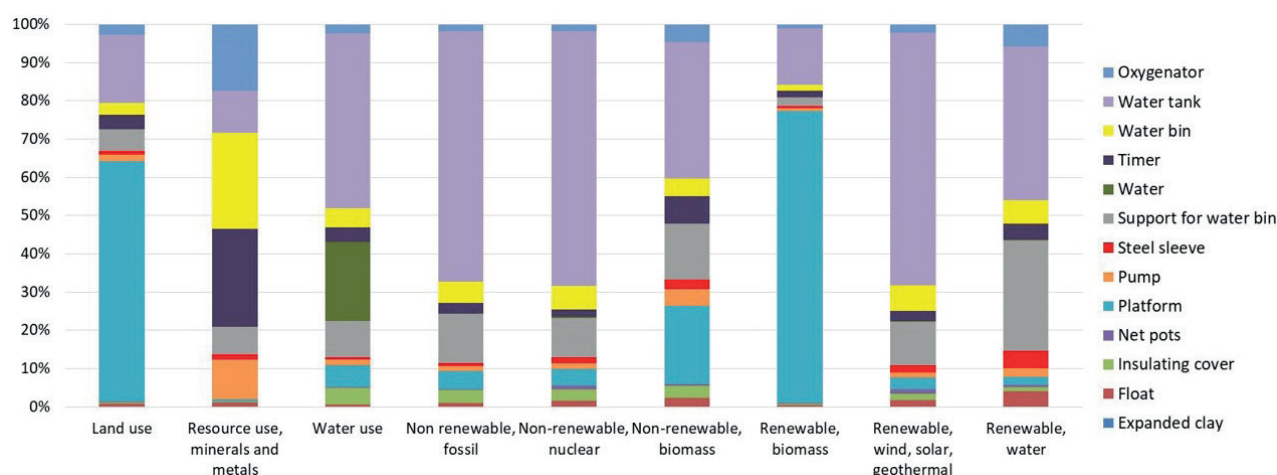


FIGURE 4: Dominance analysis of the results.

the main responsables of the impact are cables and copper. To mitigate these impacts, it is essential to adopt recycling strategies and explore the use of alternative, less resource-intensive materials. Furthermore, embracing circular economy principles and promoting the use of secondary raw materials can significantly reduce the depletion of mineral and metal resources.

- Non-renewable, fossil: this category represents the most significant contribution to the energy consumption, totaling about 81.5% of the primary energy consumption. The majority of this value is attributable to the water tank, which accounts for about 65% of the total fossil energy demand. In particular, the internal part of the water tank, made of polyethylene, is identified as the most critical hotspot. This highlights the high-energy intensity associated with the tank's production, likely due to petroleum-based plastic materials and energy-intensive manufacturing processes. The support for water bin is the second-highest contributor (12.8%).
- Non-renewable, nuclear: nuclear energy contributes to about 7.7% to the overall energy demand. Once again, water tank is the largest single contributor with approximately 67% of the total in this category. This confirms the water tank's significant role in the energy balance. Other components, including the platform, float, pump, and timer, contribute to a lesser extent.
- Non-renewable, biomass: this category has a very limited impact, lower than 0.002% of the total. Thus, the individual contributions from components are negligible in quantitative terms, indicating a minimal role of non-renewable biomass in the system's life-cycle.
- Renewable, biomass: the contribution from renewable biomass is about 6.4%, with the platform being the dominant component, accounting for 76.4% of the total. This result highlights the significant renewable energy demand involved in the platform supply chain, mainly due to the feedstock energy embodied in the wood used for this component.
- Renewable, wind, solar, geothermal: this category contributes to 1.5% of the total, with the water tank again being the main contributor (66.2%). This suggests that,

along the supply chains, part of the energy used in the tank's production comes from renewable electricity sources such as solar or wind power.

- Renewable, water: renewable energy from hydropower accounts for 2.8% of the total primary energy consumption, with the water tank again leading at 40.3%, and support for water bin at 28.8%.

Considering the existing literature studies, given the differences in system configuration, scale, and functional characteristics among the hydroponic systems investigated, a direct quantitative comparison with most previous LCA studies is not straightforward. In particular, the majority of published studies concern commercial greenhouses, vertical farms, or plant factories, which differ substantially from the household-scale rooftop system considered in this study. The study reported by Sanyé-Mengual et al. (2015) represents, to the authors' knowledge, the closest study in terms of application to rooftop, as authors assessed hydroponic cultivation in a rooftop farming context in Bologna, Italy. Their study compared nutrient film, floating hydroponic, and soil-based cultivation in a 250-m² community rooftop garden and applied LCA to the production of different crops. However, their assessment was performed using 1 kg of crop as the functional unit and therefore incorporated the productivity of the cultivation systems into the environmental results. In contrast, the present study focuses on the burdens associated with the production of the household-scale hydroponic system itself, without extending the assessment to crop production and without defining the functional unit in terms of mass of crop produced. Therefore, a direct quantitative comparison of the LCA results with those reported by Sanyé-Mengual et al. (2015) would not be methodologically appropriate. Further developments of the present study will extend the assessment to the cultivation phase, including the evaluation of crop productivity, in order to obtain results referred to a mass-of-product basis and to have the possibility to compare them with previous LCA studies. Such a comparison will also need to account for the influence of local climatic conditions on system operation and crop produc-

tivity, which may affect the environmental performance of rooftop hydroponic cultivation.

5. SENSITIVITY ANALYSIS

The LCA study was developed by using a from cradle-to-gate approach, consistently with its goal of assessing the resources consumed during the system realization. However, a sensitivity analysis was performed to evaluate the potential relevance of the operational phase.

The operational requirements of the system were estimated based on the annual consumption of water, electricity and fertilizer. Specifically, the system requires 600 l of water (excluded the 200 l used in the initial filling) for the first year and 800 l/year in the next years, 24 kWh of electricity and 100 mL of fertilizer per year. Since the service life of the system can vary depending on the durability of its individual components, three reference service-life scenarios were considered: 5, 10 and 15 years. These scenarios were selected to represent short-, medium- and long-term operation and are consistent with the range of service lives reported for components of hydroponic and soilless cultivation systems, which vary according to the type of component and its operating conditions (Martin et al., 2019b; IUCN, 2023; Pennisi et al. 2019).

The results of the sensitivity analysis, showed in Table 3, highlighted that resource use minerals and metals is dominated by the cradle-to gate impacts even if the use phase is included, with a contribution going from 65% to 85% when the service life of the system decrease from 15 to 5 years. Similarly for land use, for which the above stages accounts for 54% considering a 15-years of operation and increases at 78% when the service life has the minimum value.

The operational phase becomes the main contributor to the impacts on water use, representing from 81% (5-years service life) to 93% (15-years service life) mainly due to the use of water for plant growth. Moving to the energy indexes, the from cradle-to-gate stages remain relevant for biomass depletion (renewable and non-renewable), with a contribution higher than 53%, while operation represents the main hot-spot (higher than 66%) when other renewable energy sources (wind, solar, geothermal and water) are considered. This last result comes from the renewable share on energy in the electric mix used in the analysis (referred to

Italy). Focusing on non-renewable energy from fossil fuels and from nuclear, the incidence of operation increase from 28% to 54% (fossil) and from 39% to 65.5% (nuclear) when the service life increases.

The analysis revealed the importance to include the operational phase, which could substantially affect the magnitude and interpretation of the results obtained from the cradle-to-gate assessment.

6. POTENTIAL IMPROVEMENT STRATEGIES

The identification of the main environmental hotspots and a direct observation of the system layout provide useful information for defining qualitative eco-design solutions aimed at improving the resource-efficiency of the system, that can be applied not only for the system manufacturing but also for its operation. In particular, eco-design strategies can be oriented toward the reduction of materials/components, water and energy requirements and use of secondary raw materials:

- Use of secondary raw materials: the replacement of virgin materials with recycled or secondary raw materials provides an opportunity of improving the system performance in terms of circularity, particularly for components with a high material mass such as the water tank. For example, assuming similar characteristics, recycled polyethylene can be considered as an alternative to virgin polyethylene for the manufacturing of water tank. This substitution can result in important improvements in the resource-efficiency: for 10.9 kg of material (that is the weight of the water tank – inner part), using secondary polyethylene allows for a reduction of energy consumption of one order of magnitude, from 83.45 MJ to 9.37 MJ. Non-renewable energy sources are reduced of about 178%, while there is an increase of 67% of renewable energy sources. Land use, water use and depletion of minerals and metals resources decrease of about 84.5%, 91.9% and 91.7%, respectively.
- Reduction of the amount of materials used, with a specific focus on optimizing cable lengths. Careful components layout design, particularly for the timer, pump and oxygenator, can minimize cable routing distances. This relatively simple design choice can contribute to the overall sustainability of the system because the use

TABLE 3: Results of the sensitivity analysis.

Resource consumption index	Unit of measure	Cradle-to-gate	5 years oper.	10 years oper.	15 years oper.
Land use	pt	8.66E+02	2.48E+02	4.96E+02	7.44E+02
Water use	m3 worldeq	4.58E+01	1.93E+02	3.95E+02	5.97E+02
Use of minerals and metals resources	kg Sbeq	2.93E-03	5.25E-04	1.05E-03	1.57E-03
Non-renewable, fossil	MJeq	1.66E+03	6.39E+02	1.28E+03	1.92E+03
Non-renewable, nuclear	MJeq	1.57E+02	9.91E+01	1.99E+02	2.98E+02
Non-renewable, biomass	MJeq	3.17E-02	9.28E-03	1.86E-02	2.79E-02
Renewable, biomass	MJeq	1.30E+02	2.15E+01	4.30E+01	6.45E+01
Renewable, wind, solar, geothermal	MJeq	3.17E+01	1.59E+02	3.19E+02	4.78E+02
Renewable, water	MJeq	5.75E+01	1.11E+02	2.22E+02	3.33E+02

of shorter cables implies a reduced need for copper and insulating materials, resources whose extraction and processing have an environmental impact. For example, a reduction of 20% of cables length can reduce the impact on minerals and metals resources of about 6.6% and lower than 2% for the other examined categories.

- The current configuration of the system includes a 20-liter plastic water bin equipped with a tap, which facilitates easy refilling of water as needed. The water bin is put on a sturdy aluminium table, whose top surface is made of extruded polystyrene. An eco-design strategy, where technically and hydraulically feasible, would be to connect the hydroponic system directly to the building's water supply system, thus eliminating the water bin, the aluminium table and the top surface, thereby reducing the amount of material required for the overall system. This helps reducing the energy impacts of the system of about 17.8%, with a variation from 16% to 19% of non-renewable energy sources and from 4% to 35% of renewable energy sources. The resource consumption impacts are reduced from 9% (land use) to 32.4% (minerals and metals resources), with a water use reduction of 18.1%.
- Reduction of the water level: a possible strategy concerns the reduction of the water volume contained in the tank. In the current configuration, the tank contains 200 l of water, corresponding to a water height of about 27.5 cm. A reduction of the operating water level could be considered, provided that the minimum volume required to ensure adequate plant growth, hydraulic operation and oxygenation is maintained. For example, reducing the water height to 20 cm would decrease the water volume from 200 l to 145 l for each filling, that is from 800 l to 580 l per year, with a corresponding reduction in water demand during operation. This solution causes a reduction of the impacts due to water of the system of 27.5% during each year of operation. Considering one year of operation of the whole system (not only the water impact) a decrease of the impact lower than 2% can be obtained. However, it is important to outline that the impact on the category "water use" of the whole system can be reduced of about 23.4%.
- Reduction of electricity consumption during operation, that is associated with the pump and oxygenator. In the current configuration, the two components have a combined power of 16 W. They are connected to a timer and work for 10 minutes every hour, reaching a total of 4 hours per day. The annual consumption of the pump and oxygenator is 23.36 kWh (0.064 kWh per day). If the time of operation is changed and the two components work for 10 minutes every hour and a half, a total of 2.7 hours per day of working is obtained, with a consequent electricity consumption of 0.0432 kWh per day and of 15.77 kWh per year, and a reduction of about 32.5% of electricity consumption. In this case, a 32.5% reduction of the impacts due exclusively to electricity can be obtained.

Overall, the identified strategies suggest that improvements should primarily focus on the components and

flows responsible for the largest resource requirements. In particular, reducing the material intensity of the water tank and cables, increasing the use of secondary raw materials, optimizing water and electricity requirements, could contribute to improve the resource-efficiency performance of the system. These interventions should be considered as potential design options rather than as directly quantified improvement scenarios, since their actual effectiveness would depend on technical feasibility, structural and operational requirements, and the specific materials and technologies adopted.

7. CONCLUSIONS

This study proposes an evaluation of the circularity performance of a hydroponic green roof system, considering the life cycle resources embodied from raw material supply to system assembly. The results highlight that the system's circularity is strongly influenced by a limited set of components. In particular, the water tank and the platform emerged as the main hot-spots across multiple impact categories, with material composition playing a decisive role in their overall contribution. Other elements, such as the water bin, its support structure, the timer, and the oxygenator, also showed notable impacts.

These outcomes confirm the need to prioritize material selection and design optimization in order to improve the circularity of urban hydroponic systems.

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