An Environmental Life Cycle Assessment of Living Wall Systems

Authors: *Oquendo-Di Cosola V.[a,b], Olivieri F.[a,b], Ruiz-García L.[b, c], Bacenetti J.[d].

[a]: Department of Construction and Technology in Architecture, Universidad Politécnica de Madrid. ETS Arquitectura. Avda. Juan de Herrera, 4. 28040 Madrid, Spain.

[b]: Innovation and Technology for Development Center. Universidad Politécnica de Madrid. Av. Complutense s/n, 28040. Madrid

[c]: Department of Agroforestry Engineering, Universidad Politécnica de Madrid, Av. Complutense s/n, 28040, Madrid, Spain.

[d]: Department of Environmental Science and Policy, Università degli Studi di Milano, Via Celoria 2, 20133, Milan, Italy.

Abstract: The Life-Cycle Assessment (LCA) is a standard approach for evaluating the environmental impacts of products and processes. This paper presents the LCA of Living Wall Systems (LWS), a new technology for greening the building envelope and improve sustainability. Impacts of manufacture, operation, and use of the systems selected, were evaluated through an LCA. LWS are closely related to several environmental benefits, including improved air quality, increased biodiversity, mitigation of heat island effects, and reduced energy consumption due to savings in indoor cooling and heating. Two prototypes have been selected, taking into account the modularity and the use of organic substrate as selection criteria. The systems evaluated were a plastic-based modular system and a felt-based modular system. The inventory data was gathered through the manufacturers. The LCA approach has been used to assess the impact of these solutions by focusing on the construction phase and its contribution to both the energy balance and the entire life cycle of a building. The study found that out of the two systems through the manufacturing, construction, and maintenance stage of the LCA, the felt-based LWS has an impact on almost 100% of the impact categories analyzed, while plastic-based LWS has the lowest influence on the total environmental impact.

Keywords: Living Wall Systems, Life Cycle Assessment, Sustainability, Green Walls

***Corresponding author**: Oquendo-Di Cosola V., valentina.oquendo@upm.es

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Introduction

Today, the European construction sector represents 40% of primary energy consumed from non-renewable resources, out of a total of 87% globally. In turn, the human ecological footprint has increased to 80% between 1960 and 2000 [1]. One of the most important challenges in construction is the use of raw materials, and the implications in terms of energy balance, consumption and the sustainability of the building during its useful life [2]. The reduction in energy consumption and its associated emissions is a main issue in architecture and engineering

The duality of the life cycle concept and the construction sector can be summed up in concepts such as that of “low energy building” or “NZEB” (neat zero energy buildings), which aims to achieve the reduction of the impact on the environment during the building life cycle, the minimisation of the energy and resources consumption, as well as land use [3]. An energy efficient building uses active and passive technologies to counteract transmission heat loss that affect energy consumption. The highest energy input in a building is found in the materials, known as embodied energy. Dixit et al. [4] define the embodied energy like the energy sequestered in buildings and building materials during the entire life cycle. The construction sector has one of the most important environmental impacts on cities, and to face its consequences and reduce energy consumptions is necessary to promote solutions with an efficient performance during its entire lifecycle.

New technologies and building construction processes are being developed in order to improve the sustainability and efficiency of building envelops. Research has been carried out to develop new adaptable and intelligent facades that highlight their thermal behaviour and adaptability to different climatic contexts [5], within these, the vegetable façades are particularly noteworthy.

Greening the building envelope provides benefits related to improved efficiency, a contribution to the immediate context through temperature regulation and reduced wind speed, as well as increased biodiversity in dense urban environments [6]. Living wall systems (LWS) as part of vertical green solutions can improve the quality of urban living and reduce the global environmental impact caused by climate change [7]. The use of plants on buildings creating green facades have aesthetical and environmental benefits [8]; improve the air quality by reducing the air pollution [9,10] reduce fine dust levels in the air [11]; increase biodiversity [6]; reduce the heat island effect in cities [12,13], and reduce the energy consumption for indoor cooling and heating [14,15]. Some of the aspects that influence the performance of a LWS are the density of the foliage, the humidity of the substrate and the air chamber between some layers, as well as the properties of the materials used [16].

The following studies investigated the ability of green facades and living wall systems to reduce energy consumptions by intercepting solar radiation. A study carried out by C.Y Jim. et al., [21] [17] studied the thermodynamic transmission process of the vertical vegetation ecosystem, monitoring solar radiation and climatic conditions, and simulating heat flow and temperature variations. Their results show that seasonal heat flows in the green wall will vary with fluctuating meteorological driving forces, protecting the vegetation efficiency of the green wall that absorbs radiant energy and prevents it from reaching the building surface. Coma J. et al. [18], studied the behaviour of vegetal facades in a Continental Mediterranean climate during the summer. The results show the capacity of vegetation to reduce the surface temperature of the exterior façade by up to 14ºC, and the effect of shade on the reduction of the internal temperature by up to 1ºC. Manso M. et al. [19], studied a modular system of vegetal façade called Geogreen, through the analysis of local climatic conditions in three different periods. The experiment was carried out based on two measurements, one on a reference wall and one on a wall covered with vegetation modules. Results proved the capacity of vegetation to reduce maximum temperatures and increase minimum temperatures. Specifically, the studied system has demonstrated the ability to mitigate heat transfer up to a maximum of 75% input heat, and 60% quality heat, improving thermal insulation. Nadia S. et al., [20] studied the influence of green walls on the thermal behaviour of buildings in semi-arid regions during the summer period. Outcomes showed that vegetation coverage optimises indoor temperature and reduces heat exchange through the wall structure, characterized by reduced temperature and increased relative humidity. Perez G. et al., [21] through research determined that the surface temperature of a building wall in a shaded area was on average 5.5ºC higher than in areas partially covered by vegetation. This difference was greatest during the summer, reaching an average temperature of 15.2ºC on the southwest side in September. Olivieri F. et al., [22] carried out an evaluation of the thermal behaviour of a modular plant façade on drainage cells, and the results indicated that the performance of this pre-vegetated façade was better than a solar protection system, since it reduced overheating by 33% in the cooling system compared to other ventilated façade solutions. Mazzali U. et al., [23] tested three LWS to investigate the potential effects of energy behaviour on building envelopes under different climatic conditions in Mediterranean contexts. Their results showed similar behaviour in similar climatic conditions. During sunny days the differences in air temperature of the vegetal wall were from a minimum of 12ºC to a maximum of 20ºC, and during cloudy days the differences are reduced to 1ºC-2ºC. From these studies, the capabilities of LWS as a technology to improve the performance and thermal insulation of buildings are evident. Therefore, it can be said that these systems have the capacity to limit the heat fluxes is the same in all the vertical greening systems. The differences on the performance might be by the presence of factors like the foliage index, the moisture content, vegetation type and materials involved.

Life Cycle Assessment (LCA) is one of many tools for assessing environmental issues. It is defined by ISO 14040 as: *"A technique for assessing the environmental aspects and potential impacts associated with a product, by compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases"* [24]. The LCA approach has been used in the construction sector since the 1990s [25], and its popularity is due to the compilation of all material-related data and its environmental impact. It is a tool to promote sustainable design and construction. Jeswani et al. [26], identified LCA like a systematic and robust tool for quantifying potential environmental burdens and impacts of a process or product selection, and also for improving design and optimization. When a building LCA is carried out, only the building itself is studied, and the outcome is an assessment of the entire building process. In case the LCA concerns a part of the building, such as a component or building material, the results might be called *"building material and component combination"* (BMCC) [27].

According to the ISO standards, 14040/44 (ISO, 2006) [28] "a Life Cycle Assessment is carried out in four distinct and interdependent phases:

- Goal and scope include functional unit selection and system boundary definition;

- Life cycle inventory involves the definition of energy and material flows between the systems and the environment and through the different subsystems and operations of the evaluated systems;
- Impact assessment, during which the inventory data are converted into environmental indicators, discussion and interpretation of the results, the results from the inventory analysis and impact assessment are summarized, sensitivity and uncertainty analysis are carried out and recommendations are given".

Many researchers have made LCA studies calculating the environmental impacts of some construction materials to determine guidelines for the improvement of the building's performance. Asif et al. [29], carried out a study of CO_2 emissions from eight different building materials, including wood, concrete, aluminium, slate, glass, ceramics, and plasterboard. From the study, it was concluded that the material with the highest emissions and energy incorporated was concrete with 61%; Broun et al. [30], studied three types of partition walls from a life-cycle approach: clay bricks, hollow concrete blocks, and a traditional wooden structure. The results showed that the most relevant material is brick both in terms of energy consumption and environmental impacts related to the life cycle. Kosareo et al. [31], conducted a LCA of intensive and extensive green roofs through a comparison with conventional solutions. The results obtained demonstrated the energy benefits provided by vegetation due to the lower thermal conductivity of the substrate. Altan et al. [32], conducted the LCA of five different types of green wall systems in the UK, researching the environmental impacts and benefits associated with all phases of the life cycle. The results evidenced the lower impact of continuous unsupported solutions due to the lower maintenance and reuse of their components.

Faced with this series of studies and proven benefits, in recent years numerous LWS solutions have been launched on the market, among which the modular ones stand out. However, most of the studies developed have to do with the performance during the use phase, without taking into account the emissions and energy incorporated from manufacturing to disassembly. Living Wall Systems can be assessed through LCA to study environmental impacts related to the entire lifecycle. These results could be a useful support tool for researchers and manufacturers in sustainable design [33]. Particularly, the building sector, LCA helps to evaluate the important aspects related to embodied energy, embodied carbon and consumption energy of the materials and greenhouse gases emissions [34].

Objective

The aim of this study is to evaluate the energy and environmental life cycle of two living wall systems using different materials, types of assembly, and components. The purpose is to quantify the impacts and benefits associated with the manufacture, construction, and maintenance of a plastic and a geotextile based LWS.

A comparison of the results will also be carried out to obtain guidelines that will lead to improving the environmental sustainability of the systems during their useful life. With the final purpose of promoting design with less environmental impact and more environmentally sustainable constructions. This study will help architects, ecologists, and engineers to find new nature-based solutions to address the consequences of climate change from the construction sector.

Materials and methods

Functional unit

According to ISO 14040 [35], the functional unit is the measurement value for quantifying the results in an LCA. In this study, emissions, energy consumption, and materials are based on $1m^2$ of LWS. The results of this analysis are calculated as the total environmental impact over the lifetime, excluding the decommissioning phase. With this data, we can choose between options and select the one that is compatible with the environment. The results show the total environmental impact throughout the useful life of each system. Also, these results allow the identification of improvements compatible with the concept of sustainability and environmental awareness.

System boundaries

The system boundary comprises the manufacture of the system components, construction and maintenance (fig.2).

Manufacturing and construction cover the resources and process for producing the materials for the system components. The construction phase comprises all electricity consumption per square meter of LWS. The maintenance phase comprises the water consumption of the two LWSs, based on both system requirements and fertilization. Finally, all activities related to the use and disposal phases are excluded.

The study of the aspects that potentially affect the environment has been based on 10 years of useful life. The data that has been supplied by the manufacturers. It is assumed that the useful life of both LWS is 10 years, as well as that of all materials.

The replacement frequencies of plants for the LWS made in plastic are 10% replacement per year, and 20% replacement per year for the system made with felt layers.

The LWS need a nutrient solution if has a non-organic substrate, which is considered only for the system made with felt layers. The water consumption for the plastic-based LWS is assumed to be 8 l/day and for the felt-based LWS on 2 l/day. Irrigation systems are not considered.

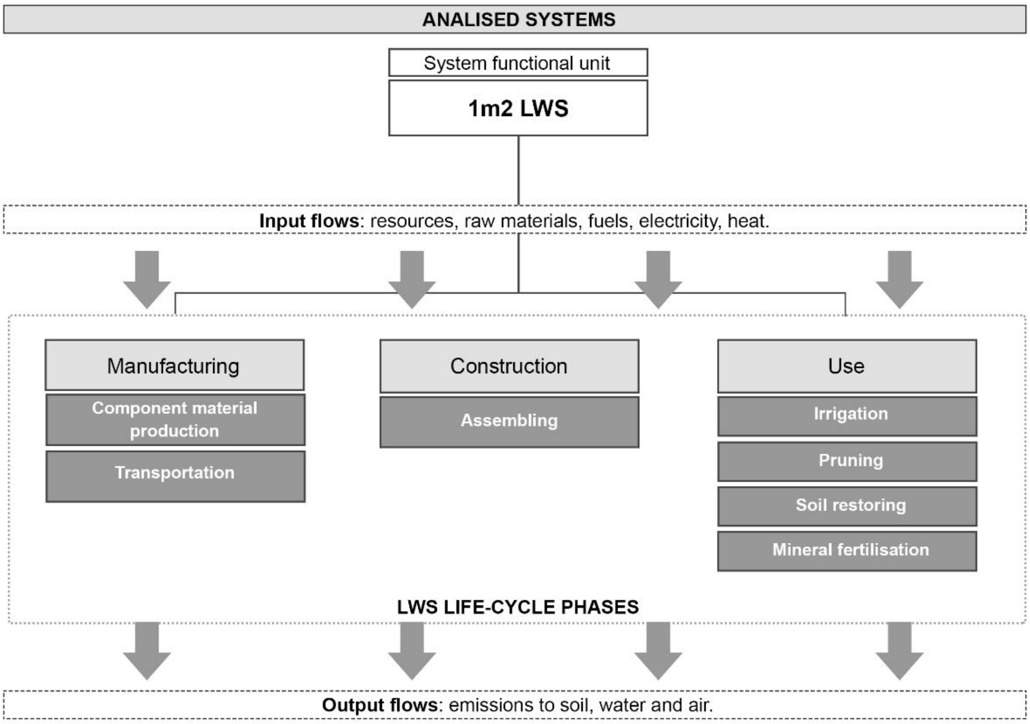


Fig.2: Boundaries of the analyzed systems

Manufacturing stage

The production phase focuses on analyzing the materials used to manufacture each of the systems. This helps to understand the energy content of the materials and the carbon emissions of the materials itself. The data was collected from the Ecoinvent Database v.3.5 [36].

During manufacturing, two methods were considered for the construction of the systems. In the case of the LWS made with felt layers it is built by hand, which may require 1 to 2 people to assembly. Thus, it is not necessary to use heavy machinery to assemble these systems. In the case of LWS made of plastic, specialized machinery is required for their assembly, and it has an electrical energy consumption of 0.044kWh for the production of panels and 0.8Wh for the production of anchoring systems.

Construction stage

In this phase, the assembly of each system and its materials, the mode of transport and the distance traveled are analyzed, as well as the CO_2 emissions resulting from the transport of these materials. These factors have been important in obtaining the total environmental impact of each material during its life cycle. Each phase is calculated using SimaPro 8.5.

Maintenance stage

The maintenance phase studies the life cycle burden of the two systems attributed to water consumption, considering the number of times the systems need to be irrigated. This phase helps to obtain data on the system with the greatest impact due to resource consumption. Water consumption is an important factor that should be considered as it provides important insights into the water input needed to keep systems operating throughout the useful life. In this case, the plastic-based LWS has the highest water consumption (8 liters/m^2 per day), while the one in the felt-based LWS is lower (2 liters/m^2 per day).

Life Cycle Inventory

Description of the studied LWS

Living Wall Systems (LWS), are often built from modular panels, in which the substrate can be organic, from natural compounds such as hummus, or hydroponics, with an artificial culture media such as foam, felt, perlite or mineral wool, i.e., that uses nutrient solutions for fertilizing the plants [32]. Figure 1 shows the difference between a LWS made with felt layers (a), and LWS made with planter boxes (b).

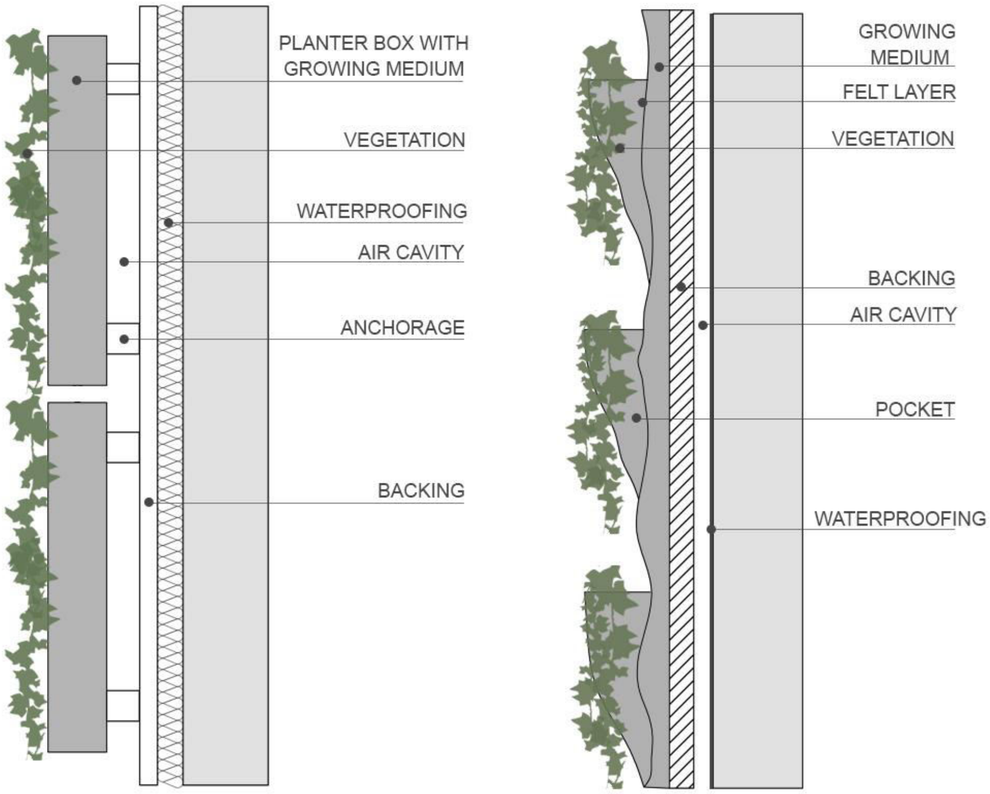


Fig.1: (a) Living wall system based on planter boxes; (b) Living wall system made with felt layers

The characteristics of the two types of living wall systems used in this study are:

- *The felt modular system, a type of modular system that uses plants, which can be pre-grown and inserted into gaps.. The system was produced by a Spanish company, whose objective is to design and manufacture sustainable solutions to create horizontal and vertical green spaces in urban environments. Its design was developed in the field of air purification, to allow the growth of roots in contact with the air, favoring* *biofiltration. Thus, the main objective is to decontaminate the air through the rhizosphere of plants.*

- *The modular system in boxes is a vertical system formed by plastic modules. These panels provide the rigidity and impermeability of the entire system. Vegetation can be inserted before or after installation. This system requires an irrigation system and can be automated.*

  This project has been carried out by a multidisciplinary group of Italian researchers in collaboration with small companies with experience in prefabricated modular construction, waste recycling, and textiles. The modules were designed, prototyped, and implemented through an environmental approach based on the use of recycled materials, high environmental performance, thermal, acoustic, and agronomic.

Through an inventory analysis, the two LWSs have been analysed. The data about the materials used in each system were collected from manufacturers and suppliers. A complete LCA includes five different stages: manufacturing, construction, use, maintenance, and end of life. In this study, only three phases have been considered: manufacturing, construction, and maintenance.

The use phase has been excluded. It is assumed that the capacities of these systems in terms of thermal insulation and temperature reduction are the same in all systems in which plants and substrates are present, with some differences that are not relevant. This statement is supported by Nyuk Hien Wong et al. [37], who studied 8 different vertical vegetation systems to evaluate their thermal impacts on system performance. Their results demonstrated the same thermal benefits in all system. These benefits minimize the demand for cooling and heating, and energy costs in buildings.

Inventory data collection

The data and details of each system were gathered by the use of Ecoinvent Database v 3.5 [36], and also provided by the manufacturers. For this LCA, all the components of the two living wall systems selected were examined. The differences between the two systems came from the materials used and the way they are assembled. In the case of the LWS made of plastic, the system has only one three-dimensional structure for the plants and another that serves as an air chamber. The second LWS is made with felts, which involve several layers to root, waterproof, and support.

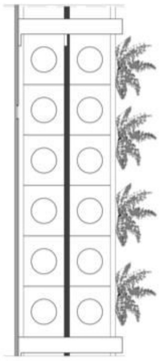
The data used for this inventory was collected from material data sheets and information obtained directly from manufacturers.

All elaboration phases play important roles in LCA studies but, the inventory analysis is considered the most important [33]**.** The final product has been studied to calculate the impacts related to its materials and processes. In this work, an inventory analysis was carried out by obtaining information on the production, construction and maintenance of the systems.

LWS is used as an external surface of buildings that provides a thermal insulation benefit that impacts on interior well-being. Modular LWSs are often made using a frame and a series of layers that act as a climatic barrier to insulate the interior and exterior of the building. The difference between the proportions of materials that impact the environmental load of the two systems comes from the layers involved (Fig.3).

In the case of the plastic modular system, the layers consist of a box made of that material which can be HDPE (High-Density Polyethylene), polypropylene and other recycled plastics, filled with potting soil. In the case of the modular felt system, it has several layers to root, waterproof, and support the substrate and plants.

Living Wall 1: plastic planter box



Material	Thickness
Aluminum anchorage	0.2cm
Polyester fiber layer	0.2cm
Polypropylene box	5cm
Polyester fiber layer	0.2cm
Polypropylene box (with the growing medium)	5cm
Polyester fiber layer	0.2cm
Total thickness	10,8cm

Living Wall 2: felt layer system

Material	Thickness
Alveolar polycarbonate in Lexan resin	0.6cm
Growing medium	3.6cm
Polypropylene monofilament geomat-grid	3.6cm
Non-woven viscose fabrics layer	0.1cm
Aluminum alloy	0.2cm
Non-woven geotextile layer with a superficial polypropylene fiber layer	0.4cm
Total thickness	3.6cm

Fig.3: Main components and thickness of the living wall systems studied

All the transportation distances used are to and from Madrid. For the LWS the majority of the materials are local; plants and substrate come from an area 40km away from Madrid. The materials used in the LWS studied are an aluminum alloy, polypropylene monofilament, polypropylene fiber, growing medium, vegetal species biomass, felts and polyester. As for fertilizers, the following have been considered in the analysis 0.73 kg Nitrogen (N), 0.73 diphosphorus pentoxide (P_2O_5), and 0.73 potassium oxide K_2O.

The materials analyzed in each LWS are shown in tables 1 and 2. The raw materials, manufacturing energy use, and emissions associated with each of these materials were obtained from processes in the Ecoinvent Database v 3.5 [36].

Components	Material	Mass (kg)	Distances (Km)	Service life (years)
External finishing layer	Polyester	0.25	50	10
Bearing structure	Polypropylene boxes	1.34	80	10
Hydrophilic layer	Polyester	0.25	50	10
Growing medium	Coconut fibre, turf and hummus	4	40	10
Closing layer	Polyester	0.25	50	10
Hooking system	Aluminium	0.6	10	10
Vegetation layer	*Hedera spp* stems biomass	1.50	40	10

Components	Material	Mass (kg)	Distance (Km)	Service life (years)
External finishing layer	Polypropylene fibre and non-woven geotextile	0.53	80	10
Bearing structure	Aluminium alloy	3.9	10	10
Hydrophilic layer	Non-woven viscose fabrics	1.15	50	10
Growing medium	Polypropylene monofilament geomat-	2	50	10

Table 1: Analysis of the components of the Living Wall System made with plastic planter boxes

containment layer	grid			
Growing medium	50% of raw soil; 30% of SAP; 15% of coco-coir; 5% of peat moss.	2.1	40	10
Closing layer	Alveolar polycarbonate in Lexan resin	2	50	10
Vegetation layer	Lonicera n. stems biomass	1.66	40	10

Table 2: Analysis of the components of the Living Wall System made with felt layers mass

Life Cycle Impact Assessment

The following impact categories were evaluated using the ILCD (International Reference Life Cycle Data System) midpoint method [38], the LCIA method endorsed by the European Commission:

- Climate Change (CC, expressed as kg CO_2 eq);
- Ozone Depletion (OD, expressed as kg CFC-11 eq.);
- Particulate Matter Formation (PM, expressed as kg PM2.5 eq.);
- Human Toxicity-No Cancer Effect (HTnoc, expressed as CTUh);
- Human Toxicity-Cancer Effect (HTC, expressed as CTUh);
- Photochemical Ozone Formation (POF, expressed as kg NMVOC eq.);
- Terrestrial Acidification (TA, expressed as molc H+ eq.);
- Terrestrial Eutrophication (TE, expressed as molc N eq.);
- Freshwater Eutrophication (FE, expressed as kg P eq.);
- Marine Eutrophication (ME, expressed as kg N eq.);
- Freshwater Ecotoxicity (FEx, expressed as CTUe);
- Land Use (LU, expressed as kg C deficit);
- Water resource depletion (WU, expressed as m^3 water eq.);
- Mineral and Fossil Resource Depletion (MFRD, expressed as kg Sb eq.)

Results and discussion

Environmental impact of the LWS

The results show that in every impact category evaluated, the plastic-based LWS is the one with the lowest environmental impact. The results show the highest impact of the systems in the manufacturing phase (Tables 4 and 5), and the use phase is the second with the highest impact.

Table 3 shows the environmental impacts for the LWS made with plastic. The results compare each phase studied concerning the impact categories, and agree with the previous works [37], where the LWS based on plastic boxes has no major environmental impact. The phase that affects in a non-proportional way in the impact categories is the manufacturing phase.

In the manufacturing phase all impact categories influence in almost the same way, excluding water resource depletion, which represents only 0.80% while the rest of the categories influence 99% during the manufacturing process. The construction phase has a low influence during the study, with an average of 0.2% in all categories. The primary impact category for the use phase is water resource depletion, which represents 99.17% of the total, while the other categories have not an impact. The phase with the highest impact is the manufacturing phase, which is focused on analyzing the materials used for making the system. This explains the environmental impact contribution of the used materials.

Impact category	Unit of measure	Manufacturing	Construction	Maintenance
Climate change	kg CO_2 eq	99.73%	0.26%	0.00%
Ozone depletion	kg CFC-11 eq	99.83%	0.16%	0.00%
Human toxicity, non-cancer effects	CTUh	99.99%	0.01%	0.00%
Human toxicity, cancer effects	CTUh	99.99%	0.01%	0.00%
Particulate matter	kg PM2.5 eq	99.87%	0.13%	0.00%
Photochemical ozone formation	kg NMVOC eq	99.86%	0.13%	0.00%
Acidification	molc H+ eq	99.76%	0.24%	0.00%
Terrestrial eutrophication	molc N eq	99.81%	0.19%	0.00%
Freshwater eutrophication	kg P eq	99.99%	0.00%	0.00%
Marine eutrophication	kg N eq	99.83%	0.17%	0.00%
Freshwater ecotoxicity	CTUe	99.99%	0.06%	0.00%
Land use	kg C deficit	97.13%	0.09%	0.00%
Water resource depletion	m3 water eq	0.80%	0.03%	99.17%
Mineral, fossil & ren resource depletion	kg Sb eq	99.99%	0.01%	0.00%

Table 3: Environmental impacts for $1m^2$ of the plastic-based LWS

Table 4 shows the environmental impacts for the system based on felts for the three phases considered. It is important to denote that the results, in this case, do not include any data related to the use of electrical energy for the construction of the system since it is done manually. The results are particularly higher to the system made in plastic. The impact generated by the system is concentrated in the manufacturing and use phase, in which it varies considerably according to the impact category.

Impact category	Unit of measure	Manufacturing	Construction	Maintenance
Climate change	kg CO_2 eq	20.74%	0.00%	79.26%
Ozone depletion	kg CFC-11 eq	26.73%	0.00%	73.26%
Human toxicity, non-cancer effects	CTUh	44.60%	0.00%	55.40%
Human toxicity, cancer effects	CTUh	48.06%	0.00%	51.94%
Particulate matter	kg PM2.5 eq	35.14%	0.00%	64.86%
Photochemical ozone formation	kg NMVOC eq	35.27%	0.00%	64.72%
Acidification	molc H+ eq	23.46%	0.00%	76.53%
Terrestrial eutrophication	molc N eq	13.99%	0.00%	86.00%
Freshwater eutrophication	kg P eq	35.90%	0.00%	64.09%
Marine eutrophication	kg N eq	16.68%	0.00%	83.32%
Freshwater ecotoxicity	CTUe	60.04%	0.00%	39.95%
Land use	kg C deficit	5.20%	0.00%	94.79%
Water resource depletion	m3 water eq	4.31%	0.00%	95.69%
Mineral, fossil & ren resource depletion	kg Sb eq	92.52%	0.00%	7.48%

Table 4: Environmental impacts for a 1m^2 of the felt-based LWS

During the production phase, related to the use of materials, the greatest impact is given by mineral, fossil and renewable resource depletion with 92.52%, followed by freshwater ecotoxicity 60.04% and human toxicity cancer effects 48.06%. On the contrary, during the use phase, the categories with greater impact were water resource depletion 95,69%, land use 94,79% and Ionizing radiation 90,33%. The rest of categories have an impact proportional to the previously mentioned. These results reveal the environmental impact that this system has related to the materials used and during the useful life considered as 10 years.

For both systems, the LCA shows that the highest environmental impacts are associated with the manufacturing and use phase, that accounts for more than 80% of the total environmental impact in almost all the categories analysed. It is particularly elevated for water resource depletion, land use, and mineral, fossil and renewable resource depletion. For these categories, the manufacturing phase accounts for 90-95% of the total environmental impacts.

The main difference between the two LWS is mainly due to the materials involved in the anchorage and supporting systems. Figure 4 and 5 show the influence of the materials for the anchorage and supporting systems on the evaluated impact categories. Because of this, the

LWS plastic-based has the lowest environmental impact. In the case of the living wall system made with felt layers, the fertilization has an impact of 99.17% on water resource depletion, due to the necessity of doing annual chemical fertilizing.

For the impact categories related to toxicity and depletion of water resources, the plastic-based early warning system has a double impact than the felt-based early warning system (Fig.4). The results showed the environmental impact of two materials, mainly polypropylene and aluminium layers. In this case, a solution could be to avoid the use of aluminum or to use recycled aluminum, since the environmental impact can be reduced.

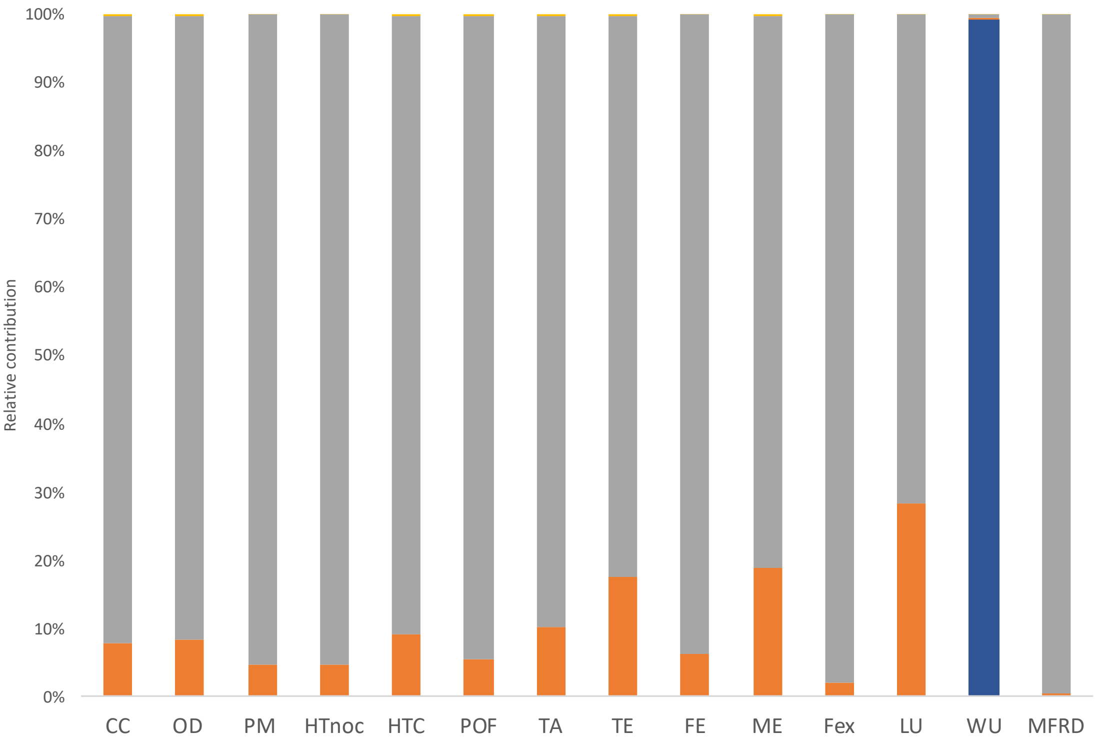


Fig.4: Environmental hotspots for the plastic-based LWS

The peat mixture used in the substrate has an impact on the category of water resource depletion, this is because peat is the result of the accumulation of dead organic matter from leaves, stems, and roots partially decomposed from different mosses and plants that have been concentrated in a water-saturated environment in the absence of oxygen.

The plastic-based LWS is a lightweight one due to the reduced number of materials, which means less energy consumption and less environmental impact. Thus, it could be used as a building element in buildings, in order to reduce energy consumption and energy incorporation.

Unlike this, the living wall system made with felt layers have the highest environmental impact in almost all the categories. This is due to the environmental impact coming from the use of aluminium for supporting the system and the use of fertilizers during the use phase of the system. Ottelé et al., [8] have investigated the environmental impact of four materials commonly used for the vertical support of living walls systems. Results show that aluminium can be up to 10 times more polluting than other materials such as plastics, wood and coated steel.

Both materials mentioned lead to increment the environmental burden profile. Furthermore, from figure 5, it can be seen that the LWS felt-based is the one without impacts in the construction phase because there are not electric energy consumptions associated. In this case, the highest environmental impacts in the use phase are due to the use of nitrogen fertilizer.

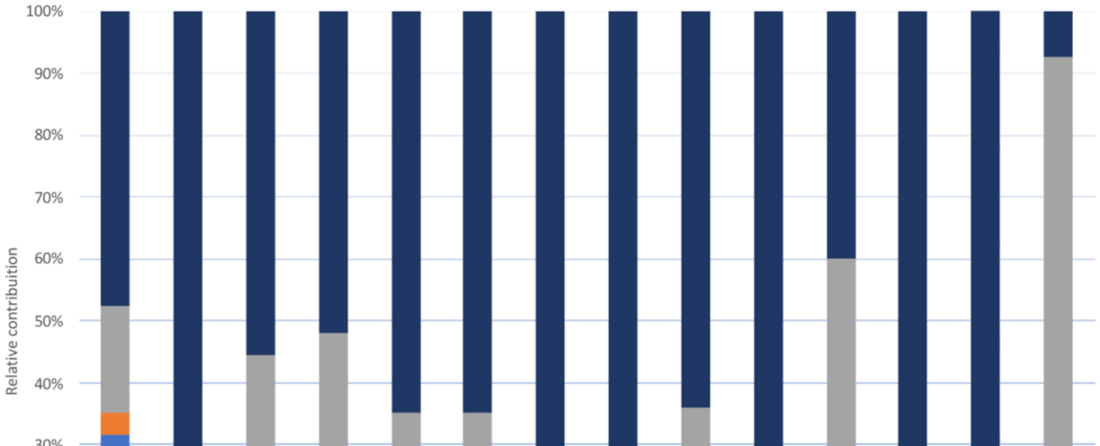


Fig. 5: Environmental hotspots for the felt-based LWS

The results obtained show the impact of the systems due to the materials used. This impact could be reduced by a sustainable choice of materials. Specifically, the profile with the highest impact is the LWS made with felt layers, due to the support system around 40% and the fertilizers around 50% of the total impact.

In general, both systems can reduce impact by selecting a more sustainable material for the support structure and other components such as the type of substrate and fertilization. In both cases, reductions can be achieved with small changes. The impact categories analysed show similar results, with some notable differences due mainly to the use of materials such as aluminium and fertilization. For instance, for felt-based LWS, the most impactful categories are freshwater eco-toxicity, land use and climate change, as the substrate needs to be fertilized ten times in a 10-year lifespan. For the mineral, fossil and renewable resource depletion, both LWS have a high impact. The same trend is perceptible for the freshwater eco-toxicity.

The relative comparison between the two systems studied is reported in **Fig.6.** For each evaluated impact category, the LWS with the greatest impact is set equal to 100% while the second one is proportionally called. LWS made with felt layers demonstrates the greatest environmental burden for all impact categories assessed, except for the depletion of water resources. This is consistent with the study of Ottelè et al., [8], which conducted a life cycle analysis comparing conventional brick solutions with continuous and modular plant facades, including systems made of plastic and felt. Great differences were found in the impact categories studied for each alternative plant façade. In that case, the results were influenced by the type of material used for each system.

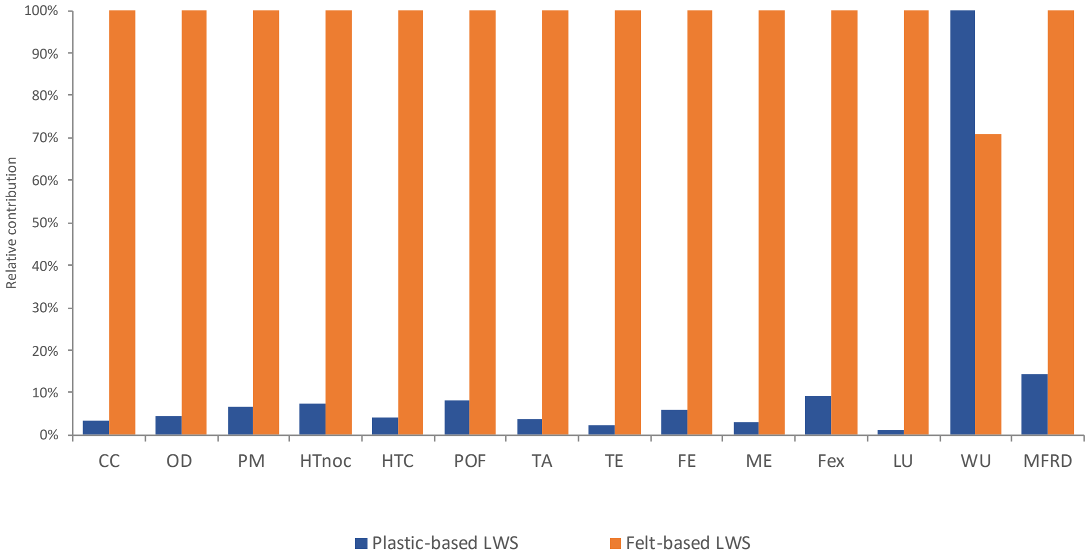


Fig.6: Comparison between the two LWS

Among the evaluated impact categories, water resource depletion is the only one for which the LWS made by plastic shows a higher impact, this is linked to the irrigation needs of the system. For the other categories, it is clear that the LWS based on felts is the one with the highest environmental impact due to the composition of the materials used and the fertilization. However, despite their environmental impact, the two LWS can counteract them through its reduction in energy consumption and temperatures.

Other authors [8,32,39] have reached similar results considering the entire life cycle of the systems and studying vegetable façade systems different from ours. It has been demonstrated that, even if we do not consider the whole life cycle and exclude some phases, the results agree that the performance of the systems is the same whenever there is the presence of substrate and vegetation. Thus, the environmental impact will depend on the materials used for construction, and the substances used during maintenance according to the type of substrate. Besides, they argue that from the results of the LCA, it is possible to make improvements in the systems, which in some cases mean that the benefit is twice as great as the impact they can generate. This benefit is related to the temperature reduction potential.

Life Cycle Impact Assessment

This section aims to weight the results of the entire analysis. The most impacting phases are shown for each category in Figure 7. The data represents the impact caused for 1m^2 of LWS.

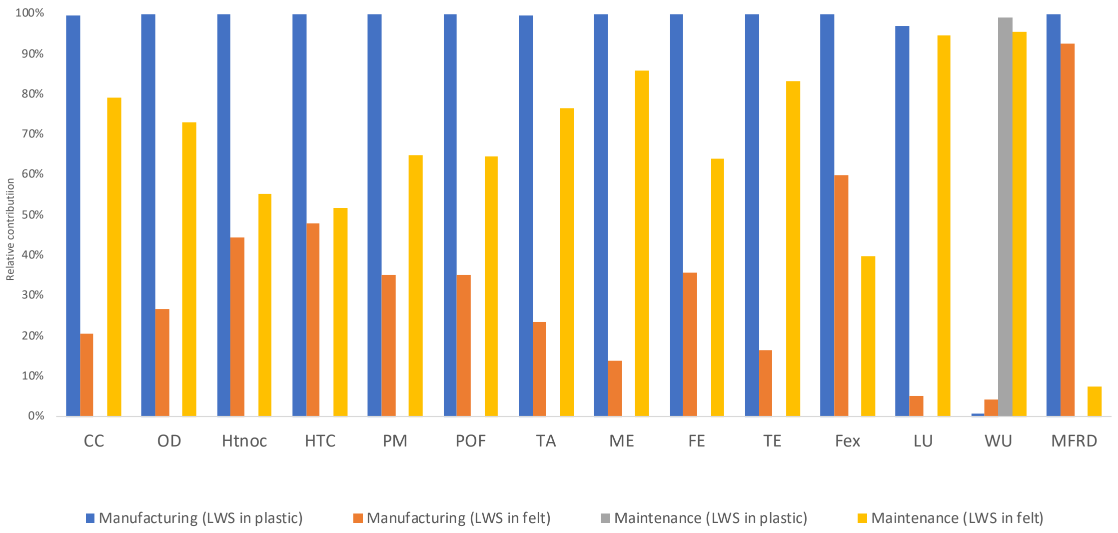


Fig.7: Impact categories per LWS studied. A comparison based upon LCA results.

The phase with the greatest weight in the process is the manufacturing phase, linked to the materials and assembly processes. The results were analyzed by comparing the systems. The impact of LWS made of plastic during manufacturing is notable due to the electricity consumption and the use of aluminum for the anchoring system. In the case of the climate change impact category, the difference is almost 80%. While the felt-based LWS has its 100% during the maintenance phase, due to the fertilizers used during its life cycle.

Limitations and future perspectives

In this study, it is assumed that the two living wall systems have the same thermal and environmental performances and the behavior of a plant façades during their life cycle is out of the system boundaries of this LCA study. On the one hand, as there are no monitoring data for the systems studied, there is no possibility of verifying their performance. In the same line of ideas, today there are no tools in which it is possible to simulate the reduction of energy consumption and temperatures to obtain a value. Also, the benefits of plant façades go far beyond the effect of thermal insulation; fundamental effects such as evapotranspiration, shade, acoustic insulation and the fixation of dust particles would be out of the study.

This study analyzed the living wall life cycle impact only in the phase of manufacturing, construction, and maintenance, to identify how the selection of materials affects, which is associated with an important series of environmental benefits.

Unlike other studies [8,31,32,40] in which these technologies and their materials are studied to identify how they affect their energy performance. These parameters should be explored in future comprehensive studies. However, even if the use phase is not included in the system boundary the achieved results can be useful. In fact, the study, quantifying the environmental impact and identifying the environmental hotspots (i.e., the process mainly responsible of the environmental impact) of the two LWS, is the starting point for a subsequent optimization.

Conclusions

This study helps designers and technology developers to understand the potential and the environmental concerns associated to LWS. Also, it is a starting point for identifying the best option on the market by understanding the impacts of the various lifecycle phases through the LCA approach.

The materials used to build an LWS have a significant environmental impact when installed in a building. From the incorporated and operational energy of a building, the role of the materials is fundamental, as it can be reduced depending on the proper selection of the materials.

Life cycle analysis of living wall systems considers several aspects, including integration into the building envelope, the selection of materials with low environmental impact and the consideration of other impacts, which can contribute to the correct decision when incorporating it as a sustainable technical solution.

The results of the LCA performed highlight the environmental impact of two LWS: a modular system made with solid plastic boxes and pre-cultivated vegetation inserted in cavities, and a system based on layers of felt with pre-cultivated vegetation inserted in pockets, both with aluminium anchoring system.

From the research during the three selected phases, it is clear that each LWS has strengths and weaknesses:

- plastic-based LWS shows lower impact during the manufacturing, construction, and maintenance phases.
- The environmental impact of plastic-based LWS shows a lower impact respect to the felt-based LWS due to the low mass of materials used. This impact could be reduced further reduced by replacing materials like polyester with other recycled textiles and recycled aluminium for the system anchors.
- The felt-based LWS has an aluminium support that deeply affects the environmental load. With this regard, to improve the system towards a more environmentally sustainable one the design and research activities should focus on the identification of less impacting materials. Besides this, the use of fertilizers during the life cycle involves a significant impact, a less impacting option would be the use of an organic fertilisers or leguminous crops.

Greening the building envelope with LWS taking into account the materials involved is a key step in selecting a solution that leads to an environmentally friendly performance. This study highlighted that the use of recycled materials, organic substrates, and low environmental impact materials are part of the sustainable strategies for the design of these systems. These should be considered as key strategies for the environment, sustainability, and low energy consumption of LWS, throughout their life cycles.

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Nomenclature

Kg CO^2 eq - Climate change (CC)

Kg CFC-^{11} eq - Ozone depletion (OD)

Kg PM2.5 eq – Particulate matter formation (PM)

CTUh – Human tocixicity-no cancer effect (HTnoc)

CTUh – Human toxicity-cancer effect (HTC)

Kg NMVOC eq – Photochemical ozone formation (POF)

molc H+ eq – Terrestrial acidification (TA)

molc N eq – Terrestrial eutrophication (TE)

Kg P eq - Freshwater eutrophication (FE)

Kg N eq – Marine eutrophication (ME)

CTUe – Freshwater ecotoxicity (FEx)

Kg C deficit – Land use (LU)

M^3 water eq – Water resource depletion (WU)

Kg Sb eq – Mineral and fossil resource depletion (MFRD)

LWS – Living wall system

LCA – Life cycle assessment

LCI – Life cycle inventory