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A comparative life cycle assessment of rain garden and green roof systems using the OpenLCA software platform

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Abstract. Global climate change and increasing urbanisation are intensifying pressure on urban infrastructure and natural resources, highlighting the importance of implementing green infrastructure to enhance urban resilience and reduce environmental impacts. The purpose of the study was to conduct a comparative life cycle assessment of a rain garden and a green roof using OpenLCA software (version 2.6, 2025) by modelling their environmental indicators, which made it possible to identify the key climate-related and resource-related parameters of their performance. For the modelling, data were collected at all stages of the life cycle of the structures and normalised per square metre over a 15-year operational period. The main environmental impact categories selected were global warming potential, eutrophication potential, acidification potential and abiotic resource depletion. The results demonstrated a different balance of environmental impacts across the various life cycle stages. The green roof was characterised by a lower impact during the construction phase, for example, a global warming potential of 50 kg CO_2-eq/m^2, due to the use of prefabricated modular blocks. By contrast, rain gardens demonstrated a lower impact during the operational phase, with 130 kg CO_2-eq/m^2 compared with 320 kg CO_2-eq/m^2 for green roofs over 15 years, due to passive stormwater runoff filtration and minimal maintenance requirements. A significant share of the construction-stage impact was associated with the use of quartz sand as a soil additive for rain gardens and bark mulch as a ground cover, which suppresses unwanted vegetation and supports the establishment of target vegetation. At the end-of-life stage, both systems demonstrated minimal overall environmental impact, with most indicators remaining negligible. The results confirmed that none of the green infrastructure systems studied is universally optimal; their effectiveness depends on the specific life cycle stage and local conditions, highlighting the need to consider local objectives and priorities when selecting a system

Keywords: green structures; life-cycle impact analysis; scenario-based modelling; global warming potential; eutrophication potential; acidification potential; abiotic resource depletion

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Introduction

Modern urbanisation is accompanied by denser development and increasing pressure on natural resources and urban infrastructure. Climate change is increasing the frequency of extreme rainfall and heatwaves, raising the risk of flooding and reducing the resilience of urban systems. Under these conditions, traditional engineering approaches are proving inadequate, bringing carbon neutrality strategies to the fore, particularly the development of green infrastructure. Its key elements are rain gardens (RG) and green roofs (GR), as components of urban ecosystems.

According to the analysis by D. Pons Fiorentin *et al.* (2024), green structures (GSs) contribute to the achievement of a number of the UN Sustainable Development Goals by 2030. In particular, they support SDG 11 "Sustainable Cities and Communities" by reducing the urban heat island effect, improving air quality and enhancing the comfort of the urban environment, as well as SDG 13 "Climate Action" through carbon sequestration and improved energy efficiency in buildings. Furthermore, RG and GR contribute to the achievement of SDG 15 "Life on Land" and SDG 6 "Clean Water and Sanitation" through the support of biodiversity and, as M.V. Kravchenko & T.M. Tkachenko (2024) argued, effective stormwater management. GR, classified as extensive or intensive, offer a range of environmental benefits. Authors D. Perivoliotis *et al.* (2023) noted that GR contribute to the thermal insulation of buildings, the regulation of the urban microclimate, and the extension of the service life of roof structures. Researchers M. Kravchenko *et al.* (2024) found that RG systems provide retention, filtration and purification of surface runoff, which helps to reduce the risk of flooding. However, both types of systems are characterised by a significant environmental impact during the construction and operation phases due to the use of materials and resources, which justifies the use of the life cycle assessment (LCA) method for their comprehensive analysis.

To quantitatively assess the environmental advantages and disadvantages of GSs, the LCA method is used, which provides a comprehensive analysis of environmental performance throughout the entire operational life of the systems. In their study, K. Bagheri & H. Davani (2024) concluded that LCA is an environmental management tool based on the "cradle-to-grave" principle, covering stages from raw material extraction to the disposal or recycling of materials. The method enables the quantitative assessment of environmental indicators based on material and energy flows and the identification of the processes with the greatest impact on the environment. In this context, the use of specialised LCA software tools becomes crucial for conducting a comprehensive analysis. Among the most widely used are SimaPro (Netherlands), GaBi LCA Software (Germany), Umberto LCA+ (Germany) and OpenLCA (Germany). According to M. Sečkár *et al.* (2025), these tools enable the assessment of environmental impacts throughout the life cycle, support management decision-making and the formulation of environmental policy, and differ in terms of functionality, databases and modelling approaches. A. Ostovar *et al.* (2026) noted that they support a full LCA cycle and are used for the comprehensive assessment of production systems. A.W. Ahmadi *et al.* (2025) emphasised that the use of commercial platforms may be limited by high licence costs, interface complexity and partial incompatibility between systems, which reduces their accessibility in scientific research. Unlike commercial solutions, OpenLCA is a free, open-source platform that serves as an affordable alternative. It features an intuitive interface and broad compatibility with international databases, which, according to Y. Pamu *et al.* (2022), enabled a comprehensive life-cycle assessment that takes into account environmental, economic and social aspects. Thanks to its open architecture and the absence of licensing restrictions, OpenLCA is widely used in academic research, but it has certain limitations, particularly regarding technical support and working with large databases.

The use of OpenLCA in practical studies enables the analysis of different types of GSs within a comparative life-cycle context. L. Pique *et al.* (2023) found that in the largest proportion of LCA studies (37%), GR are compared with gravel surfaces, whilst in 10.4% they are compared with 'white' roofs. In less than 10% of studies, GR are compared with other types of GSs, in particular RG, which indicates that this area is under-researched. There are only a few LCA studies of RG in the literature. For instance, Y. Peng *et al.* (2024), using Energy Expert, assessed only the global warming potential without considering other impact categories and without comparing with alternatives, which limits the generalisability of the results and confirms the need for a comprehensive comparative analysis. The purpose of the study was to conduct a comparative assessment of the impact of GR and RG on key climate and resource indicators using the LCA method in the OpenLCA software environment. The analysis covered the main stages of the life cycle and took into account the specifics of modelling, the selection of system boundaries and input data to formulate recommendations for standardising future LCA studies in the field of sustainable urban planning and climate adaptation.

Materials and Methods

In this study, the OpenLCA software (version 2.6, 2025) was used to model the life cycle of GR and RG. This software enables iterative model building, accounting of material and energy flows, and the calculation of environmental indicators. During the inventory analysis stage, the ELCD 3.2 (European Reference Life Cycle Database) dataset, as maintained by GreenDelta (v.2.18, 2022), was used. This database contains standardised data on material production, energy supply, and transport operations. The use of the ELCD reference database ensures consistency of results with European methodological frameworks, guarantees high reproducibility of the study, and supports comparability of indicators in the context of sustainable construction and urban planning.

The methodological basis for the study is provided by the ISO 14040:2006 (2006) and ISO 14044:2006 (2006) standards, which set out the principles, structure and procedures for conducting an LCA. In accordance with these standards, the scope and boundaries of the system were defined within the OpenLCA environment, an inventory analysis was carried out, and an impact assessment and interpretation of results were performed for the GR and RG systems, ensuring methodological consistency, comparability of results and their reproducibility (Popowicz *et al*., 2025). During the stage of defining the system boundaries and input data, a real-world study object was selected and justified – the RG, built in August 2024 in the Kyiv region (Fig. 1).

Figure 1. Construction stages of the RG (Kyiv region)

Source: created by the authors

The RG is designed to collect, retain and infiltrate rainwater runoff from the roof of an adjacent building with an area of 52.0 m². The water is channelled via a downpipe directly into the bio-infiltration system. The total area of the RG is 2.55 m² (1.7 × 1.5 m), making it a small-scale green infrastructure solution for local surface runoff management. The materials used for the construction of the structure and their specific weights are given in Table 1. In addition, the table provides the corresponding material names according to the OpenLCA software environment database.

Table 1. Materials used in the construction of the RG and their respective proportions

RG components	Material name in OpenLCA	Layer thickness (mm)	Material	Specific weight (kg/m²)
Vegetation layer	-	-	*Iris pseudacorus L., Rosa gallica L., Chrysanthemum × koreanum, Tagetes lucida, Sedum lydium*	-
Mulch	spruce wood	50	Spruce wood	12.0
Substrate	excavated material	200.0	Soil	280.0
Intermediate filtration layer	sand 0/2	300.0	Sand	480.0
Lower drainage layer	gravel 2/32	300.0	Gravel	500.0
Filter element (synthetic fibre)	polypropylene fibres	-	Polypropylene fibres	0.1
Separating element (geotextile)	polyethylene terephthalate	-	Polyethylene terephthalate	0.2

Source: created by the authors

To conduct a comparative LCA, a model GR was selected as the second study object, with parameters formulated based on common technical solutions for extensive green roofing used in sustainable urban construction practice. The use of a hypothetical structure allows for the standardisation of modelling input data and ensures a valid comparison with the RG. The GR is considered an extensive structure designed to reduce surface runoff, improve the building's thermal insulation characteristics and mitigate climatic impacts in the urban environment. For modelling purposes, a flat roof with an area of 52.0 m² was adopted, corresponding to the catchment area used for RG, in order to ensure the comparability of LCA results. The GR is multi-layered, and its composition and the relative weight of the layers are shown in Table 2.

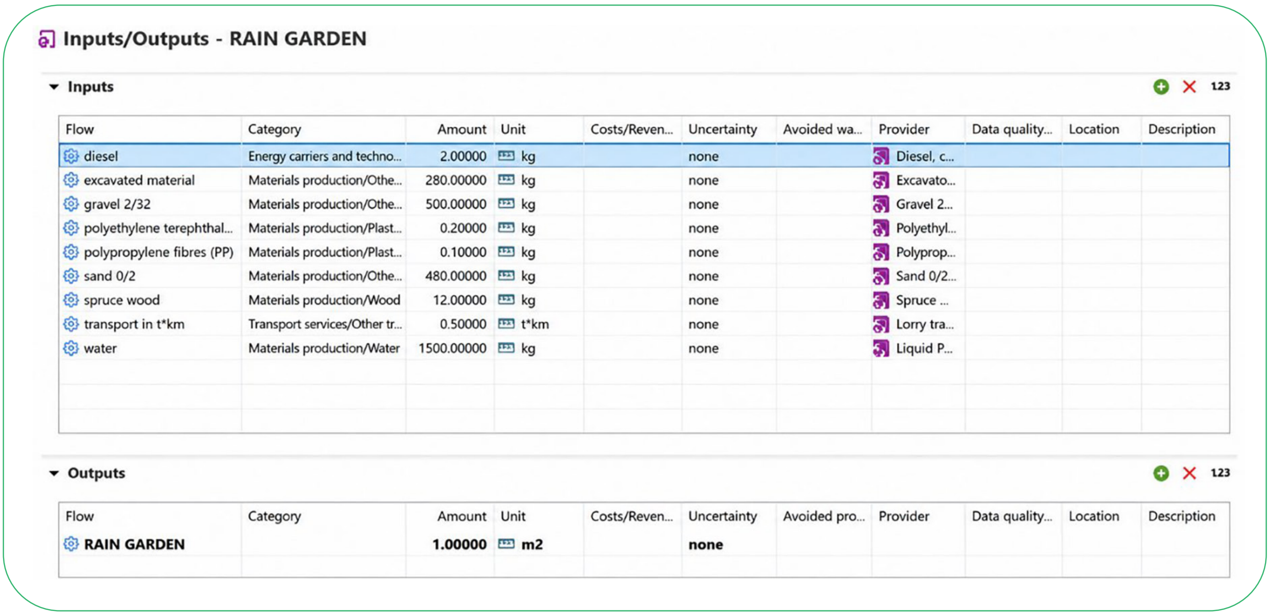
Table 2. Materials used in the construction of GR and their proportions

GR components	Material name in OpenLCA	Layer thickness (mm)	Material	Specific weight (kg/m²)
Vegetation layer	-	-	*Sedum*	5.0
Mulch	Spruce wood	30	Spruce wood	7.5
Substrate layer	excavated material	150.0	Soil	50.0
	gravel 2/32		Gravel	48.0
	sand 0/2		Sand	48.0
	kaolin coarse filler		Kaolin	30.0
Additional filter/separator	polyethylene terephthalate		Polyethylene terephthalate	0.2
Drainage layer	polystyrene (general purpose)	25.0	Polystyrene	0.5
Protective layer	polypropylene fibres	-	Polypropylene fibres	0.3
Roof barrier (waterproofing)	polyvinylchloride	1.0	Polyvinyl chloride	1.4

Source: created by the authors

Plant components in both systems were not included in the life cycle inventory analysis due to the absence of relevant processes in the OpenLCA database used. Given the relatively low mass of plant biomass compared to the mineral structural layers, their direct contribution to environmental impacts is considered negligible. In addition, vegetation helps to offset CO_2 emissions during the operation of the systems. Therefore, the modelling focused on construction materials and transport processes, which account for the majority of the environmental impact.

A list of building materials was compiled, specifying their quantitative characteristics. The resulting volumes were expressed in units of mass for subsequent use as input data in the life cycle modelling software. Figures 2-3 show the composition of materials and their quantitative indicators for modelling the RG and GR per unit area of 1 m² in the OpenLCA software environment. Among energy resources, attention was focused on diesel fuel, which is used for construction and transport operations. For the LCA modelling, the amount of diesel consumed was taken into account, as this allows for a correct assessment of the contribution of transport and construction operations to the overall environmental impact of the system's life cycle. All transport volumes were converted into tonne-kilometres (t · km), which is a standard metric for quantifying freight transport in life cycle models. This metric is used as an input parameter in the LCA modelling software.



Inputs/Outputs - RAIN GARDEN

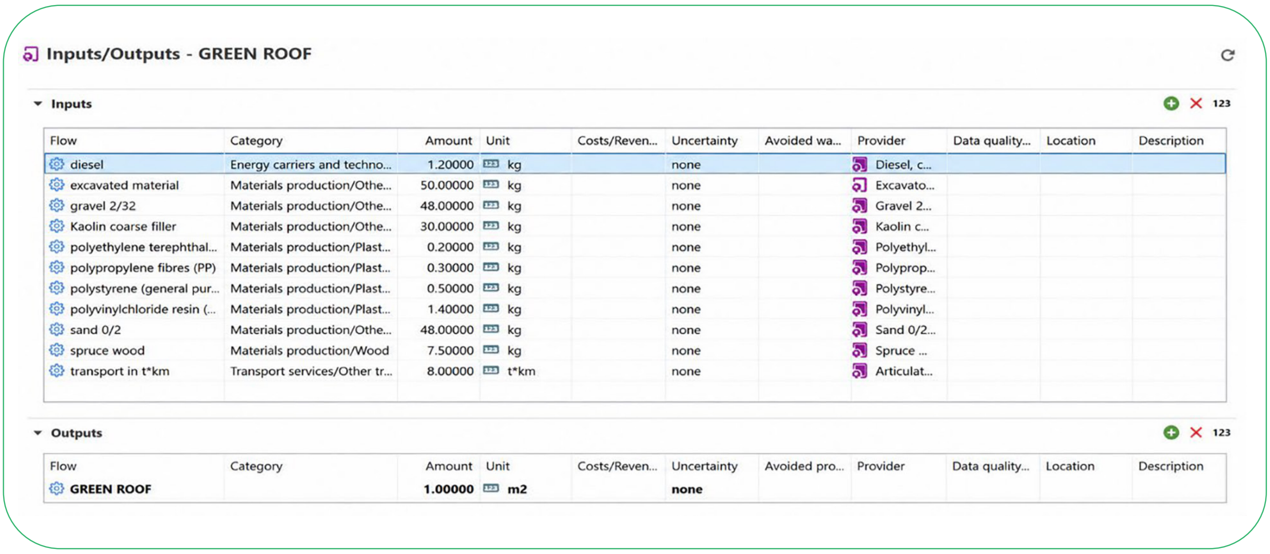
Inputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided wa...	Provider	Data quality...	Location	Description
diesel	Energy carriers and techno...	2.00000	kg		none		Diesel, c...			
excavated material	Materials production/Othe...	280.00000	kg		none		Excavato...			
gravel 2/32	Materials production/Othe...	500.00000	kg		none		Gravel 2...			
polyethylene terephthal...	Materials production/Plast...	0.20000	kg		none		Polyethyl...			
polypropylene fibres (PP)	Materials production/Plast...	0.10000	kg		none		Polyprop...			
sand 0/2	Materials production/Othe...	480.00000	kg		none		Sand 0/2...			
spruce wood	Materials production/Wood	12.00000	kg		none		Spruce ...			
transport in t*km	Transport services/Other tr...	0.50000	t*km		none		Lorry tra...			
water	Materials production/Water	1500.00000	kg		none		Liquid P...			

Outputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided pro...	Provider	Data quality...	Location	Description
RAIN GARDEN		**1.00000**	**m2**		**none**					

Figure 2. Input parameters and material composition of the Rain Garden model in the OpenLCA software
Source: created by the authors based on their own modelling in OpenLCA



Inputs/Outputs - GREEN ROOF

Inputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided wa...	Provider	Data quality...	Location	Description
diesel	Energy carriers and techno...	1.20000	kg		none		Diesel, c...			
excavated material	Materials production/Othe...	50.00000	kg		none		Excavato...			
gravel 2/32	Materials production/Othe...	48.00000	kg		none		Gravel 2...			
Kaolin coarse filler	Materials production/Othe...	30.00000	kg		none		Kaolin c...			
polyethylene terephthal...	Materials production/Plast...	0.20000	kg		none		Polyethyl...			
polypropylene fibres (PP)	Materials production/Plast...	0.30000	kg		none		Polyprop...			
polystyrene (general pur...	Materials production/Plast...	0.50000	kg		none		Polystyre...			
polyvinylchloride resin (...	Materials production/Plast...	1.40000	kg		none		Polyvinyl...			
sand 0/2	Materials production/Othe...	48.00000	kg		none		Sand 0/2...			
spruce wood	Materials production/Wood	7.50000	kg		none		Spruce ...			
transport in t*km	Transport services/Other tr...	8.00000	t*km		none		Articulat...			

Outputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided pro...	Provider	Data quality...	Location	Description
GREEN ROOF		**1.00000**	**m2**		**none**					

Figure 3. Input parameters and material composition of the Green Roof model in the OpenLCA software

Source: created by the authors based on their own modelling in OpenLCA

The study analysed four impact categories: global warming potential (GWP100), acidification potential (AP), eutrophication potential (EP) and abiotic resource depletion (AD). The selection of these categories is driven by the need for a comprehensive comparison of the environmental characteristics of GR and RG throughout their life cycle, particularly in terms of their impact on climate change, natural resource consumption and potential environmental consequences. The impact categories used are widely employed in LCA studies of green infrastructure and align with the approaches of common LCA methodologies implemented in the OpenLCA software environment. The approach to selecting indicators was based on the work of Y. Pamu *et al.* (2022), which outlines the main categories of environmental impact used to assess building and nature-based systems.

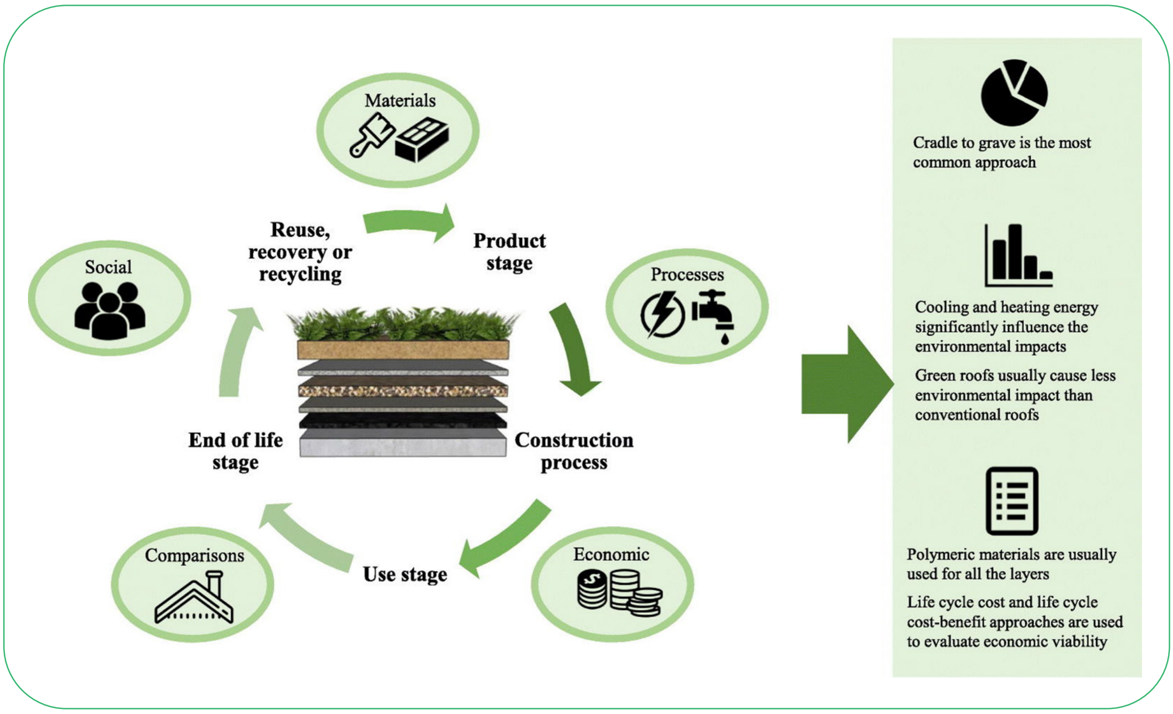
The GWP100 characterises the total contribution of all greenhouse gas emissions throughout the object's life cycle and is expressed in kilograms of CO_2 equivalent, which allows for a quantitative assessment of its carbon footprint. AP potential determines the formation of acid-forming emissions, primarily sulphur oxides (SO_2) and nitrogen oxides (NO_x), which, when interacting with atmospheric moisture, form acid rain and negatively impact soil and aquatic ecosystems. EP potential characterises the input of nitrogen and phosphorus compounds into the aquatic environment, which can cause excessive algal growth and disrupt ecological balance; for nature-based stormwater management solutions, this indicator is particularly relevant given the potential migration of nutrients from substrates and soil layers. AD characterises the consumption of non-renewable natural resources of inorganic origin, in particular mineral raw materials and fossil materials, used in the production of structural elements and building materials.

Other impact categories were not analysed within the scope of this study. This is because the systems under investigation do not involve the use of technological processes or materials associated with significant emissions of ozone-depleting or highly toxic substances on a scale capable of substantially influencing the results of the comparative assessment. The operational phase covers all input and output flows, as well as the environmental benefits accumulated over the life cycle of RG and GR. The calculation of impacts and benefits is based on an assessment of annual indicators, which are extrapolated linearly over the entire operational period. Given the limited data on the durability of such systems, a 15-year design service life has been established for the analysis.

Results and Discussion

A schematic representation of the stages of the GR life cycle is shown in Figure 4, which illustrates the interrelationship between all the key stages of its operation within the LCA approach. The system boundaries for GR assessment are defined as: extraction, transport and production of necessary materials; installation, operation, maintenance, refurbishment, dismantling and final disposal; reuse, recovery or recycling of materials.

The conceptual model for assessing the life cycle of a multi-layer GR structure has been developed taking into account the environmental, economic and social aspects of sustainable development. At the centre of the model is a structural system comprising several functional layers (vegetation layer, substrate, drainage, filtration, and waterproofing layers) that form an integrated ecological and engineering system. The main stages of the life cycle are structured around it in accordance with the cradle-to-grave approach, which is the most widely used methodology for comprehensive environmental assessment.



Cradle to grave is the most common approach

Cooling and heating energy significantly influence the environmental impacts

Green roofs usually cause less environmental impact than conventional roofs

Polymeric materials are usually used for all the layers

Life cycle cost and life cycle cost-benefit approaches are used to evaluate economic viability

Figure 4. GR life cycle diagram within the LCA approach

Source: T.P. Scolaro & E. Ghisi (2022)

The product stage (material production) covers the extraction of raw materials, the production of polymer and mineral components, transport, and the preparation of installation materials. At this stage, the primary energy and carbon costs associated with production processes are incurred. An additional contributing factor is the significant energy consumption associated with the production of individual functional layers, primarily polymer components, which are typically used in almost all structural elements, except the load-bearing structure (Scolaro & Ghisi, 2022).

The construction/installation process involves transporting materials to the site, carrying out installation work, and using construction machinery and energy resources. This stage is characterised by additional energy demand and associated emissions. Compared to traditional roofing systems, installing GR requires higher material consumption because its design features a multi-layered structure. This leads to increased use of material resources, particularly polymer and mineral components, some of which are produced from non-renewable raw materials.

The operational phase is critical in terms of environmental performance. During operation, GR influences a building's energy demand, particularly heating and cooling requirements. Reducing thermal loads through the thermal insulation and evaporative properties of the plant layer helps cut operational energy costs and, consequently, reduce greenhouse gas emissions. At this stage of the life cycle, environmental burdens associated with system maintenance are also taken into account, in particular watering, vegetation care and the periodic replacement of individual components. The LCA model includes all associated material and resource flows related to operation, in particular the use of water for irrigation, fertilisers and other auxiliary materials, which contribute to additional environmental impacts throughout the facility's life cycle.

The end of the life cycle involves dismantling the system, sorting components, and their disposal, recycling or reuse in accordance with the chosen waste management scenario. As the use of polymeric materials is characteristic of most structural layers of GR, it is necessary to model alternative end-of-life scenarios, in particular recycling or reuse. Including such scenarios within the LCA allows for an assessment of the potential to replace primary resources with secondary raw materials. In their study, G. Rizzo *et al.* (2023) concluded that end-of-life scenarios for GR may involve the reuse of the substrate, the composting of plant biomass, and the recycling or energy recovery of the polymer components of individual functional layers. The results of the analysis indicated the potential of applying reuse and recycling strategies to reduce the consumption of primary resources and lower the environmental impact throughout the life cycle of structures, which is consistent with the principles of the circular economy.

Unlike GR, the RG (Fig. 5) is a surface runoff management system that functions as an element of green infrastructure and nature-based solutions. At the material production stage, the system comprises soil mixtures, sand, gravel, vegetation and geotextiles. Compared to GR, whose design contains a significant proportion of polymeric materials, the RG structure is dominated by natural and mineral components (Kravchenko & Tkachenko, 2024).

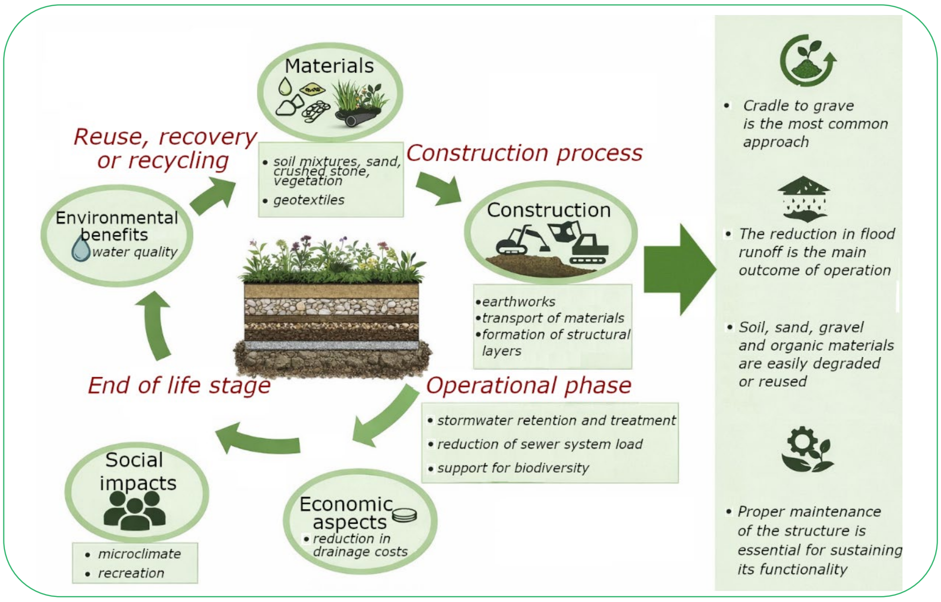


Figure 5. RG life cycle diagram within the LCA approach

Source: created by the authors

The construction phase of an RG system involves earthworks, the transport of materials and the formation of infiltration layers. The construction of an RG system does not require complex installation operations or lifting equipment, but may involve significant amounts of earthworks. The carbon footprint of this phase is primarily attributable to the use of construction machinery and logistics processes. During the operational phase, RG facilitates the retention and treatment of surface runoff, reduces the load on the stormwater drainage system and supports biodiversity. Unlike GR, which directly influences a building's energy consumption, RG has no direct energy impact. Its contribution to climate change mitigation is indirect and relates to reduced flood risk, improved local microclimate, and biomass accumulation. When assessing the GWP100 potential at this stage, it is necessary to account for material and resource flows associated with system maintenance, including periodic vegetation renewal, partial replacement of the filtration layer, and the possible use of fertilisers and irrigation water (Kravchenko *et al.*, 2024).

The end of the life cycle involves dismantling structural layers and implementing appropriate material management scenarios. Most RG materials can be reused, recycled or integrated into the natural environment with minimal environmental impact. In their LCA of biofiltration systems, K. Karabay *et al.* (2024) highlighted that at the end-of-life stage of RG, scenarios involving partial dismantling of structural layers are possible, with the materials subsequently managed in accordance with circular-economy principles. In particular, the filtration medium can be reused after regeneration or removal of contaminated fractions, reducing the need for new materials and disposal costs. In this context, the authors demonstrate the economic viability of reusing the soil (filtration) medium of biofiltration systems: in the scenario presented, the cost of reuse was approximately US$5,500, whereas the disposal cost was approximately US$6,000, confirming the potential economic advantage of material reuse approaches.

Table 3 presents the results of modelling in the OpenLCA software environment and a comparative assessment of the main categories of environmental impact from the operation of RG and GR structures per 1 m^2 over 15 years. The assessment was carried out according to the life cycle stages of the systems, specifically: C – construction stage (production of materials, transport and installation of the structure), O – operation stage (functioning of the system and its maintenance over the calculation period), D – dismantling stage or end of the structure's life cycle. The symbol Σ represents the total environmental impact for the relevant category throughout the entire life cycle of the system.

Table 3. Environmental impact categories of RG and GR based on LCA modelling results

Impact category	Unit	RG				GR			
		C	*O*	*D*	Σ	*C*	*O*	*D*	Σ
AD	kg Sb eq	4.5×10^{-3}	6.0×10^{-5}	5.0×10^{-6}	4.6×10^{-3}	1.6×10^{-5}	8.6×10^{-5}	1.0×10^{-5}	1.2×10^{-4}
AP	kg SO_2 eq	2.1×10^{-2}	6.0×10^{-2}	0	8.1×10^{-2}	2.5×10^{-3}	8.0×10^{-2}	0	8.3×10^{-2}
EP	kg PO_4 eq	4.0×10^{-3}	8.0×10^{-3}	5.0×10^{-4}	1.3×10^{-2}	3.2×10^{-4}	4.2×10^{-3}	3.0×10^{-4}	4.9×10^{-3}
GWP100	kg CO_2 eq	145.0	130.0	13.0	288.0	50	320	22.0	392.0

Source: created by the authors based on their own modelling in OpenLCA

For RG, the greatest impact is observed during the construction phase in the AD and GWP100 categories, whereas for AP and EP, the main contribution arises during operation. Overall, the total GWP100 value for RG is 288 kg CO_2-eq. In the GR design, the dominant impact occurs during the operational phase, particularly for GWP100, where the figure reaches 320 kg CO_2 eq. The other categories (AD, AP, EP) have a significantly lower impact at all stages, and the total values do not exceed 0.1 kg equivalent. The results obtained also highlighted the need to harmonise methodological approaches in future LCA studies of green infrastructure projects. In particular, comparative assessments should be carried out based on a single functional unit, clearly defined system boundaries and a transparent division of the construction, operation, maintenance and end-of-life stages. The use of a standardised set of impact categories, in particular GWP100, AD, AP and EP, will help to improve the comparability of results across studies and facilitate the development of evidence-based recommendations for sustainable urban planning.

J.R. Vaghela *et al.* (2024) demonstrated that discrepancies between LCA software tools (GaBi and OpenLCA) are primarily due to system definition, modelling assumptions and database structure, rather than differences in computational algorithms. The authors found that GWP100 values are relatively stable across different tools, whereas impact categories related to toxicity and ecosystem impacts show greater variability. This is of direct relevance to this study, as it confirms that the observed differences between RG and GR are due to the characteristics of the systems themselves – material composition, material intensity and energy consumption during the use phase – rather than software-specific features. Furthermore, the authors emphasise the need to harmonise system boundaries and ensure consistency in life-cycle inventory data to improve the comparability of LCA results, which is consistent with the methodological approaches applied in this study. The software environment supports both manual and automated modelling of product systems, providing comprehensive impact assessment results that can be visualised as graphs and diagrams and exported to spreadsheet formats, including Excel, as highlighted by B.D.M. Souza *et al.* (2025). For an in-depth analysis of the results obtained, the absolute values of the indicators were additionally converted into relative values (as percentages), which made it possible to determine the share of individual life cycle stages and components in the overall environmental impact. An analysis of the results presented in Figure 6 shows that the RG is characterised by higher environmental impact indicators during the construction phase, particularly in the AD and GWP100 categories. This trend is due to the structure's high material intensity, which involves the use of significant quantities of mineral materials and organic coating components. The extraction, transport and preparation of these materials involve substantial consumption of energy and natural resources, as well as emissions of greenhouse gases and pollutants, which account for the majority of the environmental impact at this stage of the life cycle.

Similar results were obtained in a study by X. Hu & F. Gu (2025), who assessed the life cycle of RG in Wenzhou, a coastal city in eastern China, and found that the construction phase is the main source of environmental impact. In particular, the contribution to the GWP potential at this stage amounts to 4.07 kg CO_2 eq. The results reported by the authors are consistent with the findings of this study, as both confirm that the construction phase is a key factor in the overall environmental impact of RG. However, the magnitude of the impact on GWP in their study is lower than in this assessment, which can be explained by differences in system configuration, material composition and regional context. Nevertheless, despite these quantitative differences, both studies demonstrate the same qualitative trend, namely the dominant role of the construction phase in the impact profile of RG throughout their life cycle.

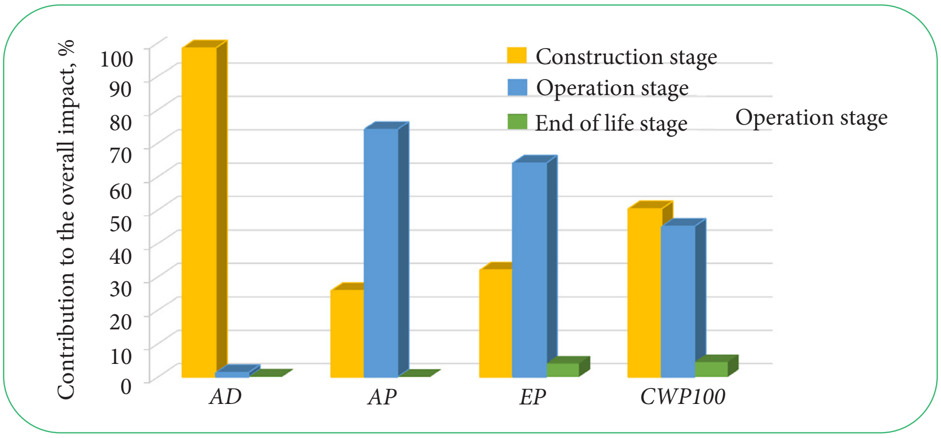


Figure 6. Relative contribution of RG life cycle stages to the main environmental impact categories
Source: created by the authors based on their own modelling in OpenLCA

For the GR system (Fig. 7), relatively lower environmental impact values are observed during the construction phase across most of the categories considered. This can be attributed to the lower mass of mineral materials in the structure and the use of relatively thinner substrate layers. However, polymer and waterproofing materials, which form part of the multi-layer system, make a significant contribution to the environmental impact profile of GR. According to L. Tams *et al.* (2022), it has been established that the production stage of the structural layers accounts for the largest contribution to the overall environmental impact of GR. In particular, synthetic components, including waterproofing membranes, drainage and protective layers, are characterised by high energy consumption during production and significant greenhouse gas emissions, due to the use of fossil raw materials and energy-intensive polymerisation processes. The production of these synthetic components involves high energy demand and greenhouse gas emissions, resulting in relatively higher indicators for the AD and GWP100 categories for GR compared with the AP and EP categories.

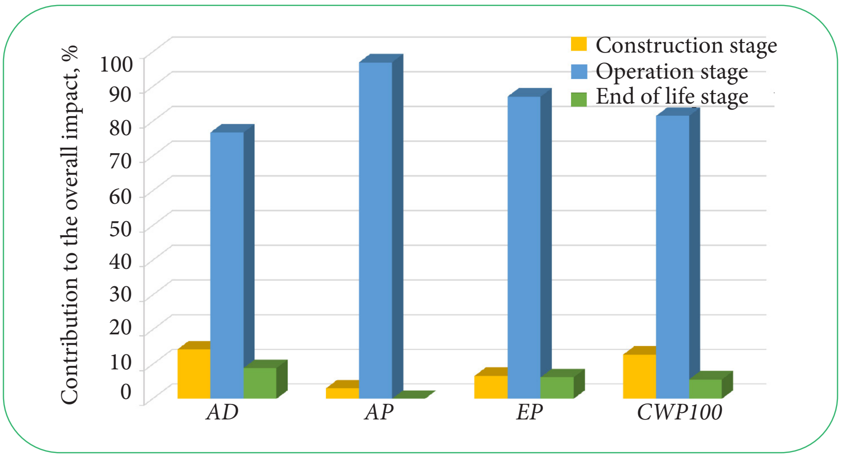


Figure 7. Relative contribution of GR life cycle stages to the main environmental impact categories
Source: created by the authors based on their own modelling in OpenLCA

During the operation and maintenance phase, the GR demonstrates a higher environmental impact compared to the RG in most of the categories studied. The main reason for this difference is the need for the continuous operation of engineering systems, in particular irrigation equipment, pumps and, where necessary, lighting systems, which results in regular energy consumption throughout the operational period. In contrast, once commissioned, RG functions primarily as a passive ecosystem, relying on natural precipitation and requiring no significant energy expenditure or intensive technical support. Minimal maintenance requirements and limited use of additional materials ensure lower operational burdens. Furthermore, the soil and vegetation layers of the RG provide retention, infiltration and partial treatment of stormwater runoff, which enhances the system's overall environmental performance throughout its life cycle due to the ecological benefits associated with improved urban vegetation, a reduction in the inflow of pollutants into water bodies, and a reduction in the load on combined sewer systems due to a decrease in surface runoff volume through infiltration and evaporation, as demonstrated in the study by M. Kravchenko *et al.* (2024). Taken together, the results indicate that RG is characterised by a more sustainable operational model and lower resource consumption compared to GR.

From a methodological perspective, the results obtained indicate the need to systematically account for resource and energy consumption associated with the operation and maintenance of systems in future LCA studies, as differences in the assumptions made can significantly affect the overall environmental profile of the facilities. Standardising assumptions regarding maintenance intervals, irrigation requirements, replacement of individual components, and estimated service life will help to improve the consistency and reproducibility of results. Similar findings were published in a paper by A.W. Ahmad *et al.* (2025), who conducted a comparative LCA of RG and green walls (GW) based on a systematic review of 25 peer-reviewed publications in accordance with ISO 14040:2006 (2006) and ISO 14044:2006 (2006) standards. Their results are consistent with the findings of this study, particularly regarding the dominant role of the operational phase in systems with active technical components. Their analysis highlights the relatively lower environmental impact during the construction of GW due to the use of prefabricated modular elements, which differs somewhat from the results of this study regarding RG, where the environmental impact during construction remains significant due to the multi-layered composition of materials. However, both studies agree that RG have a lower environmental impact during operation due to their passive functioning and the use of natural hydrological processes.

By comparison, G.M.J.A. Salah & A. Romanova (2021) found in their GW life-cycle study that the contribution to the GWP100 value during the construction phase is 2.86 kg CO_2eq/m^2, whilst during the maintenance phase it is 12.44 kg CO_2eq/m^2·year. Within the scope of our own study on GR systems, results of a similar order of magnitude were obtained: 3.33 kg CO_2eq/m^2 during the construction phase and 21.33 kg CO_2eq/m^2·year during the operational phase, confirming the dominance of the operational phase in the overall life cycle of this type of GS.

At the end of their life cycle, both RG and GR have a low overall environmental impact, with the values for most impact categories remaining negligible. This phase involves the dismantling of structural elements and the removal of substrates with minimal energy consumption and no intensive technological processes. However, the GR exhibits slightly higher GWP100 values, which may be linked to the transport and subsequent disposal of heavier materials, particularly soil substrate and individual structural layers. Nevertheless, even under these conditions, the absolute impact values remain low compared to the construction and operation phases. Figure 8 provides a graphical summary of the contribution of individual building materials and processes to the environmental impact of RG structures, broken down by key assessment categories. A value of 100% corresponds to the total impact of the construction phase for each individual environmental impact category.

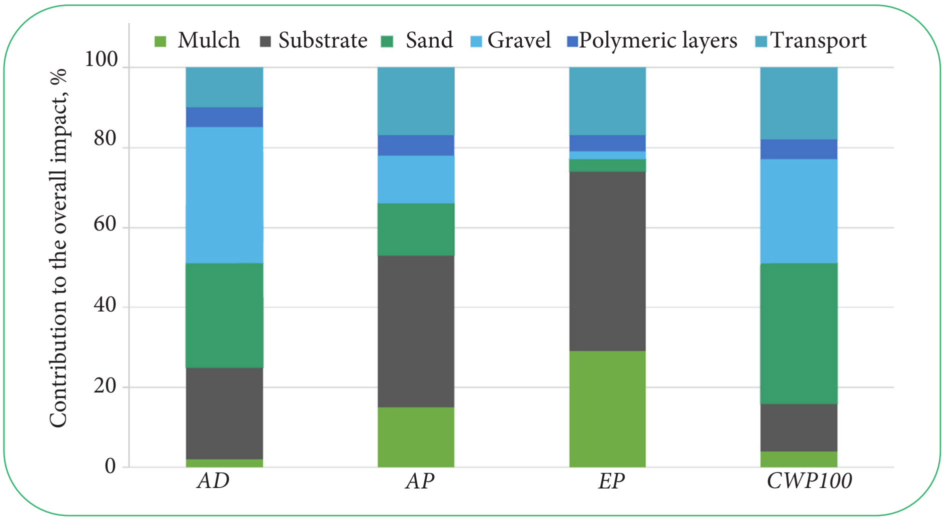


Figure 8. Breakdown of the contribution of structural elements and transport costs to the overall environmental impact of RG by main LCA categories

Source: created by the authors based on their own modelling in OpenLCA

An analysis of the contribution of individual materials to the environmental impact of RG indicates that one of the key factors is the use of quartz sand, which is employed to form the intermediate filtration layer of RG. The thickness of this layer is typically 10-30 cm, depending on the system's design features, soil type and design requirements for permeability (Kravchenko *et al.*, 2024). A significant proportion of this material's environmental impact is primarily due to the processes of its extraction, mechanical processing and transport, which involve energy consumption and the use of natural resources. Consequently, quartz sand makes a significant contribution to most of the environmental impact categories studied, particularly the AD, AP and GWP100 potentials.

Similar patterns are confirmed by the results of LCA of natural mineral aggregates by W. Xing *et al.* (2022), according to which the main sources of environmental impact are extraction processes, the operation of mining machinery and the consumption of diesel fuel during the operation of quarry equipment. An additional factor contributing to the environmental impact is the transport of materials to the point of use, which can significantly increase the total environmental footprint. The combination of these processes accounts for a significant proportion of the carbon footprint of mineral aggregate production, which explains the notable contribution of quartz sand to the GWP100 potential category within the environmental profile of the system under study. In view of this, it is advisable to consider alternative materials or design solutions that allow for a reduction in the proportion of this component within the RG substrate. One possible approach is the use of local natural soils or soil mixtures with lower infiltration rates, which may require an increase in the RG area to ensure similar stormwater management efficiency. Another option is to replace quartz sand with natural sand, sandy soil or specially prepared artificial substrates. Furthermore, a reduction in the environmental impact can be achieved by optimising the RG design, in particular by reducing the depth of the filter layer and correspondingly reducing the volume of sand used.

Another promising approach to optimising RG designs is the use of modified soil mixtures containing biochar additives, as confirmed by the results of numerical modelling of hydrological processes carried out by L. Gan *et al.* (2025). In particular, the authors found that adding biochar at concentrations of 5-15% to the soil medium significantly increases the substrate's water-holding capacity and the efficiency of rainwater runoff regulation. Substrates with a combined layered structure demonstrate a reduction in peak surface runoff of up to 19.52% and an increase in runoff retention time of up to 24 minutes, depending on the configuration of the layers, which indicates the potential to improve hydrological efficiency without a significant increase in the material intensity of the system.

The top layer of the substrate makes the greatest contribution to the formation of AP and EP potential. This is due to the presence of organic components (compost, peat, organic additives), the production and transport of which are accompanied by emissions of nitrogen and phosphorus compounds. Furthermore, during the system's operation, organic matter undergoes mineralisation, which can lead to the release of nutrients and increase the risk of eutrophication and acidification of natural ecosystems (Silva *et al.*, 2024). An additional source of environmental impact is bark mulch, which is used to form a surface cover, suppress unwanted vegetation and support the growth of target plant species. Its contribution is most noticeable in the AP and EP potential categories, which is explained by the biochemical decomposition of organic matter and the possible release of nutrients (Fér *et al.*, 2022). In addition, the stages of harvesting, preparation and transport of mulch are accompanied by additional greenhouse gas emissions, which account for its contribution to the GWP100 potential. Although mulching is an effective and economically viable method for protecting soil cover and stabilising RG vegetation, it is advisable to consider alternative materials with a smaller environmental footprint. In particular, the use of mulch produced on-site from shredded wood residues or other organic waste generated during the maintenance of green spaces is promising. In some cases, the use of recycled materials is also possible, such as rubber mulch from recycled tyres, as demonstrated by A. Mohajerani *et al.* (2020).

When using bark mulch, it is advisable to limit its application to the initial stage of RG vegetation establishment, when it is necessary to stabilise the soil and promote plant rooting. Further regular renewal of the mulch layer throughout the entire operational period of the system should only be carried out if there is an actual need to maintain the proper condition of the vegetation cover. Polymer elements in the RG are present in limited quantities (in particular, geotextiles or auxiliary protective layers), so their contribution to the overall environmental impact is relatively insignificant compared to the mineral and organic components of the system. Transport processes also make a significant contribution to all the environmental impact categories under investigation. This is due to the use of fossil fuels during the transport of construction materials to the project site. These emissions directly influence the GWP100 potential and also contribute to the AP and, to a lesser extent, the AD categories.

The distribution of the contribution of structural elements and transport costs to the overall environmental impact of GR across the main LCA categories (Fig. 9) demonstrates a different impact structure, determined by the specific design features of the system. The largest contribution to the EP potential is provided by the mulch or organic surface layer, which is associated with the presence of organic matter and the potential release of nutrients.

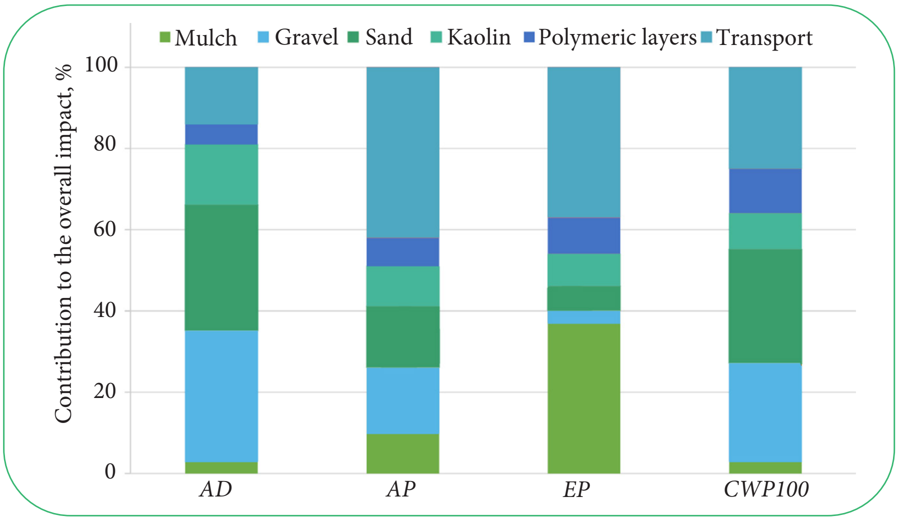


Figure 9. Breakdown of the contribution of structural elements and transport costs to the overall environmental impact of GR by main LCA categories

Source: created by the authors based on their own modelling in OpenLCA

The gravel used in the drainage layer makes the largest contribution to the AD, AP and GWP100 categories, which is explained by the energy-intensive processes of extraction, crushing and transport of mineral materials. Similar findings are reported in life cycle studies of natural aggregates conducted by J. Los Santos-Ortega *et al.* (2025), who show that the production of 1 tonne of coarse gravel aggregate is associated with emissions of approximately 4.3 kg CO_2-eq, along with significant fossil energy consumption (over 100 MJ) and resource use. These results are generally consistent with the present study, although differences in emission magnitude can be attributed to variations in processing technologies, system boundaries, and inventory assumptions. Nevertheless, both studies confirm that gravel production is a key hotspot in terms of environmental impact, driven by high energy demand and associated CO_2 emissions, which contribute substantially to AD, AP, and GWP100 impact categories.

Quartz sand in the GR also makes a significant contribution to the AD and GWP100 potential, due to similar processes involved in its extraction and preparation. Kaolin, used as a mineral additive to the substrate, is characterised by a relatively uniform contribution to all the impact categories considered. Unlike RG, in the environmental impact profile of GR, the polymer and waterproofing layers, which are necessary to ensure the watertightness of the roof structure, play a more prominent role. These observations are consistent with the findings of A. Al Rashid *et al.* (2024), who reported high energy demand and greenhouse gas emissions associated with the use of polymer and waterproofing materials in green roof systems. However, the results obtained suggest that the relative contribution of these components may vary depending on the system configuration and layer thickness. Furthermore, E. Sierka *et al.* (2026), in their study of the impact of extensive GR based on an LCA of a 4 m^2 test sample carried out using OpenLCA software and the PEF (Product Environmental Footprint) database, demonstrated that the production of structural components, particularly synthetic materials (polyvinyl chloride and polypropylene), is a key factor in the deterioration of the system's environmental performance. The authors found that removing the vapour and thermal insulation layers from the GR model reduces CO_2-eq emissions by 28.36 kg compared to the baseline scenario, highlighting the significant potential for optimising the material structure of GR to reduce their environmental impact.

Transport processes, as in the case of RG, make an additional contribution to all categories of environmental impact, since the transportation of materials involves fuel consumption and associated emissions of pollutants. J.L. Osorio-Tejada *et al.* (2022) reported that, within LCA-based road freight transport modelling, emissions from a diesel van with a payload of up to 1.3 tonnes are approximately 0.142 kg CO_2eq/km, demonstrating the significant contribution of the transport phase to the overall carbon footprint. Their study applied a diesel-fuel transport scenario, ensuring consistency with standard LCA modelling practices. These results are methodologically consistent with the present study, as both confirm that transport activities represent a measurable and non-negligible contributor to the total environmental impact within LCA models. This supports the inclusion of transport-related emissions across all impact categories considered, particularly GWP100, AP, and AD.

Based on the results obtained, it is advisable to recommend that the further standardisation of LCA studies of GR and RG should involve the use of standardised transport scenarios, harmonised baseline datasets, uniform impact assessment methods, and standardised formats for presenting results. Such an approach will reduce methodological uncertainty and improve the comparability of environmental assessments of different types of green infrastructure across varying geographical and climatic conditions. The need for harmonisation is strongly supported by Y. Zhu *et al.* (2023), who identify the lack of methodological consistency as a key limitation in comparative LCA studies across different systems and regions. The authors emphasise that differences in system boundaries, life-cycle inventory data, impact assessment methods and reporting structures significantly reduce the reliability of comparisons between studies. Their conclusions, therefore, align with the findings of this study, highlighting the importance of establishing a standardised methodological framework specifically designed for the assessment of GR and RG.

The LCA results obtained demonstrate differing environmental performance between RG and GR systems, which correlates directly with the European Union's strategic priorities regarding climate neutrality and the development of nature-based solutions. In particular, it has been established that RG systems have a lower impact during the operational phase due to their passive mode of operation, lack of energy consumption, and the use of natural processes of infiltration and surface runoff retention. This is consistent with EU provisions prioritising solutions that minimise energy consumption and enhance the ecosystem functions of the urban environment. In contrast, GR demonstrate higher operational environmental impacts, as confirmed by LCA results, primarily due to the continuous energy consumption of technical systems. This partly contradicts EU requirements regarding the reduction of energy consumption throughout the life cycle, but at the same time aligns with other policy objectives, in particular improving the energy efficiency of buildings and reducing thermal loads. The patterns identified are consistent with the European Green Deal (European Commission, 2019), which aims to reduce carbon emissions and improve resource efficiency, as well as with the EU Strategy on adaptation to climate change (European Commission, 2021), which supports the implementation of nature-based solutions to mitigate climate risks. In addition, Committee of the Regions (2013) explicitly highlights the effectiveness of systems that regulate the water balance and reduce anthropogenic pressure. Thus, the LCA results confirm that RG are more aligned with EU priorities regarding low-energy nature-based solutions, whilst GR, despite higher operational impacts, provide other ecosystem and energy benefits at the building level. This highlights the value of using LCA as a tool for quantitatively comparing the environmental performance of different types of green infrastructure within the context of EU policies.

Conclusions

The study carried out a comparative assessment of the environmental impact of two types of green urban infrastructure systems, RG and GR, using the LCA method within the OpenLCA software environment. The modelling covered the main stages of the systems' life cycle – construction, operation and end-of-life – using the ELCD 3.2 reference database and a design life of 15 years. The results indicate that the RG system is characterised by a higher environmental impact during the construction phase, due to the significant mass of mineral materials, particularly quartz sand and gravel, required to form the filtration and drainage layers. In the AD and GWP100 categories, the main contribution comes from the processes of extraction, transport and preparation of these materials. During the operational phase, the RG demonstrates relatively low impact indicators due to the predominantly passive nature of its operation, which does not require significant energy resources.

The GR system, by contrast, is characterised by lower environmental impact values during the construction phase, which is explained by the structure's lower material intensity and the use of thinner substrate layers. However, during operation, the GR generates higher impact values, which are linked to the need for regular maintenance and the operation of auxiliary engineering systems. As a result, the total global warming potential for GR is 392 kg CO_2-eq per 1 m^2 over 15 years, whereas for RG it is 288 kg CO_2-eq. An analysis of the structure of environmental impact showed that for RG, the largest contribution to the AD, AP, and GWP100 indicators comes from the mineral components of the structure, primarily quartz sand, as well as transport processes. In the GR, polymer and waterproofing materials play a significant role, the production of which is accompanied by increased energy consumption and corresponding greenhouse gas emissions.

From a practical point of view, the study's results confirm the advisability of the integrated use of various types of green structures in the urban environment, depending on the functional requirements of the area. RG systems are more effective for passive surface runoff management and reducing operational environmental impacts, whilst GR systems provide additional benefits related to improved thermal insulation performance of buildings and microclimate regulation. Furthermore, the study's results confirm the importance of applying standardised approaches to defining system boundaries, selecting databases and impact assessment methods in LCA studies of green structures. Standardising such approaches will help improve the comparability of results, justify design decisions and shape effective policies for the sustainable development of urban green infrastructure.

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Conflict of Interest

None.

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Порівняльна оцінка життєвого циклу конструкції дощового саду та зеленого покриття із застосуванням програмного середовища OpenLCA

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Анотація. Глобальні кліматичні зміни та посилення урбанізації посилюють тиск на міську інфраструктуру та природні ресурси, підкреслюючи важливість впровадження зеленої інфраструктури для підвищення стійкості міст та зменшення впливу на довкілля. Метою дослідження було проведення порівняльної оцінки життєвого циклу дощового саду та зеленого даху за допомогою програмного забезпечення OpenLCA (версія 2.6, 2025) шляхом моделювання їхніх екологічних показників, що дозволило визначити ключові кліматичні та ресурсні параметри їхньої ефективності. Для моделювання було зібрано дані на всіх етапах життєвого циклу споруд та нормалізовано їх на квадратний метр за 15-річний період експлуатації. Основними категоріями екологічного впливу було обрано потенціал глобального потепління, потенціал евтрофікації, потенціал підкислення та вичерпання абіотичних ресурсів. Результати продемонстрували різний баланс екологічних наслідків на різних етапах життєвого циклу. Зелений дах характеризувався меншим впливом на етапі будівництва (наприклад, потенціал глобального потепління становить 50 кг CO2-екв./м^2) завдяки використанню збірних модульних блоків. Натомість дощові сади продемонстрували менший вплив на етапі експлуатації (130 проти 320 кг CO2-екв./м^2 для зелених дахів за 15 років) завдяки пасивній фільтрації дощового стоку та мінімальним вимогам до технічного обслуговування. Значна частина впливу на етапі будівництва пов’язана з використанням кварцового піску як ґрунтової добавки для дощових садів та мульчі з деревної кори для покриття ґрунту, що пригнічує небажану рослинність та сприяє закріпленню цільової рослинності. На етапі закінчення терміну експлуатації обидві системи продемонстрували мінімальний загальний вплив на довкілля, причому більшість показників залишалися незначними. Результати підтвердили, що жодна з досліджених зелених інфраструктурних систем не є універсально оптимальною; їхня ефективність залежить від конкретного етапу життєвого циклу та місцевих умов, що підкреслює необхідність враховувати місцеві цілі та пріоритети під час вибору системи

Ключові слова: зелені споруди; аналіз впливу протягом життєвого циклу; моделювання на основі сценаріїв; потенціал глобального потепління; потенціал евтрофікації; потенціал підкислення; вичерпання абіотичних ресурсів