



Environmental assessment of design choices of green walls based for materials combination and plants

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Abstract

Purpose Green infrastructures have been considered as a sustainable solution to deal with the problems in dense urban spaces. This acceptance has led to the use of various materials and methods in designing and producing green infrastructures. The purpose of this study is to emphasize the components and materials used in the green walls system. By determining the environmental impact of each element, it can be replaced with another component with the same function. This approach ultimately leads to the sustainable design of systems.

Methods Accordingly, two green wall systems were selected for the environmental assessment using the life cycle assessment method. Data related to all processes and components involved in each system are reviewed for a 10-year lifespan. For each system, eight different scenarios of component composition are considered. The functional unit is 1 square meter and the ILCD method is used to evaluate the impact of the life cycle. OpenLCA software and Ecoinvent[®] v3.7 database are used to model and analyze all 16 scenarios.

Results The results clearly show that the components and materials used in the production and construction of the green wall system have a very high impact on the environmental performance of these systems. A better design can be achieved by doing an environmental assessment, identifying the undesirable components in the system, and replacing them. Different scenarios' results show the potential to improve the environmental performance of systems in all impact categories. This highlights the great importance of the green wall system's design, material selection and maintenance methods.

Conclusions Considering the ability of the LCA method to identify the weak and strong points of the systems, the lack of using this method in the design phase is strongly sensed. With this method's help, it is possible to produce more sustainable systems. On the other hand, the studies conducted in the field of green walls are limited compared to other green infrastructures. At the same time, the design of the green wall system can be changed based on geographical location, weather conditions, access to raw materials and consumer needs. As the number of studies on these systems increases in different places and weather conditions, it can help the stability of these systems.

Keywords Life cycle assessment (LCA) · Environmental impact · Green wall system · Sustainability · Green infrastructure · ILCD

1 Introduction

One of the influential factors in climate change is the environmental impact of the building's life cycle (Röck et al. 2020). This aspect is strictly related to population growth and urban

life that are responsible for a dramatically increased energy demand. In particular, thermal comfort and air conditioning systems consume about 40% of this energy (Daemei et al. 2021). Several innovative solutions can be provided to mitigate the energy consumption in buildings and consequently the structures effects on urban scale. Nowadays, developers, architects, engineers and urban planners use nature-based solutions (NBS) as a sustainable way to tackle urban problems and expand green space (Cousins 2021). The use of urban green infrastructure (UGI) can be an excellent solution to reduce these concerns and make the urban environment a greener and more desirable living space (Ouyang et al. 2020).

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Currently, green infrastructures have been widely welcomed. We can mention the green roof and green walls system among the green infrastructures, which are widely recommended (Hopkins and Goodwin 2011). In this regard, green walls and facades were born from integrating buildings and plants, which can help enrich the biodiversity of cities and meet challenges such as urban heat islands. The effect of urban heat islands can make the temperature of urban areas 2 to 5° C warmer than the circumferential and low-density areas (Mazzali et al. 2013). Reducing high temperatures in densely built-up areas with increasing green space is an adequate idea to improve the health, comfort and psychological well-being of these areas' residents (EC 2015; Coldwell and Evans 2018). There is a good potential for greening the building envelope by combining traditional roofs and walls. These systems allow vegetation to grow in places not customarily vegetated and form a microclimate. Although the use of plants in urban structures and buildings has a long history, the emergence of new technologies and materials has recently provided the possibility of presenting new designs and further developing these systems (Serra et al. 2017). In addition to aesthetics as a design advantage, green wall systems can act as a natural insulator in the building by creating an air layer on the main wall (Raji et al. 2015). Green wall systems can bring sustainability and environmental benefits to constructing new buildings and retrofitting old ones (Sendra-Arranz et al. 2020). These environmental benefits include the reduction of energy demand (Dahanayake and Chow 2018), pollution levels and the improvement of air quality (Perini and Rosasco 2013), increasing biodiversity (Koch et al. 2020), carbon sequestration. Moreover, they provide a reduction of noise pollution (Pérez et al. 2016), reduction of the inside and outside temperature of the building (Mazzali et al. 2013), creating a cooling effect and reducing the urban heat islands effect (Yu and Hien 2006), an improvement of human health (Alexandri and Jones 2008) and other positive social and cultural impacts on residents' life quality (White and Gatersleben 2011).

Alexandri and Jones (2008), examined the addition of green roofs and green walls systems in different climatic conditions. They evaluated the effects of these systems in nine cities in various parts of the world. The research results confirmed the reduction of urban temperature with the help of these systems. Mazzali et al. (2013), evaluated the energy performance and thermal behavior of three living walls in northern Italy. The results showed a 10 to 20° C difference between the bare and living walls, where the bare wall was warmer and conducted higher net energy into the building. Another study, in Japan, has reported a 10-degree reduction in building surface temperature using a green wall system (Wang et al. 2014). In another study, Feng et Hewage assessed the potential of air purification and energy savings by simulation software of the green walls studied by Ottelé et al. They found that the green wall system acts as an insulating coating on the building

surface by creating an air layer on the bare wall and it could lead to a 23% reduction in energy costs and improve thermal performance (Feng and Hewage 2014). Another case study was performed in Hong Kong by Pan and Chu (2016), which analyzed the energy saving potential of a vertical green system. This study shows that the vertical green system reduces the energy demand in the building and consequently reduces the environmental impacts.

Efforts to further expand the green wall systems in recent years to access their environmental benefits have led to many innovations in this area (Rosasco and Perini 2018). Like other new technologies, the popularity and rapid proliferation of green systems can lead to challenging issues that need to be addressed (Riley 2017). Bustami et al. (2018) cite these systems' construction and maintenance costs as a significant obstacle to their development. According to Riley's study (2017), the number of studies conducted on vertical green systems is not commensurate with the expansion of these systems, and new studies can help find appropriate answers to existing ambiguities. Since various materials and methods are used in the design of green wall systems, finding an optimal design model for these systems is challenging. The design of these systems can be changed according to consumer needs, geographical location, weather conditions and access to raw materials. On the other hand, the materials and components used in vertical green systems have a significant contribution to the environmental performance of these systems. Between 43 and 97% of all environmental impacts are caused by the extraction of raw materials, production of elements, and construction of systems systems (Pan and Chu 2016). Therefore, it is unavoidable to consider different scenarios for combining the raw materials used in these systems' production and assessing their environmental impacts over the system's life cycle.

According to the definition provided by the International Standards Organization (ISO) (2006), Life Cycle Assessment (LCA) is a methodology to identify the factors influencing the environmental impacts of a product or process that allows evaluation and comparison between different environmental profiles (Rebitzer et al. 2004). In the LCA method, the sustainability of a product or system can be well evaluated by considering all the environmental benefits and burdens (Salah and Romanova 2021). The LCA application as a systematic method for building evaluation is necessary, and its use has grown significantly since the 1990s (Ortiz et al. 2009; Gervasio et al. 2018). The advantages of using LCA are preventing unnecessary pollution and reducing resource consumption by identifying the influential factors during the system life cycle (Hauschild et al. 2018). This technique allows comparisons between different options, so it can play a key role in construction sector decisions. Countries such as the Netherlands, Finland and France have mandated LCA in the building design and construction process,

and Germany and Austria have semi-mandatory recommendations in this area. This decision is due to the incredible importance of selecting and using sustainable materials in the building sector [26]. Accordingly, many studies have examined the life cycle of buildings or specific materials (Ingrao et al. 2018; Kavehei et al. 2018). Ingrao et al. (2018), emphasized minimizing energy and resource consumption and the building's environmental impacts by the LCA. LCA is often used to evaluate products and systems after design. In contrast this tool can be used to support and improve the initial design, which is challenging due to the complexity and difficulties associated with the collection of real and accurate data, especially for the components and materials of a system such as a green wall. Despite this, the knowledge gap in the LCA of green systems is strongly present in the literature. Moreover, most studies on green systems fields have been carried out on green roofs (Kavehei et al. 2018) and studies related to vertical green systems are few.

Salah and Romanova (2021), used the LCA to examine the environmental impacts of a living green wall over its lifespan and they found that 80.67% of greenhouse gas emissions were due to the system production phase. Ottel  et al. (2011), evaluated five different vertical green systems and the results of the study confirmed the high dependence of the systems' environmental burdens on the materials used in their construction. Various studies have compared different types of living wall systems with different features and characteristics, also focusing on the effects of materials on the environmental performance of these systems over the life cycle (Oquendo-Di Cosola et al. 2020). Manso et al. 2018), compared a new modular system with a bare wall, and the results showed that the highest impact was related to the components used in the system support structure. These background studies underline the fact that further studies are necessary to find more sustainable choices for these systems and emphasize the gap in environmental impact variations based on the materials and components (Ch fer et al. 2021).

This study aims at identifying the various parts of different types of green walls, focusing on the contribution of materials and components to their environmental performance. Different scenarios are considered to assess the extent of changes in the environmental impacts over the life cycle and find suitable alternatives with the same performance and lower environmental impact, thus contributing to a more sustainable design of vertical green systems. In this article, we emphasize the importance of components and materials which contribute significantly to the systems' environmental performance. LCA is typically used to evaluate the performance of a system after it has been designed and constructed. A Life Cycle Assessment (LCA) can be used as a decision-making tool to reduce the environmental burden of a system if it is applied during the design phase and selection of materials.

2 Methods

This study refers to two types of systems. System A is a modular system that uses soil mix as a growth medium. The irrigation system supplies the water and nutrients needed by the plant, and a supporting system provides the entire system stability. System B is a felt modular system that allows plants to grow in embedded pockets without soil. The required water and nutrients are supplied through the irrigation system. The supporting system is made of a panel and a frame. The components considered in both cases and used as a basis for modeling different scenarios are shown in Fig. 1.

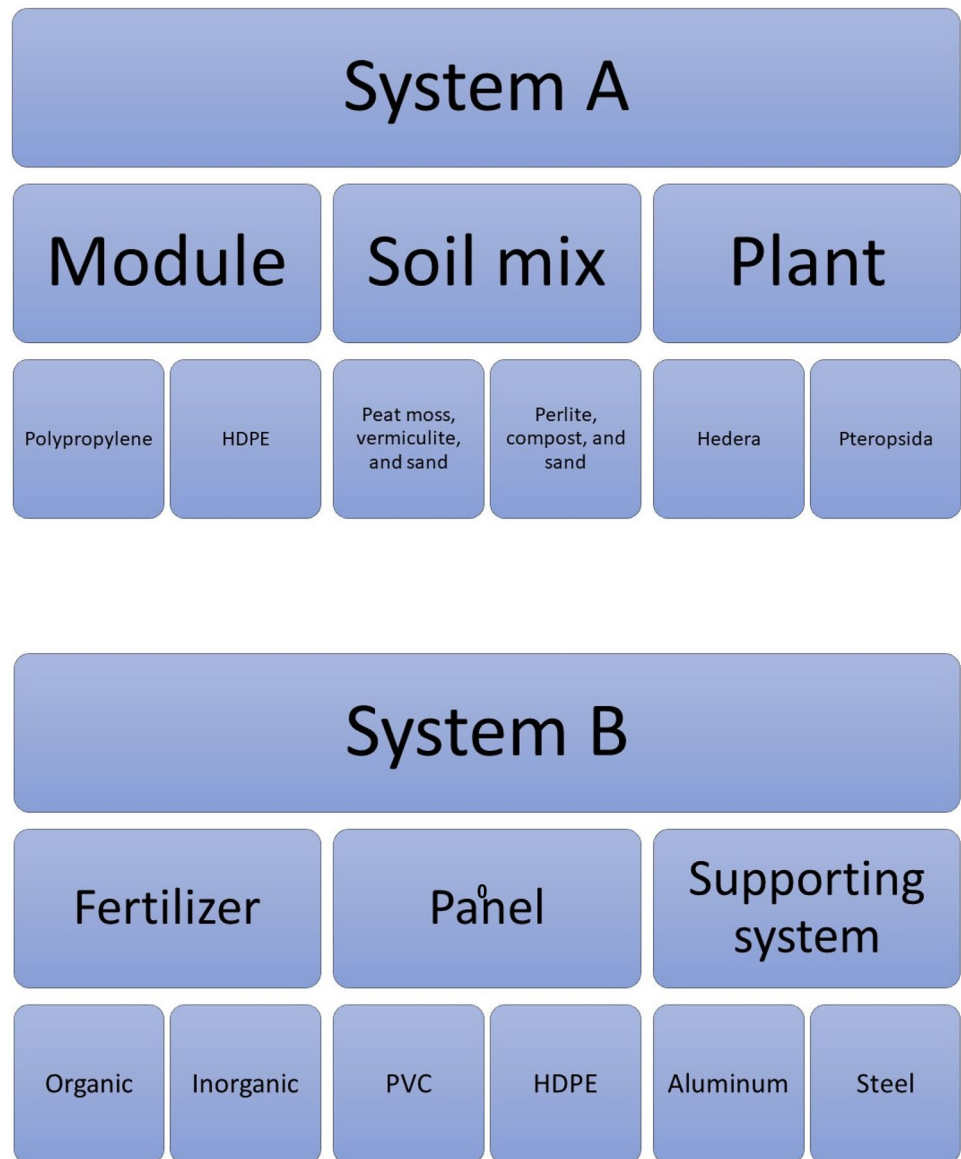
All components and processes of each system were considered over a 10-year period. According to the data, pipes and fittings related to irrigation systems need to be entirely replaced every 7.5 years due to problems caused by salt deposition and clogging (Cort s et al. 2021). In addition, we cannot ignore the effect of carbon uptake and carbon payback by plants to balance the environmental impact. For this purpose, we assumed that the carbon uptake rate per square meter of the system surface is 12 kg/year on average. This is the value suggested in similar studies (Reyhani et al. 2022).

Separate models were created in the OpenLCA software to analyze the processes associated with each scenario, and the Ecoinvent[®] v3.7 database was used to simulate the processes. We completed the data inventory with both systems' technical datasheets and assumptions explained below.

In order to perform a comprehensive life cycle assessment, 1 square meter was used as a functional unit and a cradle-to-gate approach was considered.

Life cycle impact assessment was performed using the International Reference Life Cycle Data System (ILCD) method approved by the European Commission. This methodology is presented for the targeted development of life cycle data with robust assessments and assured quality for use in the public and private sectors. This method uses 16 different categories to evaluate the impact of 1 square meter of each system on the environment and the pollutants released into the water, soil and air. Many studies' results equate material production's environmental effects with the amount of greenhouse gas emissions. The climate change impact category is directly affected by the amount of greenhouse gas emissions. On the other hand, the human toxicity impact category is essential due to the consideration of toxic compounds that can be released during the life cycle and their impact on the human environment. The effect of these toxic compounds on the freshwater ecosystems due to release in water, air and soil can be monitored by the freshwater ecotoxicity impact category. In addition to these three categories, the impact categories of water resource depletion, land use and mineral, fossil and renewable resource depletion have been recommended to understand better the

Fig. 1 Basic components used for different scenarios modeling



system's life cycle assessment results and environmental effects (Reyhani et al. 2022).

The polypropylene used in the production of modules has the most negative impact on the impact categories in system A. In addition, the composition of the potting soil and the water consumption required by the plant are among the influential components during the system life cycle. This system's high water consumption rate is related to the Hedera plant, which needs approximately 8 L of water per day. Depending on the system design and climatic conditions, the Pteropsida plant can be used, which requires 1 L of water per day. Using High-density polyethylene (HDPE) instead of polypropylene in the production of modules can be a good option. The potting soil used in system A is a combination of peat moss, vermiculite, and sand, which could be replaced with a mix of perlite, compost, and sand. Based

on these options, eight possible scenarios for system A are given in Table 1. Each column is dedicated to a unique scenario and the active components are marked.

In system B, inorganic nutrient solutions for plant nutrition can be introduced as the leading cause of adverse effects. On the other hand, most of the supporting system components are made of aluminum, which produces a significant environmental burden. Moreover, the effects of the Polyvinyl chloride (PVC) panel used in the supporting system are not negligible. The PVC panel can also be made with HDPE. Since system B needs a nutrient solution for plant growth and it is impossible to remove it, the organic compounds can be used as an alternative solution. The supporting system structure can be made of steel too. Like system A, eight scenarios were considered for all proposed combinations of system B in Table 2.

Table 1 Considered scenarios for system A based on different alternative combinations. Two options were considered for modules, soil mix and plants. Each scenario has been marked with the components involved

		Scenarios	M1-	M1-	M1-	M2-	M1-	M2-	M2-	M2-
			S1-P1	S1-P2	S2-P1	S1-P1	S2-P2	S1-P2	S2-P1	S2-P2
Modules	Polypropylene (M1)									
	HDPE (M2)									
Soil mix	Peat moss, vermiculite, and sand (S1)									
	Perlite, compost, and sand (S2)									
Plant	Hedera (P1)									
	Pteropsida (P2)									

The gray color highlight which components (columned voices) are present in each considered scenario (first table line)

Data inventory was created based on different scenarios and proposed components (Tables 3 and 4). Therefore, the new data were entered into the software and separate models were designed for various modes of each system.

3 Results

The results of different scenarios of the two systems have been compared in order to evaluate the systems' performances to determine a more sustainable design of the systems. In most impact categories, system A performs better. This difference is due to the significant effect of aluminum parts in the supporting system and fertilizer for plant growth in system B. Tables 5 and 6 show the results of the eight specific scenarios related to systems A and B respectively.

In the tables, the case with the worst results (in red) and the cases with the best results (in green) have been highlighted for all the impact categories of the impact assessment method. As the results

for system A show, in eight impact categories, the worst performance is for M1-S1-P1 and M2-S1-P1 scenarios and the best performance is for the M1-S2-P2 and M2-S2-P2 scenarios. In system B, the F2-P2-S2 scenario in 11 impact categories achieves the best performance and the F1-P1-S1 scenario has the worst performance.

By analyzing the results and trade-offs between the impact categories for system A, it can be seen that using HDPE instead of polypropylene to produce modules, despite the significant reduction in the impact category of climate change, increases the adverse effects in eight impact categories such as Freshwater ecotoxicity, Human toxicity, Land use and Ozone depletion. The results of system B also show that using HDPE instead of PVC for panel production will have an increasing effect in four impact categories, especially Photochemical ozone formation and Land use, despite reducing the environmental burden in 12 impact categories. Also, replacing steel instead of aluminum in the supporting system in all impact categories except "human toxicity, cancer effects" improves the system's environmental performance.

Table 2 Considered scenarios for system B based on different alternative combinations. Two options were considered for fertilizer, panel and supporting system. Each scenario has been marked with the components involved

	Scenarios	F1- P1-S1	F1- P1-S2	F1- P2-S1	F2- P1-S1	F1- P2-S2	F2- P1-S2	F2- P2-S1	F2- P2-S2
Fertilizer	Inorganic (F1)								
	Organic (F2)								
Panel	PVC (P1)								
	HDPE (P2)								
Supporting system	Aluminum (S1)								
	Steel (S2)								

The gray color highlight which components (columned voices) are present in each considered scenario (first table line)

4 Discussion

As shown in Fig. 2, the M2-S2-P2 model has the best performance in the climate change impact category compared to other possible models. This reduction is due to replacing the high volume of polypropylene used in this system's production and manufacturing stages with HDPE. During the

production process of polypropylene for the module of this system, approximately 110 kg of CO₂ are produced compared to the 41 kg of CO₂ in the HDPE production process. The rate of avoided emissions of CO₂ is significant between these two materials. Also, using Pteropsida instead of Hedera produces approximately 7 kg less CO₂ and replacing the compost and perlite in the soil mix instead of vermiculite and peat moss

Table 3 The components of system A in various scenarios

Components		Material	Weight (kg/m²)	Distances (km)	Service life (years)
Ordinary	Module holder	Tempered steel	5.644	96.5	10
	Upright	Aluminum (6060 T5)	3.51	55	10
	Watering system	PE	0.1	62	7.5
	Nuts and Bolts	Stainless steel (AISI 304)	0.4	96.5	10
	Filter	PP	0.288	62	10
Alternative	Potting soil	40% peat moss, 20% sand, and 40% vermiculite	12	-	10
		40% compost, 20% sand, and 40% perlite			
Module	Polypropylene	60	62	10	
	HDPE recycled				
Water demand	Hedera	29200	-	10	
	Pteropsida	3650			

Table 4 The components of system B in various scenarios

	Components	Material	Weight(kg/m ²)	Distances(km)	Service life(years)
Ordinary	White fleece	Polypropylene	0.82	167	10
	Wool fleece	Polyamide	0.93	167	10
	PE fleece	Polyethylene	0.06	167	10
	Watering system	PE	0.1	226	7.5
	Water demand	Tap water	10950	-	10
Alternative	Plastic panel	PVC	5	226	10
		HDPE recycled			
	Bracket	Aluminum	0.2	131	10
		Steel	0.58		
	Frame	Aluminum	1.578	131	10
		Steel	4.58		
	Lateral shoulder	Aluminum	2.01	131	10
		Steel	5.83		
	Water Tank	Aluminum	2.01	131	10
		Steel	5.83		
Fertilizer	Inorganic fertilizers	22.5	-	10	
	Organic fertilizers				

has about 6 kg less CO₂. Moreover, considering the assumption of the plant absorption of CO₂ around 12 kg per year, all the CO₂ produced in the manufacturing stage is compensated by the fourth year. Since the fifth year, the system could be considered as carbon capture technology, explaining the negative value of the climate change indicator.

In the human toxicity impact category for system A, the worst performance has the M2-S1-P1, which indicates the harmful effects of the HDPE production process in this category. The use of HDPE in the modules production process can have up to 42% more destructive effects than polypropylene. On the other hand, the best performance is related

Table 5 Environmental impacts for a 1 m² of system A in each scenario

Impact category	Reference unit	M1-S1-P1	M1-S1-P2	M1-S2-P1	M2-S1-P1	M1-S2-P2	M2-S1-P2	M2-S2-P1	M2-S2-P2
Acidification	molc H+eq	0.66	0.62	0.66	0.41	0.61	0.36	0.40	0.36
Climate change	kg CO2 eq	42.20	35.20	35.89	-27.08	28.89	-34.08	-33.39	-40.39
Freshwater ecotoxicity	CTUe	1428.62	1309.62	1424.13	2083.52	1305.13	1964.52	2079.04	1960.041
Freshwater eutrophication	kg P eq	0.046	0.040	0.046	0.047	0.040	0.042	0.047	0.042
Human toxicity, cancer effects	CTUh	1.17E-05	1.03E-05	1.17E-05	1.67E-05	1.02E-05	1.53E-05	1.67E-05	1.53E-05
Human toxicity, non-cancer effects	CTUh	2.33E-05	2.07E-05	2.32E-05	3.03E-05	2.07E-05	2.77E-05	3.02E-05	2.77E-05
Ionizing radiation E (interim)	CTUe	5.88E-05	5.08E-05	5.87E-05	6.51E-05	5.06E-05	5.71E-05	6.5E-05	5.69E-05
Ionizing radiation HH	kBq U235 eq	21.86	18.80	21.82	23.80	18.77	20.74	23.76	20.71
Land use	kg C deficit	113.53	104	77.40	198.18	67.87	188.65	162.05	152.52
Marine eutrophication	kg N eq	0.115	0.108	0.114	0.085	0.107	0.079	0.085	0.078
Mineral, fossil & renewable resource depletion	kg Sb eq	0.007	0.007	0.002	0.006	0.002	0.006	0.001	0.001
Ozone depletion	kg CFC-11 eq	3.52E-06	3.12E-06	3.5E-06	4.23E-06	3.1E-06	3.83E-06	4.21E-06	3.81E-06
Particulate matter	kg PM2.5 eq	0.067	0.064	0.067	0.042	0.063	0.039	0.042	0.038
Photochemical ozone formation	kg NMVOC eq	1.07	1.053	1.069	0.81	1.052	0.793	0.809	0.792
Terrestrial eutrophication	molc N eq	1.167	1.106	1.162	0.737	1.101	0.676	0.732	0.671
Water resource depletion	m3 water eq	5.051	0.876	5.05	4.907	0.876	0.732	4.907	0.732

Table 6 Environmental impacts for a 1 m2 of system B in each scenario

Impact category	Reference unit	F1-P1-S1	F1-P1-S2	F1-P2-S1	F2-P1-S1	F1-P2-S2	F2-P1-S2	F2-P2-S1	F2-P2-S2
Acidification	molc H+eq	0.819	0.716	0.809	0.242	0.705	0.139	0.232	0.128
Climate change	kg CO2 eq	25.15	4.17	21.77	-68.39	0.794	-89.37	-71.77	-92.75
Freshwater ecotoxicity	CTUe	2435.98	2279.75	2394.08	598.528	2237.85	442.29	556.63	400.39
Freshwater eutrophication	kg P eq	0.046	0.037	0.046	0.019	0.036	0.009	0.018	0.009
Human toxicity, cancer effects	CTUh	1.55E-05	1.75E-05	1.55E-05	5.64E-06	1.74E-05	7.57E-06	5.59E-06	7.52E-06
Human toxicity, non-cancer effects	CTUh	3.73E-05	3.26E-05	3.66E-05	1.12E-05	3.19E-05	6.44E-06	1.05E-05	5.76E-06
Ionizing radiation E (interim)	CTUe	3.5E-05	2.45E-05	3.51E-05	2.29E-05	2.45E-05	1.23E-05	2.3E-05	1.24E-05
Ionizing radiation HH	kBq U235 eq	10.918	7.499	10.955	7.512	7.535	4.092	7.549	4.129
Land use	kg C deficit	205.98	188.72	209.72	54.58	192.46	37.33	58.32	41.07
Marine eutrophication	kg N eq	0.169	0.143	0.167	0.061	0.141	0.036	0.059	0.034
Mineral, fossil & renewable resource depletion	kg Sb eq	0.014	0.014	0.013	0.0009	0.013	0.0009	0.0006	0.0006
Ozone depletion	kg CFC-11 eq	1.26E-05	1.15E-05	7.21E-06	8.13E-06	6.06E-06	6.99E-06	2.69E-06	1.55E-06
Particulate matter	kg PM2.5 eq	0.09	0.074	0.089	0.031	0.073	0.014	0.03	0.013
Photochemical ozone formation	kg NMVOC eq	0.442	0.341	0.48	0.197	0.38	0.097	0.236	0.135
Terrestrial eutrophication	molc N eq	2.04	1.845	2.016	0.499	1.821	0.304	0.475	0.28
Water resource depletion	m3 water eq	2.184	2.153	2.165	1.908	2.135	1.878	1.89	1.86

to the M1-S2-P2 combination (Fig. 3). The Pteropsida plant has about 12% fewer adverse effects and using the compost and perlite also helps improve the system's performance, although it is insignificant (0.2%).

Replacing HDPE with polypropylene in system A increases the adverse effects in the freshwater ecotoxicity impact category, indicating that polypropylene can perform better than HDPE. But the use of Perlite, compost, and sand as a soil mix and Pteropsida plant can help improve the system's environmental performance and to some extent reduces the negative effects, as visible in Fig. 4.

Referring to the results of system A in the first and fourth columns in the land use impact category, most of the unfavorable effects arise from the HDPE production process and using the peat moss, vermiculite, and sand as a soil mix in system A. Replacement of HDPE significantly increases this

negative effect (up to 75%). Still, by replacing perlite, compost, and sand, as illustrated in column third, the results are much better and the harmful effects of the potting soil are close to zero. The reason for this is the 28% contribution of peat moss production, which is practically eliminated by replacing the potting soil mix. Therefore, as can be concluded from Fig. 5, the optimal model is the M1-S2-P2 scenario.

Vermiculite is an ingredient of the S1 soil mix that was used as potting soil in system A. About 70% of the adverse effects in the mineral, fossil and renewable resource depletion category are related to the vermiculite extraction process. The environmental impacts are reduced by changing the composition of the potting soil, as shown in Fig. 6. The replacements of the modules with HDPE and plants with Pteropsida also have positive outcomes. So, the M2-S2-P2 model can achieve the most desirable results.

Fig. 2 The Climate change impact category for system A

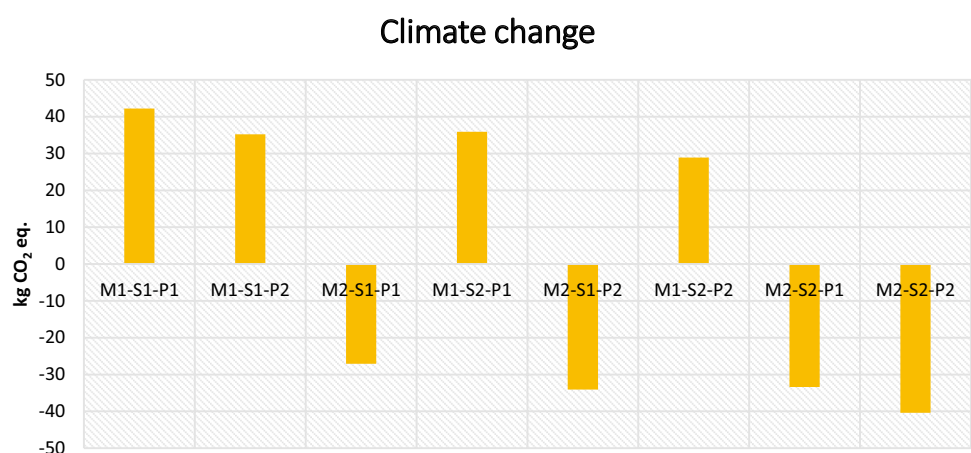
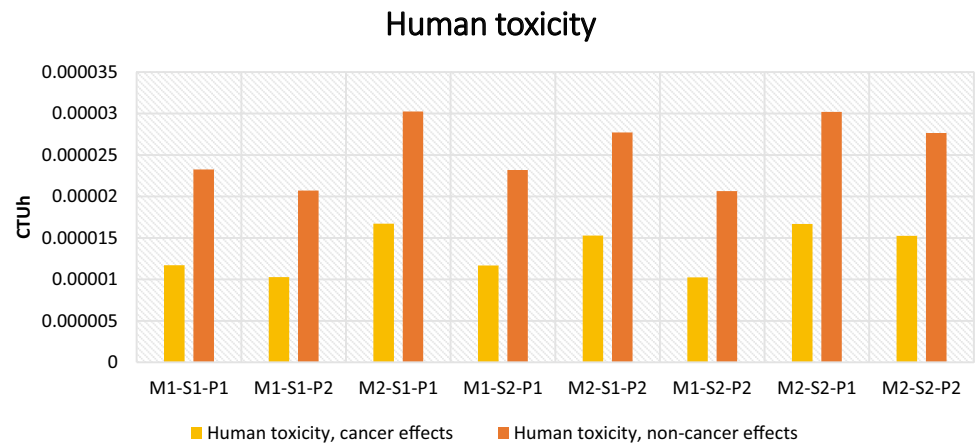


Fig. 3 The Human toxicity impact category for system A



The HDPE production process negatively affects the ozone depletion impact category more than polypropylene. Therefore, substituting HDPE does not help improve the system's environmental performance. However, changing the plant can reduce the system's water consumption, which will have an 11% positive effect on the impact category. Comparing the results shows that more positive effects can be expected in the M1-S2-P2 model.

The most influential parameter in the water resource depletion impact category is the water needed to irrigate the plant. As revealed in Fig. 7, we can significantly reduce this negative effect by changing the type of plant used in the system. In addition, HDPE production requires less water than polypropylene. The results confirm that using the proposed components in the M2-S2-P2 scenario can lead to better performance.

In system B's climate change impact category, the most positive effect is using organic fertilizers instead of inorganic fertilizers which produce approximately 93 kg less CO₂. As seen in Fig. 8, the F2-P2-S2 model has the best performance. The reason for the negative value of the climate change category in some columns is the assumption of carbon absorption by plants at a rate of 12 kg per year. Based on this, all the volume of CO₂ released during the

manufacturing process is absorbed by plants within three years, and from the third year onwards, the system acts as a CO₂ capturer.

There were different results in the human toxicity impact category. The best performance in the cancer effects category is for the organic fertilizer and HDPE panel (Fig. 9). This occurrence is mainly due to the reduction of harmful effects of inorganic fertilizers. However, in the non-cancer effects category, the F2-P2-S2 model showed better performance using organic fertilizer, HDPE panel and steel. This difference between the two impact categories is due to steel. In the cancer effects category, steel increases the adverse effects. In the non-cancer effects category, all three components, namely steel, organic fertilizers and HDPE, help reduce the environmental impact.

Seventy-seven percent of the environmental effects of the F1-P1-S1 model are in the freshwater ecotoxicity impact category due to inorganic fertilizers. The use of steel (6%) and HDPE (2%) has a reducing effect, but the reduction rate is more significant with the help of organic fertilizers (75%). In this impact category, the F1-P1-S1 scenario of system B had the worst performance and the proposed combination of the F2-P2-S2 model had the best performance (Fig. 10).

Fig. 4 The Freshwater ecotoxicity impact category for system A

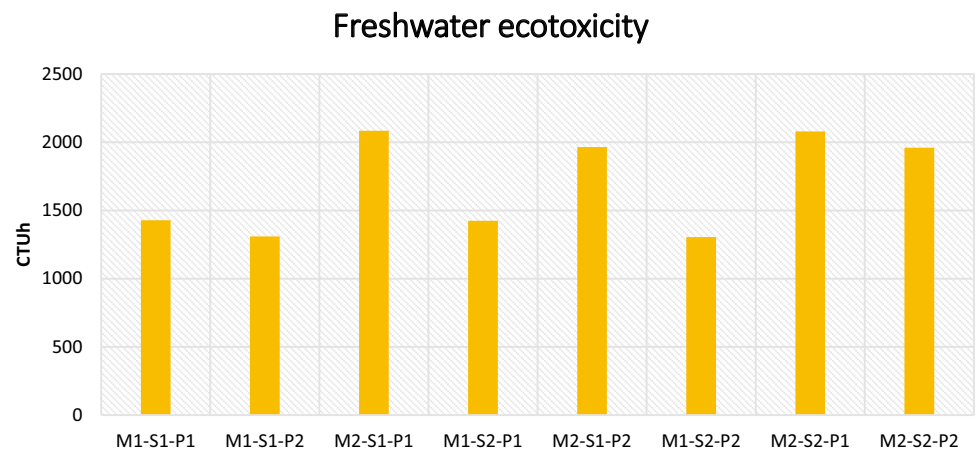


Fig. 5 The Land use impact category for system A

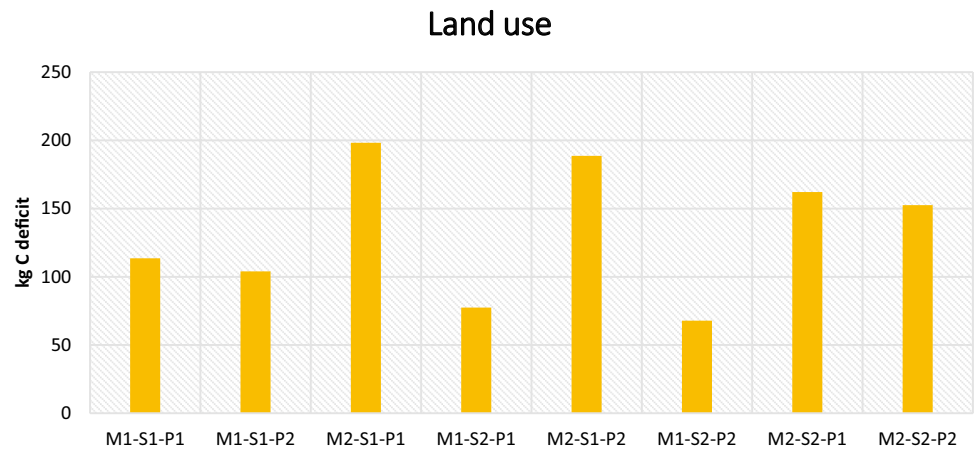


Fig. 6 The Mineral, fossil and renewable resource impact category for system A

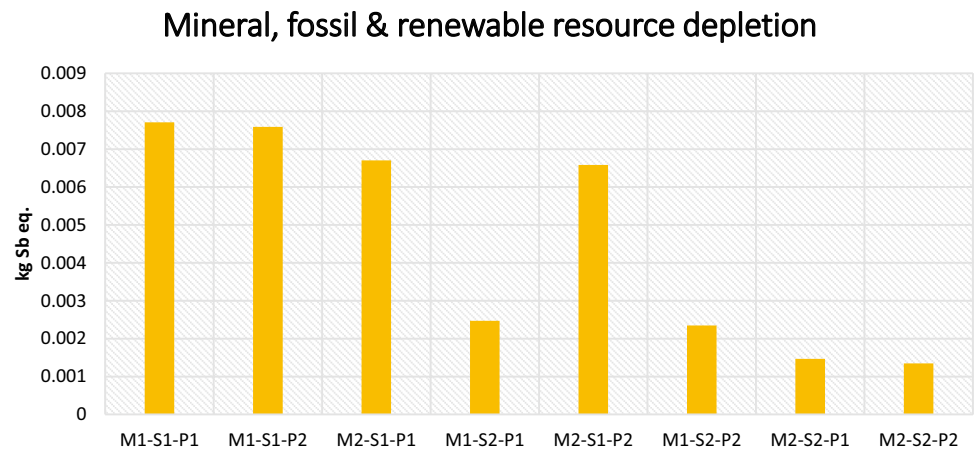


Fig. 7 The Water resource depletion impact category for system A

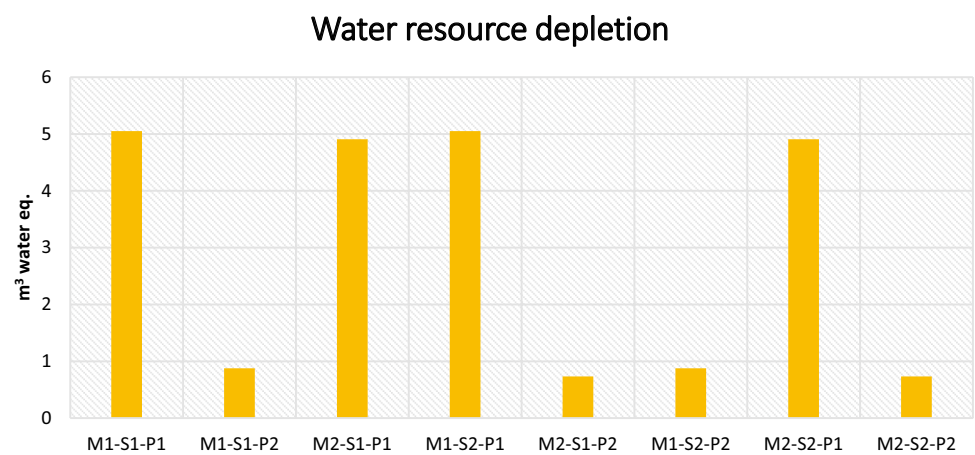


Fig. 8 The Climate change impact category for system B

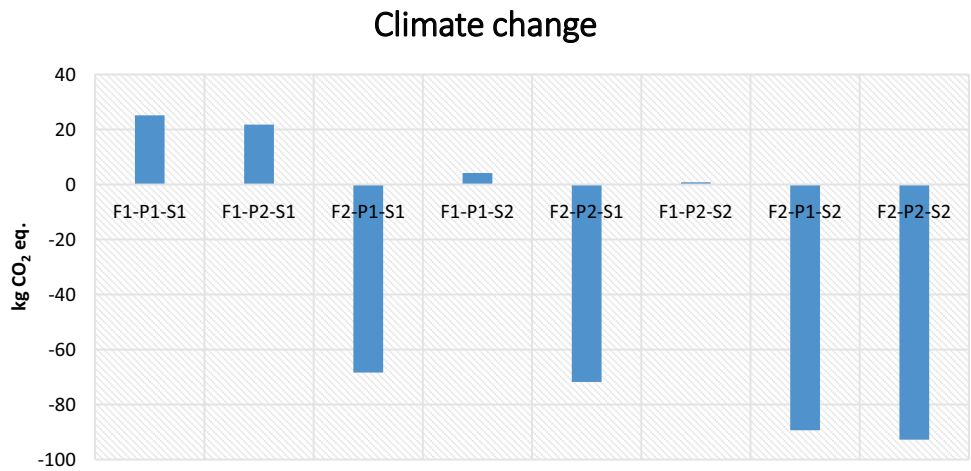


Fig. 9 The Human toxicity impact category for system B

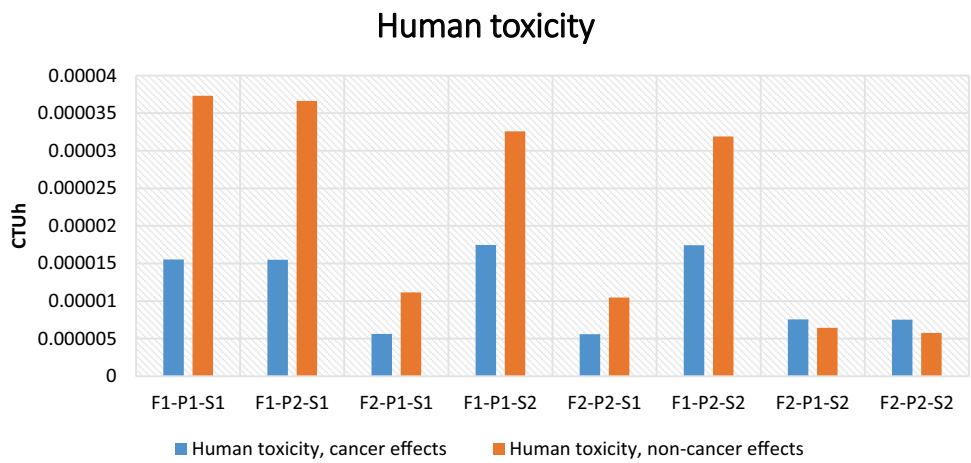


Fig. 10 The Freshwater ecotoxicity impact category for system B

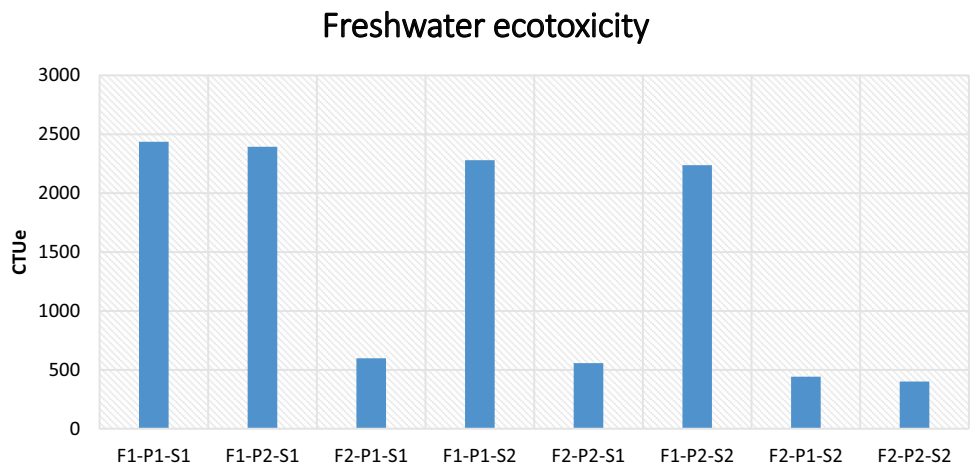


Fig. 11 The Land use impact category for system B

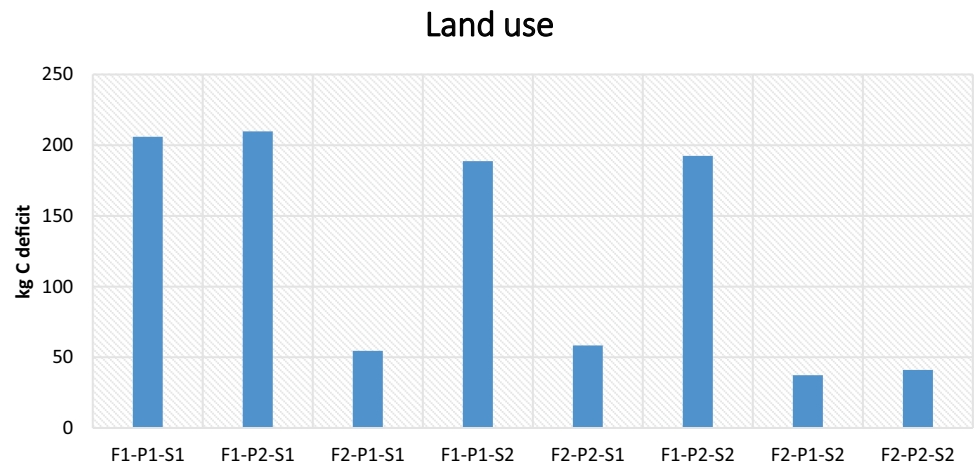


Fig. 12 The Mineral, fossil and renewable resource impact category for system B

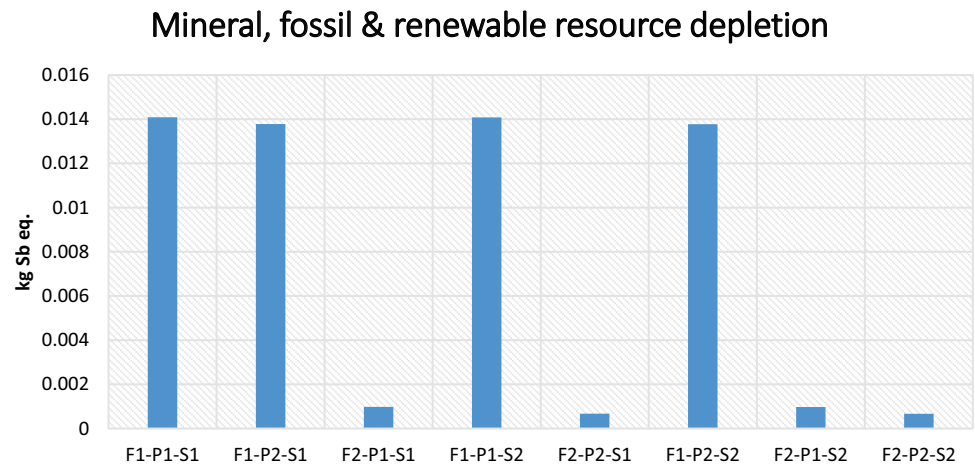
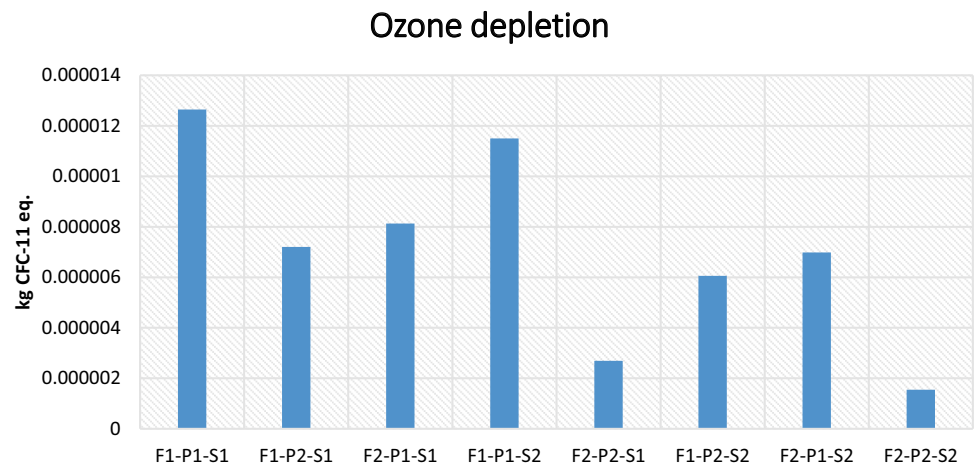


Fig. 13 The Ozone depletion impact category for system B



According to Fig. 11, applying HDPE in system B increases the unfavorable effects (approx. 2%). At the same time, using organic fertilizers drastically reduces the negative consequences by up to 73% in the land use impact category. Steel also has a reducing effect of about 8% in this category. By examining different modes, we can conclude that system B's best combination is the F2-P1-S2 scenario.

In the mineral, fossil and renewable resource impact category (Fig. 12), as visible in the third column the most positive effect is the use of organic fertilizers with a 93% improvement. Although the use of steel and HDPE with 0.03% and 2% have positive results, they are still not comparable with organic fertilizers' positive effects. In general, the impact of all proposed models, especially the F2-P2-S2 model consisting of steel, HDPE and organic fertilizers, have a better environmental performance than the F1-P1-S1 model (Fig. 12).

In the results related to the F1-P1-S1 model, 45% and 42% of the total unfavorable effects in the ozone depletion impact category were associated with PVC panels and inorganic fertilizers. The aluminum parts used in system B also had an 11% negative effect. Analyzing the results obtained from the proposed models, we find that the replacement of HDPE, organic fertilizers and steel will have the most outstanding performance improvement, respectively (Fig. 13). For this reason, the combined model with these three elements has the lowest environmental impact.

As mentioned before, most negative effects in the water resource depletion impact category are related to the water used to irrigate the plant. Since the water required in system B was reasonable, we did not have any suggestions about the change of plant type used in the system. However, the results from the proposed models show that the replacement of HDPE, steel and organic fertilizers simultaneously in system B can reduce the effects by up to 15%.

5 Conclusions

We can clearly see the significant impact of materials and components involved in each system on its environmental performance. It highlights the importance of selecting materials and maintenance methods for systems. This comparative study tried to improve systems' ecological performance by altering their initial design while keeping their functions unchanged. The alternative scenarios show that we can improve the environmental effects of systems' life cycles in all impact categories.

The integration of LCA in the design phase of these systems can significantly help improve the environmental performance of these systems and can be absolutely essential for their sustainability. Applying this method can lead to extending insights for fewer environmental effects in the

components of the system. LCA makes it possible to identify significant areas of impact and ways to correct them. For this reason, LCA can play a critical role as a decision-making tool during the design processes of these systems. However, one of the limitations of evaluating the vertical green systems' performance is the lack of sufficient data for benefits such as improved welfare and life quality, aesthetics, urban agriculture, biodiversity, etc. In addition, considering these systems' use phase, energy-saving benefits can be considered a determining factor. Energy consumption accounts for a significant share of a building's environmental impact, and saving energy with a green wall system can reduce these environmental impacts. Alternatives were selected based on components, which are commonly available on the Italian market. Due to the lack of required information, this study does not include economic considerations, and the authors suggest this aspect for future studies. By considering these aspects in future studies, a proper balance can be struck between the environmental benefits and burdens of the green wall systems.

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Data availability statements The authors declare that the data, supporting the findings of this study, are available within the article.

Declarations

Conflict of interest All authors declare that they have no conflicts of interest.

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