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Assessing the environmental performance of plastic-based and felt-based green wall systems in a life-cycle perspective

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Abstract

With the remarkable growth of cities and the increase of built-up areas, mitigation of urban heat island effects has become one of the most crucial challenges in social and environmental sustainability with significant impacts on public health. This has led to an increasing development of urban green infrastructure. Among those nature-based solutions, green wall systems have been receiving a growing attention, being a passive technology with their ability to reduce greenhouse gas emissions, adapt to climate change, improve air quality and reduce the heat island effect in urban environments. Despite that growing interest in studying the functions and features of such green systems, and the various types of living walls nowadays available, most studies evaluate their energy efficiency and performance only during the use phase. This study aimed to assess the overall environmental performances of two types of green walls in a life cycle perspective, considering the embodied energy, greenhouse gas emissions, materials and energy consumption, and embodied carbon. After collecting inventory data related to all components and processes of each system, a life cycle assessment with cradle to gate approach has been performed by means of the OpenLCA software to compare the performances of a felt-based system without organic growth medium and a system based on plastic modules with organic growth medium. The main impacts have been detected in the production stage and materials used in systems structure. By comparing the results achieved in the 16 impact categories analyzed, the felt-based system showed the highest overall impact, with the use of fertilizers and aluminum components playing a crucial part. Polypropylene used to produce the panels, water used for plant irrigation and potting soil composition are the main environmental impact contributors in the plastic-based system. The results pointed out the importance of accurate choice of materials for the design and production of green walls.

Keywords: Life Cycle Assessment; Green walls; Green infrastructure; Environmental performance; Sustainability.

1. Introduction and goals

The world's population is growing and is expected to reach 9.3 billion by 2050, most of whom will be living in cities [1]. This high tendency to urban life reminds us of the need to revise urban development. 87% of energy consumption from non-renewable sources worldwide is allocated to the construction sector, 40% of Europe [2]. According to statistics provided by the United States Green Building Council (USGBC), commercial and residential buildings are responsible for 30% of greenhouse gas emissions and 65% of US electricity consumption [3]. Given the increasing environmental problems such as global warming, deforestation, waste generation, applying the construction sector's sustainability concept is of paramount importance [3]. All active and passive technologies must be used to design an energy-efficient building and minimize its energy consumption. The embodied energy, the energy sequestered throughout the life-cycle of buildings and materials, constitutes the most significant energy input in a building [4]. Given the widespread environmental impacts of the construction sector, it is necessary to consider efficient strategies to reduce energy consumption and its consequences throughout the life cycle [5]. The development of environmental friendly construction processes to save energy, reduce greenhouse gas emissions, reuse, and recycle materials is a fundamental goal of green construction [6]. Some governments and municipalities, and researchers see integrating green systems in building design as a viable solution to change this situation [7].

In recent years, the green walls system has been prevalent and used as a tool for urban space sustainability [8]. Green infrastructures can improve urban life quality and reduce the world's environmental impact caused by climate change [9, 10]. Building facades are an excellent option to green the dense urban areas and create a bond between nature and buildings [11]. The direct impact on temperature regulation, wind speed reduction, and increased biodiversity in dense urban environments are among the benefits of greening the building envelope to improve energy efficiency [12]. Wind can reduce a building's energy efficiency by up to 50%, while a plant layer acts as a buffer by preventing wind from moving along the building's surface [11]. Moreover, direct sunlight is filtered through the leaves, preventing direct contact with the building's body. Such a natural cover layer lowers the buildings' temperature during the summer while hindering internal heat escape in the winter. On the other hand, green roofs and facades cool the heated air by evaporating [11, 13]. Greening the facades of buildings using plants also has aesthetic and environmental benefits [11]. These systems can reduce air pollution and improve air quality by capturing fine dust in the air [14, 15]. By using green façades in the building, some economic, social, and environmental benefits will be achieved, such as reducing greenhouse gas emissions, adapting to climate change, reducing the impact of heat island on urban environments [13], increasing biodiversity, thermal insulation, social and psychological well-being of city dwellers [16]. It should be noted that by reducing the indoor air temperature by 0.5 ° C, it would save up to 8% on electricity consumption for air conditioning [9]. Also, using this system can reduce the building's electricity usage by 16% in the hot summer months [17]. Vegetation can also be used to decrease sound transmission [18].

One of the most effective tools for quantifying environmental issues is the Life Cycle Assessment (LCA). *"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"* is a definition provided by ISO 14040 for LCA [19]. It has been widely acclaimed for collecting data on materials and their environmental impacts and developing sustainable design and construction [20]. The LCA can be a powerful and systematic tool to improve design and optimization, and to determine the likely environmental burdens of a process or product. The life cycle assessment is an effective method to compare the building’s environmental impacts during the production, construction, maintenance, and disposal phases [21]. LCA studies have been conducted to establish guidelines to calculate some of the building materials' environmental impact and improve building performance. In Asif et al., different building materials were evaluated on CO_2 emission, and the results showed that concrete with 61% had the highest share of emission and energy incorporated [22]. Kosareo and Ries applied the life cycle assessment to evaluate green technologies, such as intensive and extensive green roofs, then, have been compared to conventional solutions. They were concluded that vegetation has more energy advantages due to its lower thermal conductivity in the substrate [23]. In another LCA study on green roofs, Saiz, Susana, et al. found out the environmental impacts can be reduced 1 to 5% on average with applying a green roof [24]. In Altan et al. 2015, five different types of green wall systems were evaluated for their environmental impacts and benefits over their cradle to grave life-cycle (cradle to grave). The results showed that the effects of unsupported systems were far lower due to the less need for maintenance and reuse of their components [25]. Based on LCA analysis to measure the effects of a living wall system include felt pockets, Natarajan et al. found that halving the irrigation volume could save 46% in energy usage and 37% in carbon emissions [26]. In Hong Kong, a commercially vertical green system was analyzed to quantify its environmental burden and benefits during manufacturing, transportation, use, and disposal stages. Results showed that the production phase is characterized by the highest impacts (47-93%) in all environmental impact categories [17]. Based on Feng et al. that performed an LCA analysis on three living wall system (LWS), the materials and plants used in these systems in combination with the weather conditions and the building type strongly influence these systems' performance [27].

The proven benefits of these technologies have contributed to their distribution in recent years and the development of numerous types of systems with different components and characteristics. Despite the growing interest in studying the various specific functions and features of such green systems, most studies evaluate their energy efficiency and performance only during the use phase, regardless of their emissions and energy incorporated from manufacturing to dismantling. Therefore, further research is needed to address their overall environmental performances and accounting and in a life cycle perspective, considering the embodied energy, greenhouse gas emissions, materials and energy consumption, and embodied carbon, thus providing a systemic evaluation contributing to sustainable design of living walls system (LWS).

This work aims to evaluate two typologies of green wall systems with different characteristics and production processes, assessing their production, construction, and maintenance phases, in order to better understand their strengths and weaknesses, at the same time providing useful elements to improve the design and manufacturing of environmentally friendly systems. The green wall systems are compared to assess their environmental performances depending on their structure and composition. The study aims to evaluate materials and processes related to the final product and quantify the various environmental impacts, highlighting the contribution of each factor at each phase of the life cycle, determining the efficiency and sustainability of the system. The research will thus identify factors negatively affecting the environmental burdens of these systems, allowing to reduce their environmental effects.

2. Materials and methods

2.1. Description of the studied systems

This study was performed on two modular green wall systems, a plastic-based and a felt-based system, each one with a different structure. Figure 1 shows a schematic drawing of the studied systems.

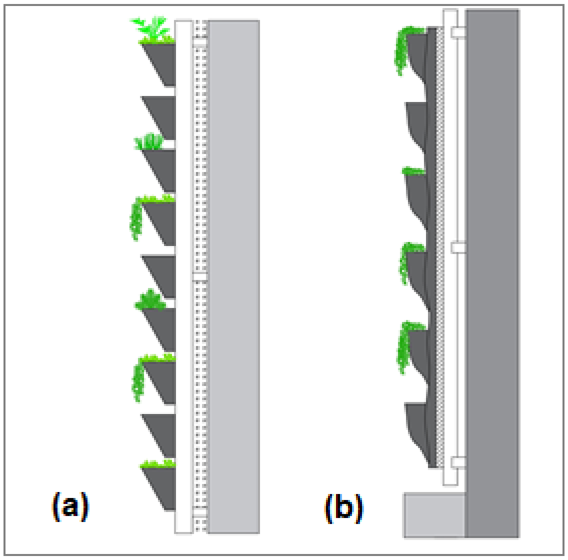

Fig. 1. a. Plastic-based green wall system. b. Felt-based green wall system.

- The first system is a vertical green system made of plastic modules. These panels provide the system rigidity and impermeability. These modules are made of recyclable EPP and weigh 60 kg per square meter. Vegetation can be placed before or after installation and can be easily replaced during the system's use. An irrigation system is required and can be automated. The main components of the supporting system are aluminum and soil is used as a growing medium.

- The second one is a type of modular system composed of the felt layers. 3-4 felt layers make the planting pockets, and a plant can be placed into each pocket. Plants that can be pre-grown and inserted into gaps. The supporting system is made of an aluminum frame and an expanded PVC panel. Fertirrigation powered by an automated irrigation system is used to provide water and fertilizers required by plants. The system's daily water consumption is ½ liter per square meter.

2.2. Functional unit and system boundaries

The LCA's functional unit is defined by ISO 14040 as the reference unit for determining system performance [19]. This study considers 1 m^2 of the reference surface area of the green wall as a functional unit.

Steps and activities related to the production and assembly of various parts of a green wall create the system boundaries from the beginning to the end. In this study, the system boundaries consist of the production, construction, and maintenance phases.

- **Production stage**

At the production phase, the main focus is on analyzing the raw materials, resources, and energy used to produce all the components and pieces of each system. The parameters of greenhouse gas emissions, resource consumption, materials, and energy are measured at this stage [11].

- **Construction stage**

Assembly of the system and its components occurs during the construction phase. Aspects such as shipping distance, mode of transport, and CO_2 emission are crucial to obtain the entire materials environmental impacts over its life cycle.

- **Maintenance stage**

The most critical factor in the maintenance phase is the amount of water required by the irrigation system. The amount of impact due to resource consumption that depends on the number of times the system is irrigated. Investigating the amount of water needed to maintain the systems gives us an understanding of water consumption over each system's life cycle. Moreover, the used fertilizers, pruning and plants substitution, and other system elements and materials replacement must be considered during operation.

2.3. Software, database and data inventory

Since the various green wall systems usually differ in terms of the materials used in their production and the method it is assembled, all components used in these systems must be examined through the LCA framework. The environmental burden, caused by each system, is influenced by the proportion of materials used in its components. They are evaluated and simulated by the OpenLCA software and the Ecoinvent® v3.7 database. The results of this software will be used for life cycle analysis.

All the components of both systems are given in Tables 1 and 2. Materials and processes related to the final product will be evaluated to calculate the environmental impacts. Inventory analysis is possible with access to information on production, construction, and maintenance. All stages of a life cycle assessment are essential, but inventory analysis plays a key role. The processes in the Ecoinvent® database can be used to perform the inventory analysis process [28].

Table 1. The components of plastic-based system and some data for LCA analysis.

Components	Material	Weight (kg/m^2)	Distances (km)	Service life (years)
Module	EPP recyclable	60	62	10
Module holder	Tempered steel	5.644	96.5	10
Upright	Aluminum (6060 T5)	3.51	55	10

Nuts and Bolts	Stainless steel (AISI 304)	0.4	96.5	10
Filter	PP	0.288	62	10
Potting soil	Potting soil mix (40% peat moss, 20% sand, and 40% vermiculite)	12	-	10
Watering system	PE	0.1	62	7.5
Water demand	Tap water	29200	-	10
Vegetation	Hedera	1.5	-	10

Table 2. The components of felt-based system and some data for LCA analysis.

Components	Material	Weight(kg/m²)	Distances(km)	Service life(years)
PVC panel	Expanded PVC	5	226	10
White fleece	Polypropylene	0.82	167	10
Wool fleece	Polyamide	0.93	167	10
PE fleece	Polyethylene	0.06	167	10
Bracket	Aluminum	0.2	131	10
Frame	Aluminum	1.578	131	10
Lateral shoulder	Aluminum (painted)	2.01	131	10
Water Tank	Aluminum (painted)	2.01	131	10
Watering system	PE	0.1	226	7.5
Water demand	Tap water	10950	-	10
Fertilizer	Nitrogen (N), diphosphorus	22.5	-	10

	pentoxide (P_2O_5), and potassium oxide K_2O			
Vegetation	Pteropsida	7.5	-	3.5

Given that the lifespan of green walls is usually estimated to be ten years, factors potentially affecting the environment during this period are evaluated. Input data used in the LCLA represent the characteristics of these types of systems available on the market. Based on previous studies, to balance the environmental burdens of the green walls system, the CO_2 uptake by plants is assumed 12kg/year for one square meter [7]. Only the felt-based green wall system needs a nutrient solution for plant growth due to a lack of organic substrate. The LCA of the intelligent irrigation system responsible for monitoring and injecting the nutrient solution required for the felt-based system, as well as processes related to growing plants on the farm lie outside the system boundaries therefore are not considered in this study. Pipes used for irrigation become clogged due to salt crystallization and sediments and must be replaced every 7.5 years.

2.4. Life Cycle impact Assessment

According to the European Commission-endorsed LCIA method, the following categories should be examined using the ILCD (International Reference Life Cycle Data System) method [37]:

- Acidification (molc H^+ eq.);
- Climate Change (kg CO_2 eq.);
- Freshwater Ecotoxicity (CTUe);
- Freshwater Eutrophication (kg P eq.);

- Human Toxicity-Cancer Effect (CTUh);
- Human Toxicity-Non-Cancer Effect (CTUh);
- Ionizing radiation E (interim) (CTUe);
- Ionizing radiation HH (kBq U235 eq.);
- Land Use (kg C deficit);
- Marine Eutrophication (kg N eq.);
- Mineral and Fossil Resource Depletion (kg Sb eq.);
- Ozone Depletion (kg CFC-11 eq.);
- Particulate Matter (kg PM2.5 eq.);
- Photochemical Ozone Formation (kg NMVOC eq.);
- Terrestrial Eutrophication (molc N eq.);
- Water resource depletion (m^3 water eq.);

Based on the literature, due to the very small impact of other categories, climate change, human toxicity, and freshwater ecotoxicity are more important to show the study's results. [29]. In addition, reviewing the results obtained in the categories of land use, Mineral, fossil and ren resource depletion, ozone depletion, and water resource depletion can help to understand better the negative effects of each system on the environment. The amount of greenhouse gas emissions during the system life cycle directly affects the category of climate change. Many studies equal gas emissions and climate change with the environmental impact of materials [30]. The potential effects of releasing toxic compounds into the human environment are considered in the human toxicity category. The freshwater ecotoxicity category focuses on releasing toxic substances into the air, water, and soil and their effects on the freshwater ecosystem [13]. The main purpose of this section is to weigh the results of the entire analysis. The impact of 1 m^2 of green wall system will be assessed based on the above mentioned categories separately.

3. Results and discussion

As it is clear from the impact results obtained for the two systems under study shown in Table 3, the felt-based system has higher negative effects than the plastic-based system in all the main impact categories, with the exception of climate change and water resource depletion.

Table 3. Environmental impacts for a 1 m^2 of the plastic-based and felt-based systems.

Impact category	Reference unit	Plastic-based	Felt-based
Acidification	molc H^+ eq	0.66414	0.81995
Climate change	kg CO_2 eq	42.2056	25.15523
Freshwater ecotoxicity	CTUe	1428.6235	2435.9842
Freshwater eutrophication	kg P eq	0.0468	0.046612
Human toxicity, cancer effects	CTUh	1.1704E-05	1.5543E-05
Human toxicity, non-cancer effects	CTUh	2.3251E-05	3.7312E-05
Ionizing radiation E (interim)	CTUe	5.8794E-05	3.5006E-05
Ionizing radiation HH	kBq U235 eq	21.86134	10.91895
Land use	kg C deficit	113.5358	205.9807
Marine eutrophication	kg N eq	0.11503	0.1693
Mineral, fossil & ren resource depletion	kg Sb eq	0.00771	0.01409
Ozone depletion	kg CFC-11 eq	3.5156E-06	1.2647E-05
Particulate matter	kg PM2.5 eq	0.06751	0.090744

Photochemical ozone formation	kg NMVOC eq	1.070754	0.44234
Terrestrial eutrophication	molc N eq	1.16789	2.0404
Water resource depletion	m^3 water eq	5.05124	2.18408

As predicted and confirmed by the results of previous studies, the production phase has the largest share of environmental impacts. This is mainly due to the type of materials and components used in the production of these systems [31, 32]. Since the assembly process of these systems is done manually and no special machines are used, the construction stage has the lowest impact [31]. The water used to irrigate the plants and the fertilizer used in the felt-based system are the main environmental impact factors in the maintenance phase [32].

The impact of the plastic-based system on the climate change category is greater than the felt-based system (Fig. 2.a). This negative impact is due to the processes related to the production of polypropylene panels, which play the most important role. Polypropylene production processes alone account for 88% of the total negative effects. After that, water consumption with 5% has the most negative impact (Fig. 2.b). Vegetation due to CO_2 uptake can compensate for up to 74% of these negative effects. These effects are calculated for a period of 10 years. As the results show, if the process of CO_2 removal by vegetation continues, it will reach equilibrium after 14 years. Fertilizers used in the felt-based system have the greatest impact on the climate change category. In addition, the supporting system components are made of aluminum, which contributes significantly to increasing CO_2 production. The negative effects of inorganic nitrogen, inorganic potassium and inorganic phosphorus used in the production of nutrient solution are 32, 19 and 15% and 67% in total. Furthermore, the aluminum sections have a 17% negative effect (Fig. 2.b).

However, thanks to photosynthesis by plants, these negative effects are reduced up to 83% and can be expected to reach equilibrium after about 12 years.

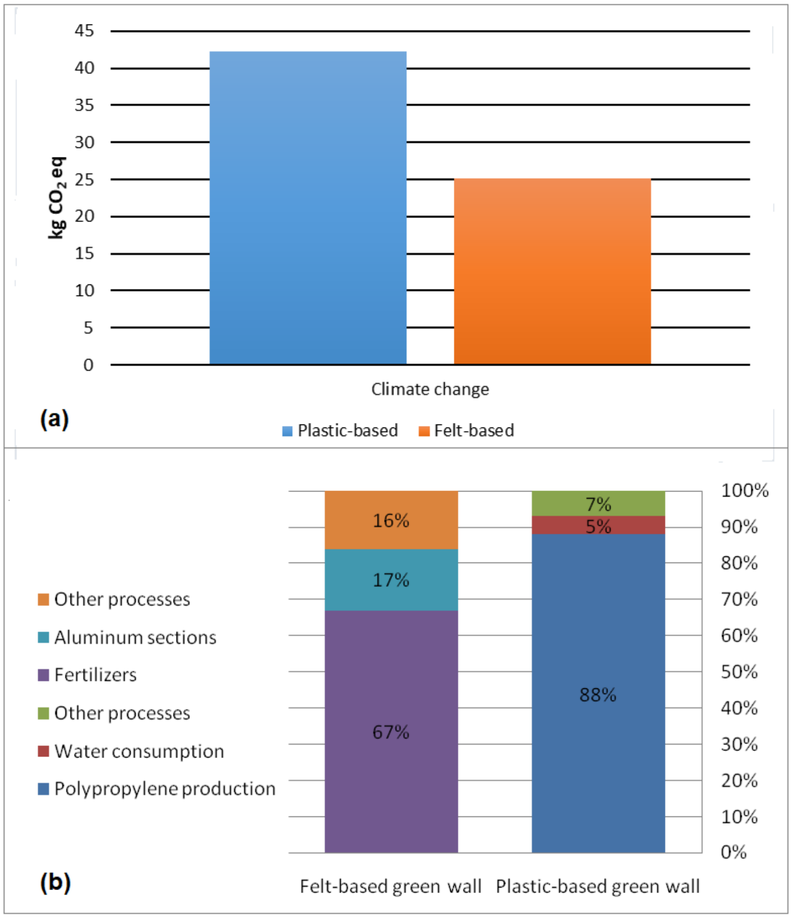

Fig. 2. (a) The climate change impact category; (b) Contributions of systems processes in the climate change impact category

In the case of categories related to human health, for the plastic-based system, between 70 and 80% of the impact is related to the production of polypropylene panels. Then, water consumption with 13% and production of supporting system elements with 11% have the most negative effect (Fig. 3.b). On the other hand, 66% of the total negative effects are related to inorganic fertilizers in the felt-based system. Of this amount, 31% is related to inorganic nitrogen, 19% is related to inorganic potassium, and 16% is related to inorganic phosphorus. This has led to an increase in the negative effects of this system compared to the plastic-based system. In addition, we can mention the impact of the aluminum sections production process with 17% and PVC panels used in the supporting system with 8% (Fig. 3.b).

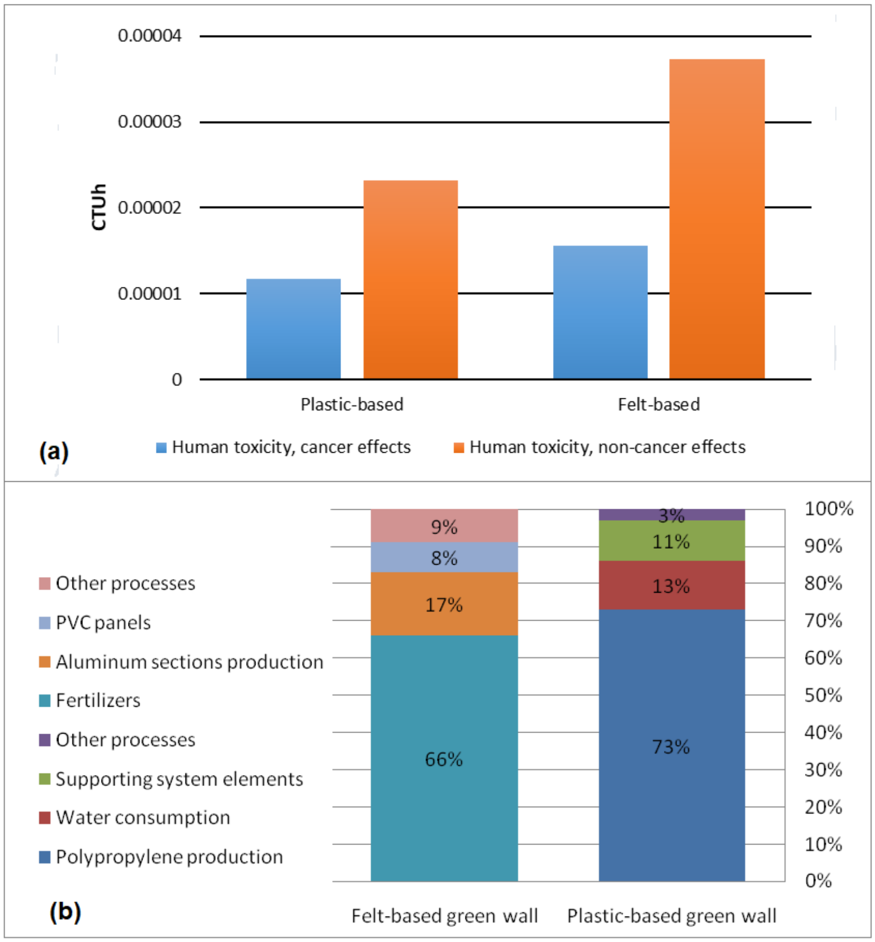

Fig. 3. (a) The human toxicity impact categories; (b) Contributions of systems processes in the human toxicity impact categories.

As shown in figure 4, in the freshwater ecotoxicity category, the impact of the felt-based system is greater than the plastic-based system. 77% is the nutrient solutions contribution in the felt-based system, that inorganic nitrogen, potassium and phosphorus share are 37%, 20% and 20%, respectively. Casting of aluminum parts in the supporting system and PVC panels are also effective with 11 and 8% (Fig. 4.b). On the other hand, 84% is the share of the plastic panels production contribution in the plastic-based system. Water consumption is the next effective process in the plastic-based system with a 10% impact (Fig. 4.b).

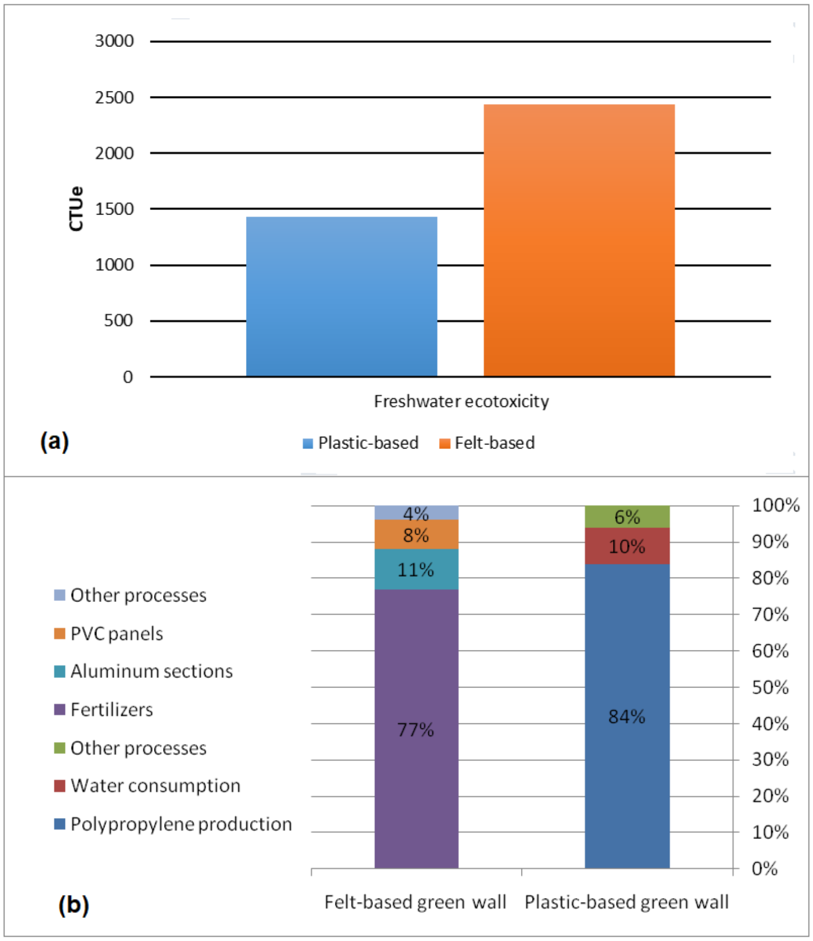

Fig. 4. (a) The freshwater ecotoxicity impact category; (b) Contributions of systems processes in the freshwater ecotoxicity impact category.

Like most other categories, in the land use category, nutrient solutions and aluminum components of the supporting system in the felt-based system have the greatest impact. 34% for inorganic nitrogen, 26% for inorganic potassium, 21% for inorganic phosphorus and 11% for casting aluminum parts (Fig. 5.b). In the plastic-based system, the processes related to polypropylene production with a 51% share are the most effective. But the remarkable point in this category is the significant share of potting soil with 33%, that 28% is the share of the peat moss production process. The share of water consumption in this category is 10% (Fig. 5.b). Figure 5 shows the overall impact of the felt-based system in this category is almost twice that of the plastic-based system.

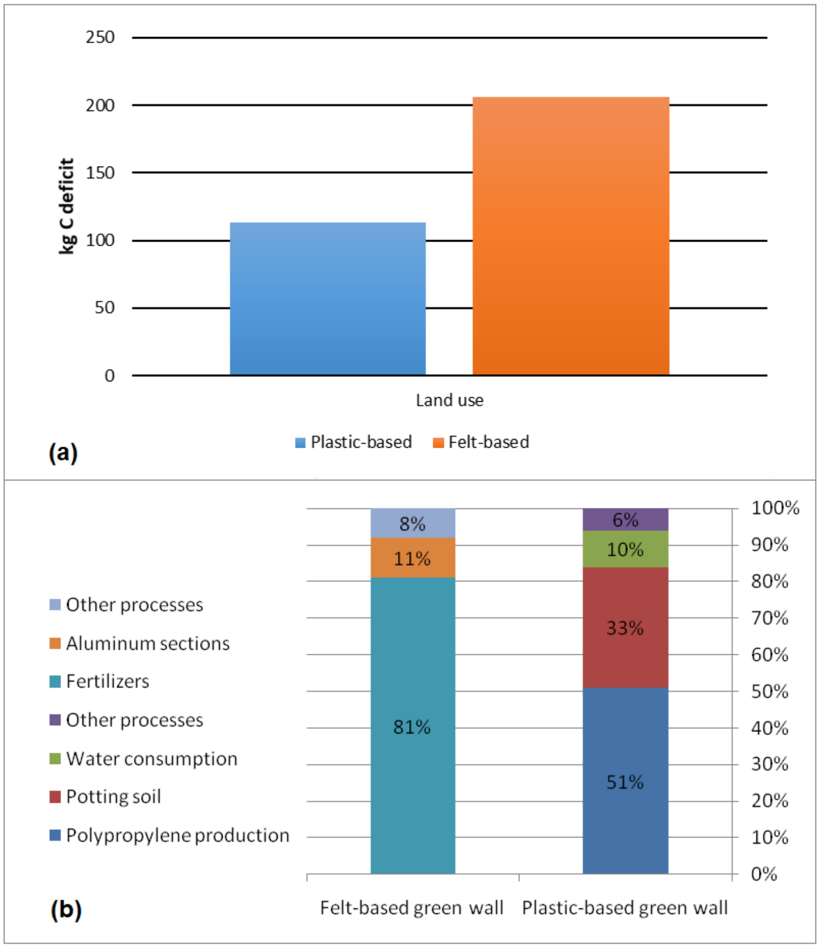

Fig. 5. (a) The land use impact category; (b) Contributions of systems processes in the land use impact category.

The results related to the mineral, fossil & renewable resource depletion category show that the potting soil used for the plastic-based system has a 70% share singly, which is related to the vermiculite mining operation. Polypropylene panels have a 27% share too (Fig. 6.b). In the felt-based system, the impact due to the inorganic nitrogen fertilizer production process is about 68%, which is the highest. The share of inorganic phosphorus is 17% and inorganic potassium is 9%

(Fig. 6.b). Figure 6 shows that the felt-based system impact in this category is approximately twice that of the plastic-based system.

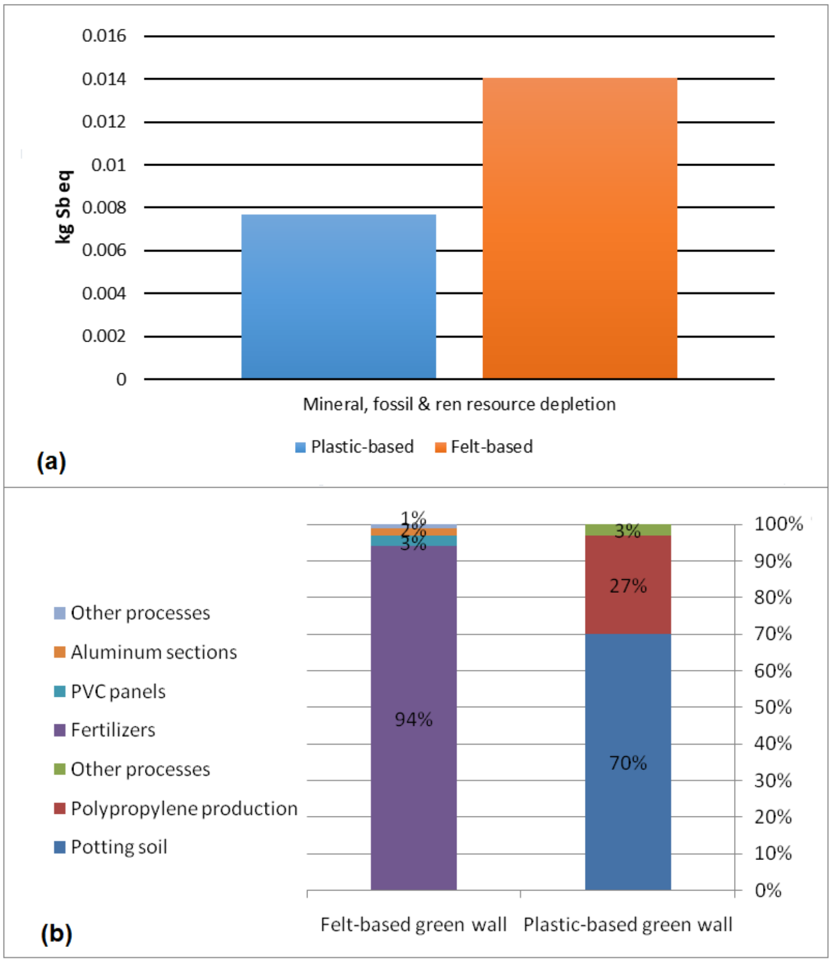

Fig. 6. (a) The mineral, fossil & ren resource depletion impact category; (b) Contributions of systems processes in the mineral, fossil & renewable resource depletion impact category.

Like other categories in the impact category of ozone depletion, for the plastic-based system, the largest share is related to the plastic production process with 77%, and water consumption and Aluminum sections are in the next ranks with 13 and 5% (Fig. 7.b). But for the felt-based system in this impact category, the results are different. The PVC panel production process used in the supporting system accounts for 45% of the impact. In addition, inorganic fertilizers with 42% (20% for inorganic nitrogen, 12% for inorganic potassium and 10% for inorganic phosphorus) and the use of aluminum components with 11% exacerbate this negative impact (Fig. 7.b) and make the negative effects of the felt-based system in this category far greater than the plastic-based system (Fig. 7).

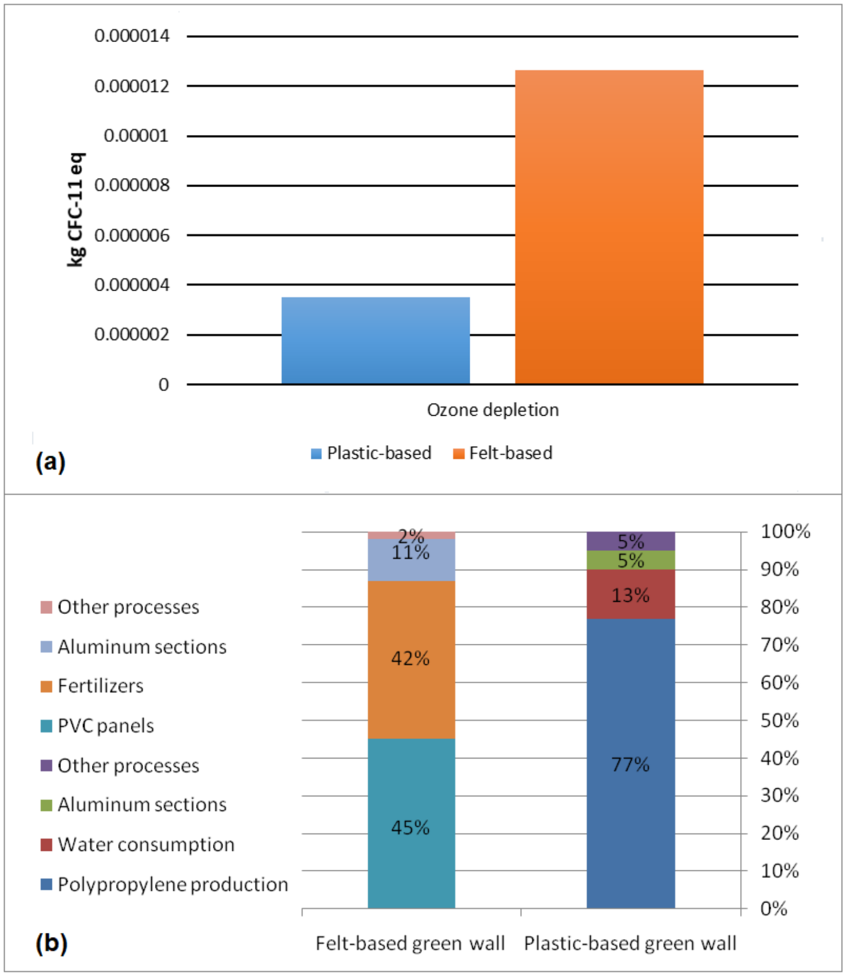

Fig. 7. (a) The ozone depletion impact category; (b) Contributions of systems processes in the ozone depletion impact category.

As mentioned before, in the impact category of water resources depletion, the largest share is related to the use phase. Water used to irrigate plants has a 94% share in a plastic-based system, compared to 82% for a felt-based system (Fig. 8.b). In addition, the effect of nutrient solution used is about 13%. However, the main reason for the difference in the results of the two systems is related to the difference in vegetation, as the plant used in the plastic-based system needs more water for irrigation (Fig. 8).

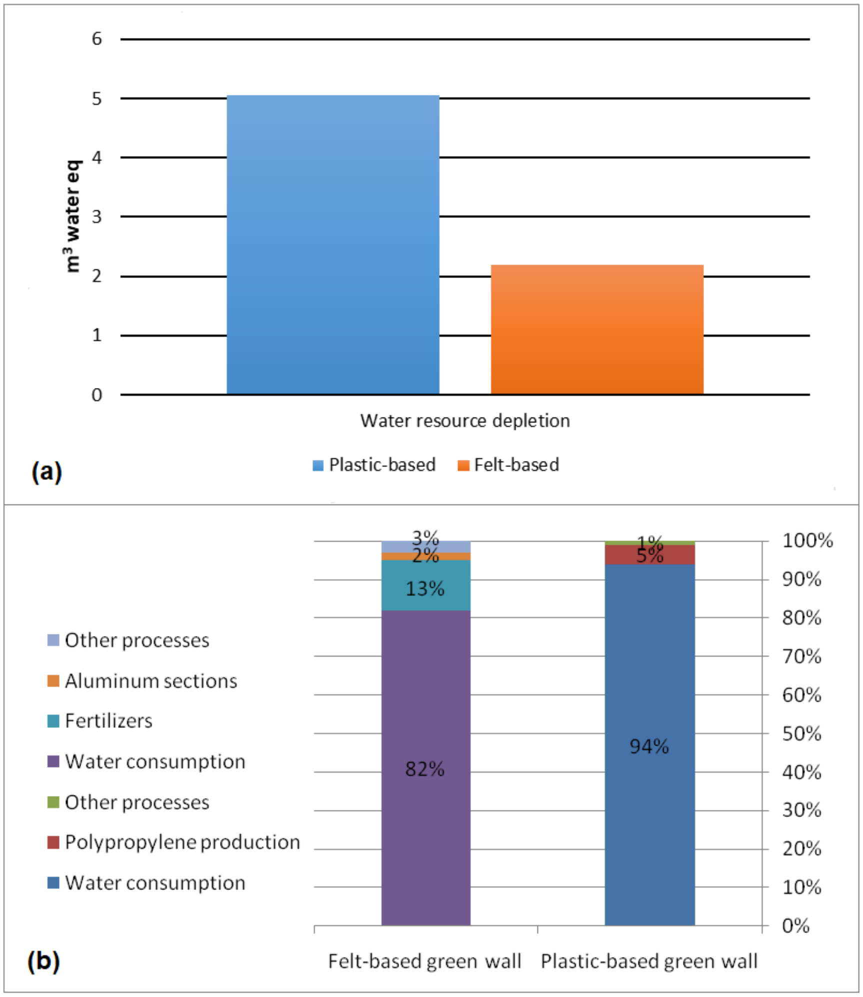

Fig. 8. (a) The water resource depletion impact category; (b) Contributions of systems processes in the water resource depletion impact category.

We can understand that the felt-based system has the greatest environmental impact in almost all categories due to aluminum components in the supporting system and inorganic chemical fertilizers necessary since no growing medium is used for plants. These results are consistent with the results reported in previous studies [11, 31]. Examining the results of the plastic-based system, it can be concluded that the high volume of polypropylene used to produce the panels and the water used for the plant irrigation and the potting soil composition have the greatest environmental impact. The role of materials used in the production of these systems should be highlighted. By making changes in the structure of both systems, a more stable design can be achieved. In addition, by replacing aluminum with other materials in the support system of both systems, environmental impacts can be reduced. Aluminum can have up to 10 times more environmental impact than any other material [29]. Using recycled plastics to produce the required panels in the plastic-based system can be expected to reduce environmental impacts. Also, the use of plants with the need for less irrigation, changing the growing medium composition, and fertilization can be led to a significant reduction.

4. Conclusions

In this research, by evaluating the life cycle of two green walls system, all the advantages and disadvantages of the systems during their lifespan can be identified and expressed quantitatively. With the quantification of environmental impacts, the contribution of each factor at each phase of the life cycle can be understood, and the efficiency of the system can be determined according to all the effective phases and factors. In this way, critical points can be identified, and their environmental effects can be eliminated or reduced. Moreover, one of the factors affecting the environmental burden of these systems is the materials used in their production process that can be reduced by replacing them with suitable materials. By trusting the results of this study and increasing consumer confidence, the use of these systems can be increased.

We can achieve more sustainable structures and fewer environmental impacts by pursuing this study. It can help architects, ecologists, and engineers find new nature-based solutions to solve environmental problems. It is also expected to improve the ecological sustainability of systems throughout their lifecycle by comparing the results.

In general, we can conclude that the production stage has the most environmental effects compared to other stages. This shows the importance of the careful selection of materials for the system components production. By replacing more sustainable materials, we can reduce environmental impacts in both systems. Plants can recoup the carbon released in the production process after 12 and 14 years, and since the lifespan of a building is often estimated at 50 years, they can help purify the air in later years. However, choosing plants suitable for climatic conditions, choosing the right growing medium, and not needing nutrient solutions, and excessive irrigation can minimize the negative effects of the use stage.

Since the green wall system is a new technology, there is still a need for further studies on them. Increasing the number of case studies with specific data and results will help improve the design and development of these systems. On the other hand, due to the expansion of these systems in recent years, there is still no accurate information about their fate and effects at the end of life.

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