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Evaluating the Life Cycle Assessment of Rain Gardens and Green Walls for a Sustainable Environment

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Abstract

With fast urbanization and increasing climate pressures, Green Infrastructure (GI) has emerged as a feasible sustainable alternative to urban environmental issues. Among the many GI strategies, Rain Gardens (RGs) and Green Walls (GWs) are frequently applied for storm water management, thermal insulation and biodiversity. This study conducts a comparative Life Cycle Assessment (LCA) of RGs and GWs on the basis of a systematic review of 25 peer-reviewed studies, adopting the ISO 14040/14044 standard. Data were taken for each life cycle stage construction, operation, maintenance and end-of-life and normalized per square meter for a 50-year service life. The main environmental impact categories were Global Warming Potential (GWP100), fossil fuel consumption, water consumption and solid waste generation. Re-CiPe 2016 method of impact assessment was used to ensure comparability between studies. The results show a balance between LCA phases. Green walls have lower construction-phase impacts (*e.g.,* GWP: 0.58 kg CO_2 eq/m^2) due to prefabricated modular units. Rain gardens, on the other hand, have lower operational-phase impacts (*e.g.,* 419 vs. 796 kg CO_2 eq/m^2 per year), due to passive water filtering and minimal maintenance needs. RGs also outperformed in delivering ecosystem services such as storm water infiltration, groundwater recharge and urban cooling. The outcome of this study reinforces that no GI system is supreme. Instead, performance is on lifecycle stage and conditions. Deciding on a choice should rely on local objectives energy performance, water efficiency or biodiversity. The innovation lies in combining spatial-functional performance and ecosystem service valuation with conventional LCA indicators. This hybrid approach bridges the gap between environmental science and applied sustainability by providing a new decision-support system that increases the relevance of Life Cycle Assessment (LCA) for policymakers and urban planners.

Keywords: Green infrastructure; Rain gardens; Green walls; Urban sustainability; Ecosystem services

Introduction

Urbanization and climate change present urgent challenges for sustainable water and energy management. With 68% of the global population projected to live in urban areas by 2050 as it's up from 55% in 2018 [1,4]. Thus, cities face mounting pressure to reduce environmental degradation, resource depletion and climate vulnerability. Urban areas already contribute over 70% of global CO_2 emissions due to transportation, energy consumption and infrastructure development [2,11]. Therefore, these pressures highlight the importance of sustainable infrastructure in mitigating environmental impacts and enhancing urban resilience. However, the GI, including green roofs and green walls, plays a pivotal role in sustainable urban development [3,6]. Hence; these systems contribute to storm water management, reduce energy demand and support urban biodiversity. Green roofs, categorized as extensive or intensive, offer various ecological benefits, including thermal insulation, urban cooling and extended roof lifespan. Intensive systems provide greater biodiversity and recreational use, while the insulation provided by vegetation reduces building energy consumption, often offsetting the environmental cost of materials and installation [4,13]. In addition, similarly rain gardens and green walls or bio retention systems are effective in capturing, filtering and treating storm water at its source. Additionally, such systems can significantly reduce pollutant loads, recharge groundwater and lower peak flows, though the construction phase contributes the most environmental burden due to materials like silica sand and mulch [5,9].

Moreover, to quantify these benefits and trade-offs, LCA provides a systematic framework for evaluating the environmental performance of green infrastructure across all life stages from construction to operation and end of life. On the other hand, LCA studies have shown that while green roofs are more effective in energy conservation and urban heat island mitigation, rain gardens outperform in water quality improvement and flood control [6,20]. Integrating both systems can enhance climate resilience and maximize hydrological benefits.

However, several challenges hinder broader implementation, including high upfront costs, complex maintenance and site-specific constraints. Consequently, tools such as SimaPro, GaBi, OpenLCA and Umberto LCA+ enable researchers and policymakers to analyze environmental trade-offs with precision. For instance, studies using SimaPro indicate that green roofs reduce emissions by 35% to 83% and nearly eliminate ozone depletion effects [7,18]. Nevertheless, the U.S. Environmental Protection Agency (EPG) reported that green roofs can reduce surface temperatures by up to 56°F and cut cooling energy demand by as much as 70%. However, green roofs and green walls each offer unique environmental benefits.

Green roofs improve energy efficiency and reduce the urban heat island effect, while rain gardens excel in water quality and stormwater management. Integrating both systems can optimize urban sustainability, though high costs and maintenance remain challenges [8,4]. However, this paper aims to critically review LCA studies of green roofs and rain gardens, highlight methodological inconsistencies and offer recommendations for standardizing future assessments. By doing so, it seeks to support data-driven decision-making in sustainable urban planning.

Materials and Method

Study design

This study employed an evaluated literature approach to examine recent research on LCA applications in the 3 phases of RG and GR. The purpose was to synthesize recent literature on LCA applications in the construction sector, with a focus on tools, practices and methodological variations. This structured approach ensured transparency in article selection, data extraction and synthesis.

Goal and scope definition

This review aims to evaluate how LCA methodologies are applied in the construction industry, with particular focus on three key life cycle phases (construction, operation and maintenance and dismantling). Following the ISO 14040 and ISO 14044 standards, the scope of each study was assessed in terms of its system boundaries and functional units. Although variations exist, most studies defined their functional unit as a square meter of building area or a complete building system. Studies were included only if they assessed at least one of the targeted phases and provided sufficient detail on LCA modeling and impact evaluation. Boundaries were categorized as partial such as cradle-to-gate or full like cradle-to-grave, depending on whether they incorporated all three phases under review. This focus allowed for a deeper understanding of environmental performance across a building's lifespan.

Inventory analysis

The data were collected from the four academic databases such Scopus, Web of Science, Science Direct and Google Scholar. Search terms included the life cycle assessment, LCA tools, building materials, construction and sustainable buildings, combined with Boolean operators. The timeframe was restricted to English and Turkish language peer reviewed journal articles published between 2015 and 2025. The review considered environmental data across key phases: Material extraction and production (construction), operational lifespan and maintenance and end-of-life scenarios including deconstruction and disposal. Duplicates were removed using Mondeley software and all selected articles were reviewed in full to ensure alignment with the research scope.

Impact assessment

The research explored a broad range of environmental impacts to analyze the comparative life cycle performance of RG and GR. The most frequently reported impact category was Global Warming Potential 100 years (GWP100), reflecting carbon footprint concerns. Other frequently utilized categories included Ozone Layer Depletion (OLD), Eutrophication Potential (EP), Acidification Potential (AP) and Abiotic Depletion (AD), which measure nutrient runoff, acidifying emissions and non-renewable resource consumption respectively. Other types used in some of the research included Human Toxicity (HT), Marine Aquatic Eco toxicity (MAE), Freshwater Aquatic Eco toxicity (FWA), Terrestrial Eco toxicity (TE) and Photochemical Oxidation (PO), which examine emissions' effects on human health and ecology and air quality. The majority of the studies utilized

LCA instruments such as Open LCA, Mobius, Ecochain both of which provide access to multiple impact assessment methods, for instance, ReCiPe, CML and TRACI. Some studies also applied Mobius for scenario testing, although its usage was rarely elaborated upon. Ecoinvent and Ecochain were the most commonly cited life cycle inventory databases, ensuring data consistency and methodological transparency. The selection and application of impact categories varied depending on study objectives, regional relevance and the availability of background data.

Interpretation and selection criteria

Based on the inclusion criteria, studies had to clearly apply LCA methodologies to construction contexts and report objectives, boundaries and impact methods in a transparent manner. Studies that were conference papers, dissertations or sources written in languages other than English and Turkish were not included. An initial screening of titles and abstracts was followed by a full-text review as part of a two-stage screening procedure. Nonetheless, a standardized form was used for the data extraction process, which recorded details about the study's purpose, functional unit, boundary, LCA tool, geographic location and LCA phase. To facilitate organized synthesis and comparison, the extracted data were grouped thematically.

Literature search strategy and selection criteria

The selection process of articles involved three main filtering stages. First, title screening was carried out to exclude articles unrelated to LCA, rain gardens or green walls. Second, during abstract screening, studies that did not perform an LCA analysis were removed. However, then, the full-text review was conducted to ensure that only studies meeting methodological rigor and relevance were included. Thus, this systematic process, a total of 90 studies focusing on LCA being selected, of which 22 studies specifically addressed rain gardens and green walls for in-depth analysis.

Results and Discussion

The comparative analysis evaluates the environmental performance of RG and GW systems using key LCA impact categories across their LCA stages such as construction Phase, operation & maintenance and dismantling which has been explained here in the corresponding order. Based on the LCI, GRs utilize significantly more organic material specially soil and vegetation whereas GWs depend more on processed materials like steel, EPDM membranes and backing panels. In the impact of LCA, GWs exhibited a notably higher impact in categories such as GWP100 and MAE primarily driven by operational inputs like electricity and fertilizer. Additionally,

GRs showed higher impacts in fossil fuel depletion due to heavy substrate requirements and generated more organic waste during dismantling. The **Table 1** visually emphasizes these differences, illustrating that while GWs have higher emissions and toxicity impacts, GRs are more resource-intensive. These outcomes underscore how design and material choices shape the environmental footprint of urban green infrastructure systems.

Table 1: Previous LCA studies on sustainable green infrastructure.

Reference	Focus	Key Findings
[9,10]	LCA of rain garden	Showed significant carbon reduction potential; 810-ton CO_2 eq net reduction
[11,12]	Residential rain gardens vs. traditional systems	Rain gardens had lower environmental impacts and costs
[13,14]	Sustainable rainwater management LCA	Reviewed challenges of LCA for rainwater systems
[15,16]	Rain garden performance under rainfall events	LCA framework shows variable performance under rainfall scenarios
[17,18]	Green vs. grey infrastructure	Green infrastructure more sustainable than grey
[19,20]	Felt-system green wall	Cradle-to-grave LCA for felt-based living green wall
[21]	Living wall systems	Identified construction and materials as major impact drivers

[22,23]	Green wall design choices	Emphasized importance of component/material selection
[24,25]	Systematic LCA review of green walls	Production & construction stages have largest impacts
[26-27]	Green façades vs. living wall systems	Façades have lower environmental impacts than complex wall systems
[28,29]	Living walls in Mediterranean region	Assessed energy + environmental performance of 4 systems
[30,31]	Environmental benefits of green wall systems	Found key benefits in thermal regulation and carbon footprint
[32,33]	Green wall full life cycle	Impact highest in manufacturing and maintenance
[34,35]	Environmental impact of wall systems	Focused on manufacturing impacts and suggested mitigation
[36,20]	LCA of vertical greenery systems	Highlighted long-term benefits in urban areas
[37,38]	Comparative analysis of wall types	Living walls have higher cost but greater energy savings
[39,40]	Indoor green wall systems	Showed reduced cooling demand and energy use
[41,42]	Green roofs in stormwater management	Significant reduction in storm runoff in Seoul
[43,44].	Carbon sequestration in green roofs	Green roofs act as carbon sinks
[45,46]	Environmental impact of green roofs	Emphasized green roofs as urban sustainability tools
[47,43]	Green *vs.* blue roofs	Water management and energy efficiency in urban areas
[48,49]	Pollution reduction *via* green roofs	Filter pollutants from rainwater; improved air and water quality

Basic on the **Table 2** shows the LCA inventory data per 1 m^2 over a 15-year lifespan, as the comparison between GW and GR reveals key differences in material use and lifecycle impact. GW use more structural materials like steel and backing panels, while GR rely on bulk landscape materials such as gravel, sand and a larger quantity of waterproofing membrane. During operation, GR require more resources, including electricity, fertilizer and water, indicating higher maintenance demands. At dismantling, GR generate more waste, especially organic and solid waste. Additionally, the GW is more material-intensive during construction, whereas GR have higher operational and end-of-life impacts. This data highlights key differences in material intensity and maintenance demands, offering a comparative foundation for assessing their environmental impacts in urban green infrastructure planning.

Table 2: LCA inventory data for rain gardens and green walls (per1 m^2) over a 15-year lifespan.

Phase	Item	Amount (GW)	Amount (GR)	Unit
Construction	EPDM / TPO	Wall-integrated	1.2	kg
	Geotextile	N/A	0.3	kg
	Gravel, sand	Built-in	20	kg

	PE / PVC	2	2	kg
	PVC	0.5	0.5	kg
	Soil, coco coir	20	12	kg
	Steel	10	0.2	kg
	Vegetation	5	1.5	kg
	Backing panel	5	-	kg
Operation and maintenance	Electricity	1.5	15	kWh
	Emission to water	-	0.6	kg
	Fertilizer	0.3	1.5	kg
	Manual labor	3	3	kg
	Plant replacement	4	6	kg
Dismantling	Chemical waste	-	0.4	kg
	Solid waste	5.4	11	kg
	Vegetation waste	5	15	kg

Construction phase

The RG system shows substantially higher impacts than the GW system across most environmental indicators during the construction phase. For instance, RG has a Global Warming GWP100 of 4.07 kg CO_2 eq, while GW has only 0.58 kg CO_2 eq. This disparity arises because RG incorporates heavier materials such as drainage layers, insulation boards, waterproof membranes and bulk soil substrates. These components contribute to elevated emissions from material production, transportation and installation. The use of foamed plastic insulation and adhesives can also raise OLD impacts. Furthermore, abiotic resource use, AD and ADF, is higher in RG due to its reliance on mineral and petrochemical-based materials. However, the GW system uses lighter prefabricated panels, which are more materials and energy-efficient, thereby lowering emissions and resource use. Its reduced installation demands result in lower PO and toxicity emissions.

Operation and maintenance phase

In the part of operation and maintenance, the GW system shows higher impacts than RG across almost all categories. Overall, GW exhibits a GWP100 of 796 kg CO_2 eq, significantly higher than RG's 419 kg CO_2 eq. This is primarily due to the continuous energy demand from irrigation systems, pumps and sometimes lighting used in vertical garden modules. These systems often operate autonomously and require frequent fertilization, which increases impacts in categories such as EP and AP. In contrast the GW's consistent use of liquid fertilizers and chemical additives also results in greater Eco-toxic impacts, particularly in MAE and FWAE, due to runoff and nutrient leaching. Additionally, the HT and TE are similarly elevated due to increased application of chemical agents. On the other side, RG systems, once established, are often low-maintenance and passive, typically relying on natural rainfall and needing minimal chemical inputs. This makes them more environmentally favorable during this phase. Furthermore, their soil systems help filter runoff and reduce Eco-toxic emissions.

Dismantling phase

In the Phase of dismantling, the minimal for both systems, with all categories showing negligible values. This part mainly involves manual or mechanical removal of structural elements and substrates, with no significant chemical or energy use. Hence, the rain garden shows slightly elevated GWP100 and OLD during dismantling due to the transport and disposal of heavier elements such as soil and insulation layers, which may contain residual substances with minor environmental impacts. Nonetheless, these values are very small in absolute terms.

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According to **Table 3**, the LCA of GR and GW reveals diversified environmental impacts at construction, operational and dismantling phases. GRs reflect greater impacts in resource depletion due to intensive vegetation and soil usage during construction, while GWs are more material-intensive with the use of steel and polymers. Operationally, GWs consume more water, electricity and fertilizer, which translate to greater maintenance needs. In later stages of life, GRs perform more organic waste production, whereas GWs produce more environmental material return. These differences reflect the influence of material composition and upkeep on their environmental performance **(Figures 1-3)**.

Table 3: Environmental impact categories for GR and GW

Impact Category	**Unit**	**GR**				**GW**			
		Construction	**Operation & M**	**Dismantling**	**Total**	**Construction**	**Operation & M**	**Dismantling**	**Total**
Abiotic Depletion	kg Sb eq	$4.\times10^{-3}$	5.8×10^{-5}	0.00×10^{0}	4×10^{-3}	1.3×10^{-6}	8.5×10^{-5}	0.00×10^{0}	8.6×10^{-5}
Fossil Fuel Depletion	MJ	9.3×10^{1}	1.2×10^{2}	0.0×10^{0}	2.1×10^{2}	4.8×10^{0}	1.7×10^{2}	0.00×10^{0}	1.8×10^{2}
Acidification	kg SO_2 eq	2×10^{-2}	5×10^{-2}	0.0×10^{0}	6×10^{-2}	2×10^{-3}	7×10^{-2}	0.00×10^{0}	7.1×10^{-2}
Eutrophication	kg PO_4 eq	4.3×10^{-3}	5×10^{-3}	0×10^{0}	10×10^{-3}	3×10^{-4}	7.68×10^{-3}	0.00×10^{0}	8×10^{-3}
Freshwater Toxicity	kg 1,4-	5×10^{-2}	7×10^{-2}	0.0×10^{0}	1×10^{-1}	4×10^{-3}	1×10^{-1}	0.00×10^{0}	1×10^{-1}
Human Toxicity	DB eq	1.2×10^{0}	2.21×10^{0}	0.00×10^{0}	3.4×10^{0}	1.15×10^{-1}	3.24×10^{0}	0.00×10^{0}	3.35×10^{0}
Global Warming Potential	kg CO_2 eq	4×10^{0}	5×10^{2}	2×10^{1}	4.4×10^{2}	5.8×10^{-1}	7.96×10^{2}	2.05×10^{0}	7.8×10^{2}
Ozone Layer Depletion	kg CFC-11 eq	2×10^{0}	6×10^{-1}	2×10^{-2}	2.6×10^{0}	2×10^{-4}	1.06×10^{0}	2.8×10^{-3}	1.06×10^{0}
Photochemical Oxidant Formation	kg C_2H_4 eq	1×10^{-3}	2×10^{-3}	0.00×10^{0}	3×10^{-3}	1×10^{-4}	3×10^{-3}	0.00×10^{0}	3×10^{-3}
Solid Waste	kg1, 4-	5.4×10^{0}	0.0×10^{0}	0.00×10^{0}	5.4×10^{0}	1.10×10^{0}	1.1×10^{0}	0.0×10^{0}	2.2×10^{0}
Terrestrial Toxicity	DBeq	3×10^{-2}	2×10^{-2}	0.00×10^{0}	4×10^{-2}	7.3×10^{-4}	2×10^{-2}	00×10^{0}	2.2×10^{-2}
Marine Eutrophication	kg 1,4-DB eq	1.2×10^{3}	8.3×10^{3}	0.0×10^{0}	9.5×10^{3}	2.3×10^{2}	1.2×10^{4}	0.00×10^{0}	1.3×10^{4}

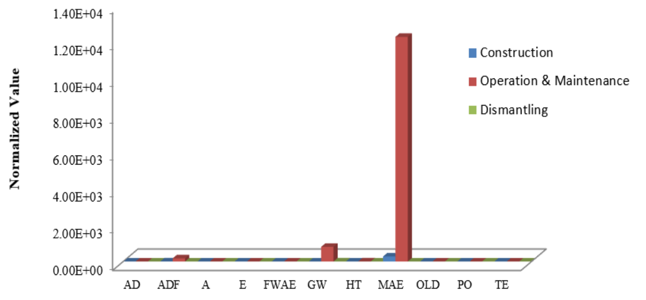

Figure 1: Environmental Impact assessment of GW contribution per measurement categories.

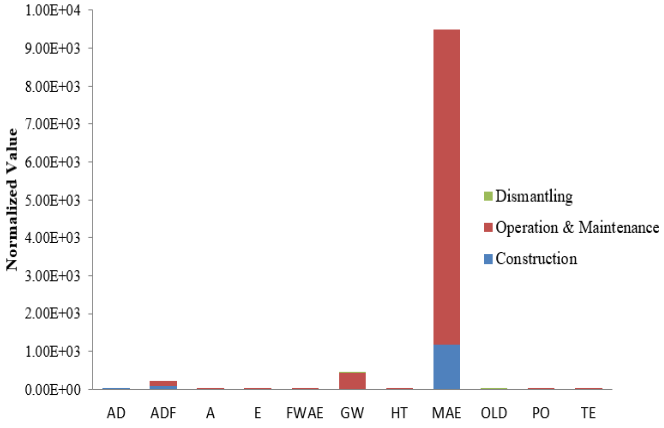

Figure 2: Environmental Impact assessment of GW contribution per measurement categories.

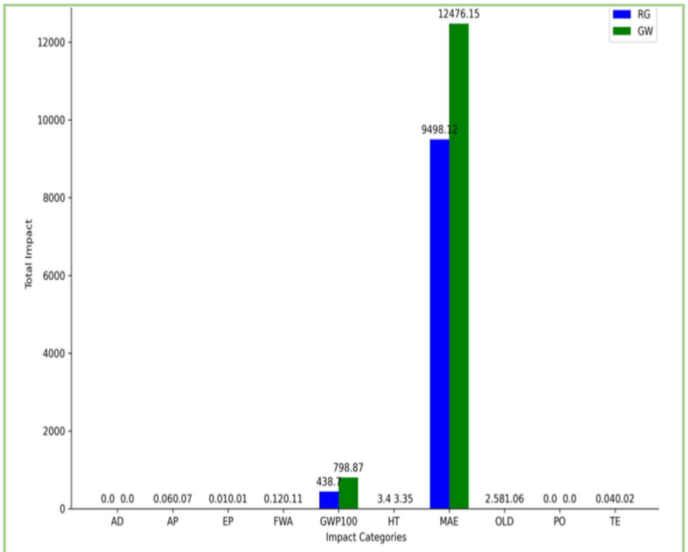

Figure 3: Comparison of LCA impact by category for RG and GW.

Based on the **Figure 4** comparative LCA, the GR system demonstrates a superior environmental performance overall, particularly in terms of GWP with emissions of 439 kg CO_2 eq, GR contributes approximately 45% less to GW than the GR, which emits 799 kg CO_2 eq. This makes GR the more climate-friendly option, which is a critical consideration in sustainable construction and climate mitigation strategies.

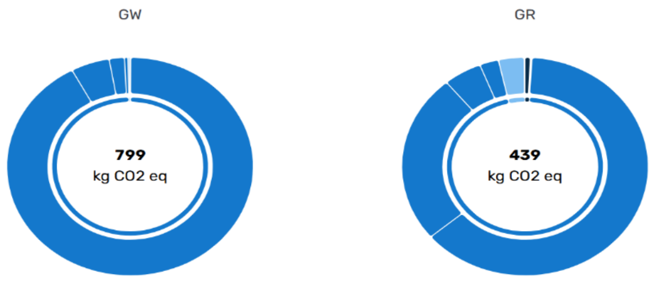

Figure 4: Comparison of impact per item on global warming.

In other word, it is important to note that GR exhibits higher impacts in OLD about 3 kg CFC-11 eq and TE (0.04 kg 1,4-DB eq) compared to GW. Although, these increases, the significantly reduced carbon footprint of GR positions it as the more environmentally advantageous solution when global warming is prioritized as the most urgent impact category. For both systems, it is shown in a separate and comparative form in **Figures 5-14**.

Figure 5: Comparison of impact per item on abiotic depletion.

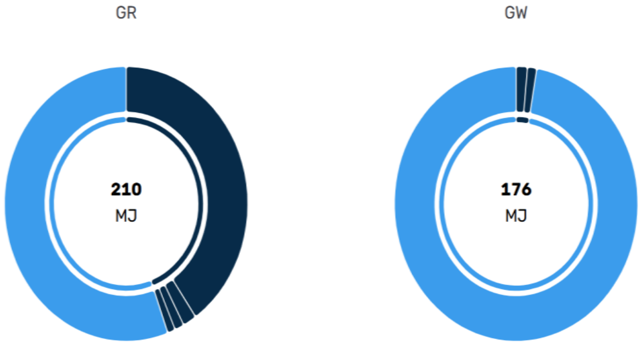

Figure 6: Comparison of impact per item on Abiotic depletion (fossil fuels).

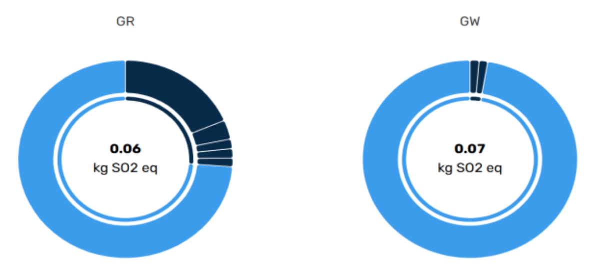

Figure 7: Comparison of impact per item on acidification.

Figure 8: Comparison of impact per item on eutrophication.

Figure 9: Comparison of impact per item on Fresh water aquatic eco-toxic.

Figure 10: Comparison of impact per item on human toxicity.

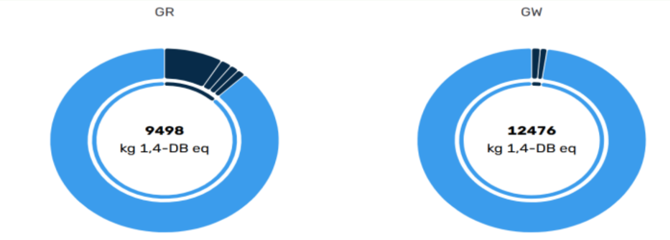

Figure 11: Comparison of impact per item on marine aquatic eco-toxicity.

Figure 12: Comparison of impact per item on ozone layer depletion.

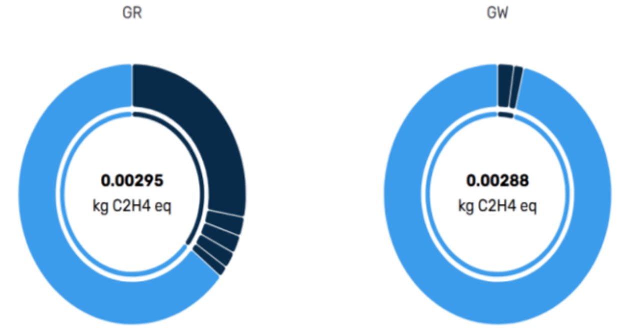

Figure 13: Comparison of impact per item on photochemical oxidation.

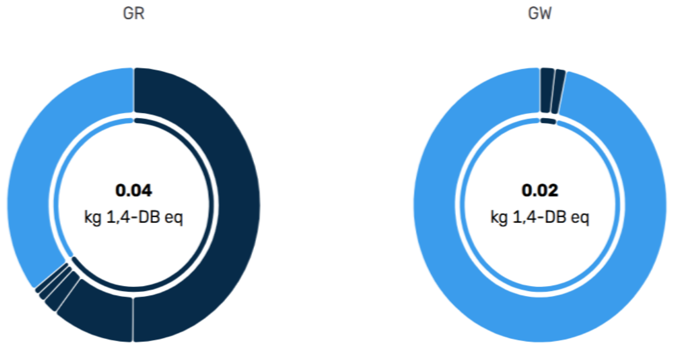

Figure 14: Comparison of impact per item on terrestrial Eco-toxicity.

Conclusion

This research study critically evaluated the environmental performance of RGs and GWs throughout their life cycle using a systematic review approach with ISO-conformant LCA methodology as its basis. Results show that RGs have better performance during the operational stage due to their passive water management and low energy use, while GWs are lower in impact during the construction stage due to their prefabricated, lightweight material design. Quantitatively, GW systems also had a lower global warming during construction (0.58 kg CO_2 eq versus RG's 4.07 kg CO_2 eq), but much higher GWP100 during operation (796 kg CO_2 eq versus 419 kg CO_2 eq for RG). Although, RGs also had greater fossil fuel depletion and solid waste generation at end-of-life. These findings highlight that while GWs systems are defined by energy-efficient buildings, RGs offer more long-term environmental performance. Therefore, application of both systems together, based on priorities at the site level such as improvement of water quality or thermal management as can ensure maximum sustainability outcomes in urban infrastructure. Standardization of LCA boundaries and cyclical impact assessment methodology is critical to improve comparability and assist smart policy and design decisions in green infrastructure planning.

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