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Life Cycle Metrics for Geosynthetic Reinforced Structures in Comparative Retaining System Assessment

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ABSTRACT: This study compares the environmental and economic performance of three retaining systems — geosynthetic-reinforced soil (GRS), gabion (GBS), and precast reinforced concrete (PRC) — designed for the same functional and geometric requirements. The analysis combines Life Cycle Assessment and Life Cycle Costing within a harmonised framework, using EN 15804+A2 modules and the Environmental Footprint 3.1 method for impact modelling. The functional unit is one meter length of retaining structure supporting a 3.0 m high embankment. The reference case is a full-scale GRS wall built with recycled construction and demolition waste aggregates, developed within the CDW_LongTerm research project at the University of Porto. Material quantities for all systems were estimated from detailed designs, with common assumptions for geometry, foundations, and service life. Environmental impacts were calculated with One Click LCA®, applying EF 3.1 characterization factors and background data from the Ecoinvent 3.8 database. The LCC covered only initial costs (A1–A5), reflecting early-stage decision contexts. Results show clear contrasts. The GRS system recorded the lowest global warming potential (~270 kg CO_2eq/FU), followed by GBS (~440 kg) and PRC (~1,400 kg). Similar patterns appeared for most indicators, although PRC achieved higher end-of-life credits (Module D) due to steel recovery. GRS obtained the highest Material Circularity Indicator (50%), benefiting from recycled aggregate content and potential geosynthetic reuse. In cost terms, GRS (€472/m) was the most competitive, ahead of GBS (€661/m) and PRC (€692/m). These findings suggest that, in small- to medium-height retaining applications, GRS with recycled backfill can deliver comparable technical performance while reducing embodied impacts and costs. However, indicator prioritisation may vary by project context: PRC's higher recovery potential could be valued in some cases, while water use or resource depletion may weigh more heavily in others. Integrating LCA and LCC at the design stage offers a practical path to more circular, resource-efficient geotechnical solutions.

KEYWORDS: Geosynthetic-reinforced soil, LCA, recycled aggregates, sustainable retaining systems, circular construction.

1 INTRODUCTION

The construction sector ranks among the largest global consumers of raw materials and is also one of the biggest generators of waste. In the European Union, construction and demolition (C&D) waste alone accounts for more than 35% of total waste production (European Commission, 2023). The reuse of such materials in geotechnical works has been steadily explored, yet when it comes to geosynthetic-reinforced soil (GRS) retaining structures, questions persist — particularly around their long-term behavior and environmental consistency (Ferreira et al., 2020; Vieira et al., 2024).

At the same time, GRS systems have become increasingly common as alternatives to more traditional retaining solutions. Their appeal lies in their flexibility, modular construction, and compatibility with a wide spectrum of fill materials — even lower-grade or recycled aggregates (Moncada et al., 2024; Fraser et al., 2012). Under proper design, GRS walls may perform on par with, or even outperform, gravity and reinforced concrete walls, particularly in low- to medium-height applications (Moncada et al., 2024).

Yet mechanical performance, while well-documented, tells only part of the story. The sustainability dimension of GRS — especially when incorporating alternative backfills — remains underexplored in a holistic way. Literature increasingly points to the need for integrating Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) into geotechnical design (Samuelsson et al., 2023; Araújo Junior et al., 2025). But side-by-side evaluations of GRS, gabion structures, and precast reinforced concrete under identical functional and boundary conditions are still rare.

This paper addresses that gap by applying a combined LCA–LCC framework to compare the environmental and economic performance of three retaining systems: GRS, gabion, and precast reinforced concrete. The work builds on a real-world case — a full-scale GRS wall constructed with recycled C&D aggregates (Vieira et al., 2024) — ensuring that the analysis is anchored in practical constraints rather than hypothetical designs. Methodologically, it follows EN 15804+A2 and the Environmental Footprint (EF) 3.1 method for impact modelling, both in line with current European regulations and LCA practice (European Committee for Standardization, 2019; European Commission, 2021).

By framing the comparison in this way, the study aims to inform design decisions that must weigh cost, environmental burden, and resource efficiency — particularly in contexts where the reuse of recycled materials is not only technically feasible but also aligned with broader circular economy ambitions.

2 MATERIALS AND METHODS

2.1 *Reference case study: GRS structure built with recycled C&D waste*

To ground the comparative analysis, this study takes as its reference a full-scale GRS structure constructed with recycled C&D aggregates. The embankment was developed within the CDW_LongTerm research project, coordinated by the Faculty of Engineering of the University of Porto (FEUP), with the goal of assessing the long-term mechanical behavior of GRS systems using recycled backfills (Ferreira et al., 2020).

The structure measures 3.0 m in height, 10.4 m in length, and 3.0 m in width. Its two wrap-around face slopes, inclined at 2:1 (vertical:horizontal), were each reinforced with a different geosynthetic: one with a uniaxial woven geogrid, the other with a high-strength geotextile (HSG). Reinforcements were placed at vertical spacings of 0.6 m (Figure 1) (Ferreira et al., 2020; Vieira et al., 2024).

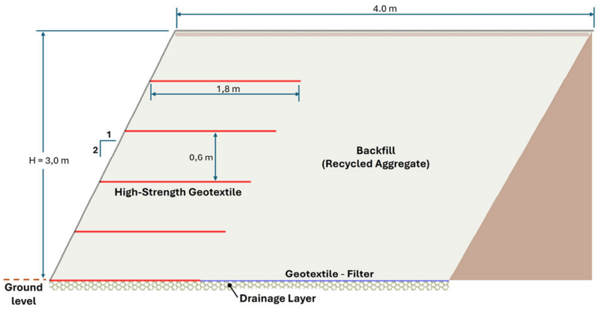

Figure 1. Schematic representation of the full-scale experimental GRS embankment used as the reference case.

The backfill consisted of fine-grained recycled C&D aggregates (FRA) sourced from a Portuguese recycling plant. Although such materials are often regarded as environmentally advantageous, their in-situ performance — especially over the long term — is not yet entirely predictable. One aim of the project, therefore, was to strengthen confidence in the technical feasibility of using CDW in reinforced soil structures, through multi-year monitoring of field performance.

To this end, an extensive network of instrumentation was installed, including inclinometers, magnetic extensometers, settlement plates, strain gauges, and earth pressure cells. These devices captured both global and local responses during and after construction, providing a detailed picture of displacements, stresses, and strains (Ferreira et al., 2020).

While the mechanical data themselves are not fully presented here, they underpin the life cycle analysis developed in this paper. Anchoring the LCA in a real-world build — rather than a purely theoretical design — adds practical relevance and keeps the findings tied to actual design and site constraints.

Of course, as with any site-specific study, local factors such as material availability, transport distances, and prevailing construction practices may influence the transferability of results. These nuances are revisited in later sections, where the comparative systems are introduced and examined.

2.2 *Comparative systems description*

For comparison, two conventional retaining systems were selected alongside the GRS: a gabion structure (GBS) and a precast reinforced concrete configuration (PRC). Both are widely used in infrastructure projects and are common in contexts similar to that of the reference case.

All three designs were sized to support the same functional requirement — a 3.0 m high embankment. The GRS follows the configuration already described, built with recycled C&D aggregates and geosynthetic reinforcement.

The GBS consists of six modular cages, each measuring 1.0 m × 1.0 m × 0.5 m, stacked to reach the full slope height (Figure 2). The cages are filled with coarse stone aggregate, acting both as facing and as structural mass in a gravity-based system. Behind the gabions, the same FRA backfill as in the GRS was used. A horizontal drainage layer of coarse recycled aggregate (CRA) was placed at the base of the backfill, topped with a nonwoven geotextile filter. This geotextile also runs vertically along the gabion's rear face, following the arrangement proposed by Vieira et al. (2024) and Ferreira et al. (2020).

The PRC alternative features an L-shaped cross-section with a vertical stem and horizontal base slab (Figure 3). The slope face was inclined to match the geometry of the other systems. The backfill was again the FRA, with CRA drainage layers placed both vertically along the rear face and horizontally at the base. A nonwoven geotextile filter separates these layers from the backfill, preventing clogging and helping maintain drainage capacity over the structure's service life.

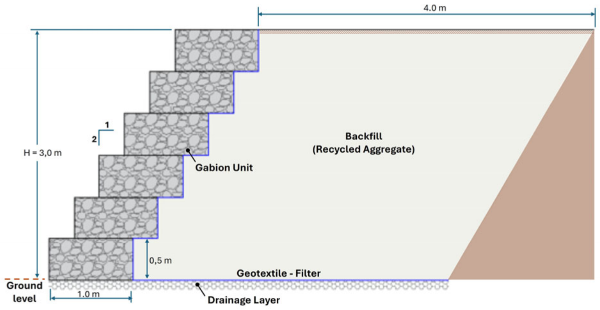

Figure 2. Typical configuration of the gabion structure analyzed in this study.

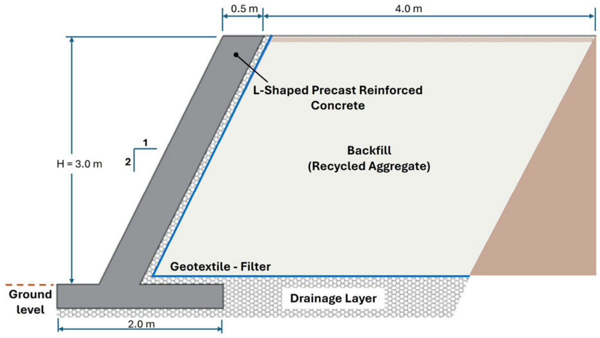

Figure 3. Typical configuration of the precast reinforced concrete configuration analyzed in this study.

To ensure a fair comparison, common assumptions were set across all alternatives — identical geometry, foundation conditions, excavation volumes, and a 100-year service life. This harmonization allows the analysis to focus on how material choice and construction method influence life cycle impacts, without the noise of differing design parameters.

2.3 *LCA methodology*

The environmental performance of the three retaining systems was assessed using a cradle-to-grave LCA, in line with the principles set out in ISO 14040 (International Organization for Standarization, 2006a) and ISO 14044 (International Organization for Standardization, 2006b). These standards define the general framework and methodological requirements for LCA studies.

The analysis followed the modular structure of EN 15804+A2:2019 (European Committee for Standardization, 2019), which is widely applied to construction products and infrastructure works. All life cycle stages — from raw material extraction (A1) through to end-of-life processing (C1–C4) — were included, ensuring methodological consistency across the alternatives.

The functional unit (FU) was defined as one linear meter of retaining structure designed to support a 3.0 m high embankment, with equivalent slope angle, loading, backfill, and foundation configuration across all three systems. This definition allows for direct comparison of environmental and cost results while keeping the focus on differences arising from material selection and construction approach.

Although the geotechnical requirements were the same, the structural configurations and construction techniques differed, leading to variations in material quantities. These were estimated from detailed cross-section designs and engineering judgment, then used as inputs for both LCA and LCC models (Table 1).

Table 1. Estimated material quantities per meter of structure length for each retaining system.

Material	GRS	GBS	PRC
FRA	14.8 m^3/m	11.8 m^3/m	11.4 m^3/m
CRA	0.6 m^3/m	0.6 m^3/m	2.2 m^3/m
HSG	18.5 m^2/m	-	-
Reinforced concrete (RC)	-	-	2.1 m^3/m
Gabion Unit (GU)	-	3.0 m^3/m	-
Geotextile filter (GT)	4.8 m^2/m	9.3 m^2/m	9.3 m^2/m

Environmental impacts were calculated using the One Click LCA® platform, with midpoint characterization factors from the Environmental Footprint 3.1 (EF 3.1) method — as recommended by European Commission (2021). Background data came from the Ecoinvent 3.8 database. Transport was modelled using the software's regional average distances and modes (e.g., lorry, Euro 6, 16–32 t), which, while generic, are reasonable for comparative purposes and applied consistently to all systems.

The ten selected midpoint indicators — required by EN 15804+A2 and covered by EF 3.1 — were:

- Global warming potential (GWP);
- Ozone depletion potential (ODP);
- Acidification potential (AP);
- Eutrophication potential – freshwater (EP-f);
- Eutrophication potential – marine (EP-m);
- Eutrophication potential – terrestrial (EP-t);
- Photochemical Ozone Formation Potential (POCP);
- Abiotic Depletion – non-fossil (ADP-nf);
- Abiotic Depletion – fossil resources (ADP-f);
- Water use (WU).

These indicators are commonly adopted in European LCA practice for geotechnical applications and, based on recent discussions in the field, may provide a balanced view of the main pressures relevant to retaining systems (Samuelsson et al., 2023; Araújo Junior et al., 2025).

The system boundaries adopted in the study are illustrated in Figure 4. Modules A1–A3 cover the production of construction materials; A4 models transportation to the site; and A5 includes on-site equipment operation, water consumption, and expected material losses, as recommended by One Click LCA guidelines. End-of-life scenarios (C1–C4) consider deconstruction, material sorting, transport to treatment facilities, and final disposal or recycling.

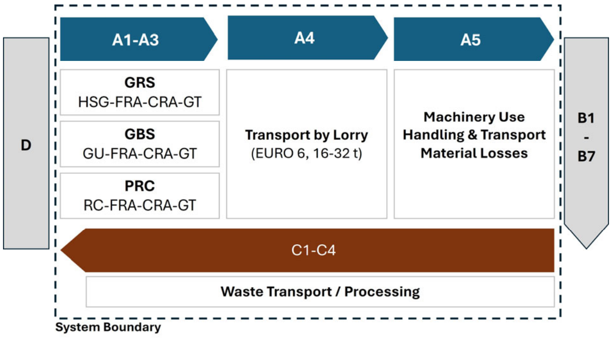

Figure 4. System boundaries and life cycle modules considered in the LCA, based on EN 15804+A2.

Although not part of the core cradle-to-grave comparison, Module D was also quantified to estimate potential benefits beyond the system boundary (e.g., aggregate recycling, geosynthetic reuse). These credits are reported separately to avoid masking cradle-to-grave differences. In addition, a Material Circularity Indicator (MCI) was computed with the method embedded in One Click LCA®, drawing on the Ellen MacArthur Foundation framework (Ellen MacArthur Foundation, 2019), to offer a complementary view of material efficiency and circularity potential.

2.4 *Initial cost assessment*

A complementary LCC analysis was conducted to assess the economic performance of the three retaining systems. While the LCA focused on environmental impacts, the LCC provides insights into the financial implications of material choices and construction methods, supporting a more holistic evaluation of sustainability in early design stages.

The analysis adopted a simplified approach, considering only the initial investment costs associated with life cycle modules A1 to A5. This scope includes material production and supply (A1–A3), transport to the construction site (A4), and on-site construction activities (A5). Costs related to operation, maintenance, and end-of-life (modules B and C) were excluded based on the assumption of minimal maintenance and similar deconstruction procedures across the three systems. This is consistent with common practice in early-stage infrastructure design assessments (Gluch & Baumann, 2004).

The FUt used in the LCC was the same as in the LCA: one linear meter of retaining system, designed to retain a 3.0-meter-high embankment under comparable conditions. This ensures alignment between environmental and economic evaluations.

Cost estimates were developed using national construction cost databases and public procurement references widely used in Portugal, which provide standardized, regionally contextualized unit prices for construction materials, labor, equipment, and transport. Where required, unit costs were adjusted to reflect 2025 values, using sectoral inflation indices published by national authorities.

All costs were expressed in euros per functional unit (€/m), and results are presented and compared in Section 3, alongside the LCA outcomes.

3 RESULTS AND DISCUSSION

3.1 *Life Cycle Environmental Performance*

The LCA revealed substantial variation in the environmental performance of the three retaining systems. A summary of the absolute values across ten environmental indicators is presented in Table 2, where the GRS clearly emerges as the lowest-impact alternative. Its total GWP, for instance, is approximately 270 kg CO$_2$eq per functional unit, in contrast to 440 kg CO$_2$eq for the GBS and 1,400 kg CO$_2$eq for the PRC.

Table 2. Life cycle environmental impacts per functional unit (FU) for each retaining system (EF 3.1, EN 15804+A2).

Impact	Unit	GRS	GBS	PRC
GPW	kg CO$_2$ eq	271.9	441.6	1 402.2
ODP	kg CFC$_{11}$ eq	4.3E-05	4.8E-05	1.2E-04
AP	mol H+ eq	1.2	2.0	7.4
EP-f	kg P eq	1.3E-02	1.2E-02	4.0E-02
EP-m	kg N eq	0.4	0.7	1.9
EP-t	mol N eq	4.4	7.7	22.7
POCP	kg NMVOCeq	1.2	2.1	6.3
ADP-nf	kg Sb eq	0.7	0.7	0.8
ADP-f	MJ	5 101.0	6 992.5	12 148.9
WU	m^3	94.8	69.1	458.1

The differences become even more evident when the results are normalized, as shown in Figure 5. Compared to the GRS baseline, the PRC system exhibits markedly higher environmental impacts in most categories. The most pronounced disparities are observed in GWP — a key indicator — as well as in acidification, terrestrial and marine eutrophication, photochemical ozone formation, non-fossil resource depletion, and water use, where values exceed the GRS by more than fourfold.

Although the remaining indicators — such as freshwater eutrophication, ozone depletion, and particularly fossil resource depletion — show less dramatic differences, their values remain consistently higher in the PRC alternative, reinforcing the overall trend of greater environmental burden.

The environmental load of the PRC is primarily associated with its reliance on precast concrete elements and steel reinforcement. While concrete production already contributes significantly to GWP and acidification, the inclusion of steel is likely responsible for elevated impacts in resource depletion and ozone-related categories, due to its energy-intensive manufacturing and dependence on mineral extraction. These results align with prior findings on the environmental profiles of reinforced concrete infrastructure (Samuelsson et al., 2023).

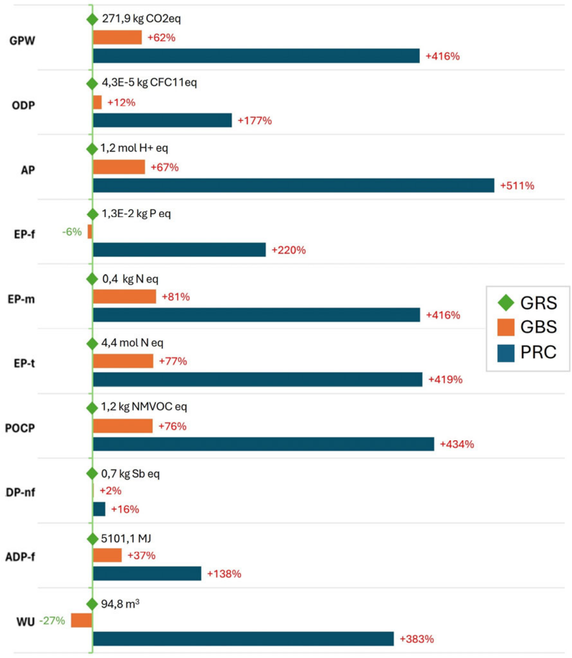

Figure 5. Life cycle environmental impacts per functional unit (EF 3.1, EN 15804+A2).

Conversely, the GRS system benefits from a combination of recycled aggregates and geosynthetics, which involve lower embodied environmental loads and less energy-intensive processing. This contributes to its strong performance across nearly all categories, despite a relatively higher value in water use — possibly stemming from the washing of recycled materials or processes in geotextile production.

The breakdown of impacts by life cycle stage, presented in Figure 6, offers additional insights. While over 80% of the PRC's impact is concentrated in the product stage (A1–A3), the GRS system shows a more distributed profile, with notable contributions from transportation (A4) — likely reflecting the distances traveled by recycled materials. The GBS exhibits a broader spread across all stages, including installation (A5) and end-of-life processes (C1–C4), consistent with the modular nature and disassembly requirements of gabion structures.

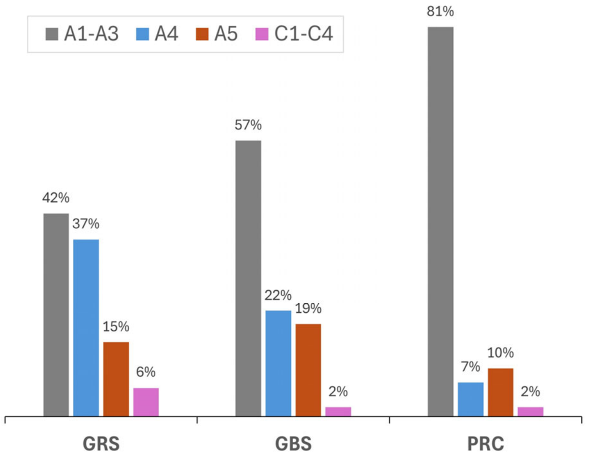

Figure 6. Relative contribution of life cycle stages to total GWP for each system.

A deeper look into the contribution of material types is shown in Figure 7, which displays the distribution of environmental impacts by component and life cycle module. In the PRC system, precast concrete elements dominate the footprint, followed by impacts from machine operation and aggregates. The GBS shows significant influence from the gabion units and recycled backfill, while the GRS benefits from a more balanced material profile — driven largely by recycled aggregates and geosynthetics. These findings further support the role of material selection and construction strategy in determining environmental performance.

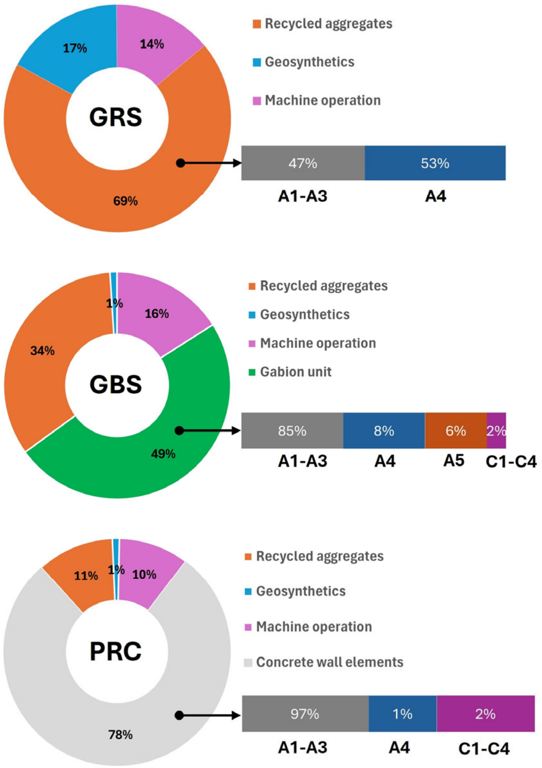

Figure 7. Environmental impact distribution per category and retaining system (EF 3.1).

Taken together, these results reaffirm the environmental advantages of the GRS configuration, particularly in early-stage design scenarios seeking to reduce emissions and resource consumption. Although results remain sensitive to regional assumptions and background data, the consistent performance of the GRS system across impact categories supports its potential as a more sustainable retaining solution. These trends align with recent findings in geotechnical life cycle studies (Ramezannia et al., 2024; Araújo Junior et al., 2025).

3.2 *Complementary Indicators: Circularity and Module D*

As shown in Figure 8, the GRS system achieved the highest circularity score, with an MCI of 50%, driven by the exclusive use of recycled aggregates and the potential for geosynthetic reuse. Interestingly, while the PRC presents a slightly lower score (46.3%), this performance is largely due to the proportion of material returned to the system (7.3%), which may reflect the recoverability of steel in demolition waste. However, its overall profile remains more resource intensive. The GBS alternative showed the lowest MCI score (42.2%), limited by the low recovery of the steel gabion units and the fragmented potential for reuse.

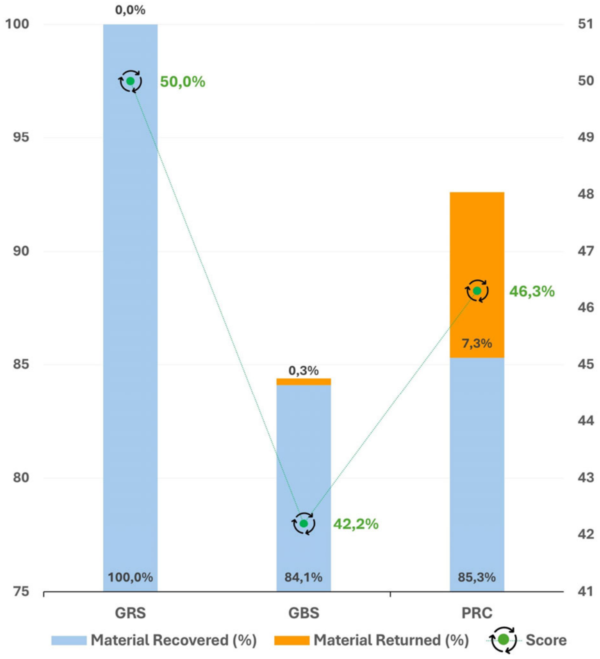

Figure 8. Circularity scores of the three retaining systems, based on material recovered (%) and material returned (%) indicators (One Click LCA®).

While MCI values offer a high-level view of material circularity, they are sensitive to assumptions on reuse rates and recovery efficiencies. Nonetheless, they reinforce the role of material selection and modularity in promoting resource-efficient geotechnical structures.

A more direct contribution to environmental performance is reflected in the Module D results, presented in Figure 9, which show the net GWP credits from potential reuse, recycling, and recovery beyond the system boundary. The GBS and PRC systems demonstrate significant potential benefits — around –236 kg CO₂eq — mostly derived from the recycling of steel components in their structures. In contrast, the GRS exhibits more modest credits (–60.4 kg CO₂eq, or –22% GWP), primarily from geosynthetic reuse and the downcycling of recycled aggregates.

These results are not contradictory. In fact, they highlight a trade-off: systems like PRC and GBS may offer higher end-of-life recovery value, especially in terms of recyclable metals, while GRS stands out for its lower impacts upfront (A1–A3) and more circular material sourcing. Depending on project priorities — whether minimizing embodied carbon or maximizing end-of-life recovery — these differences can inform more nuanced decision-making.

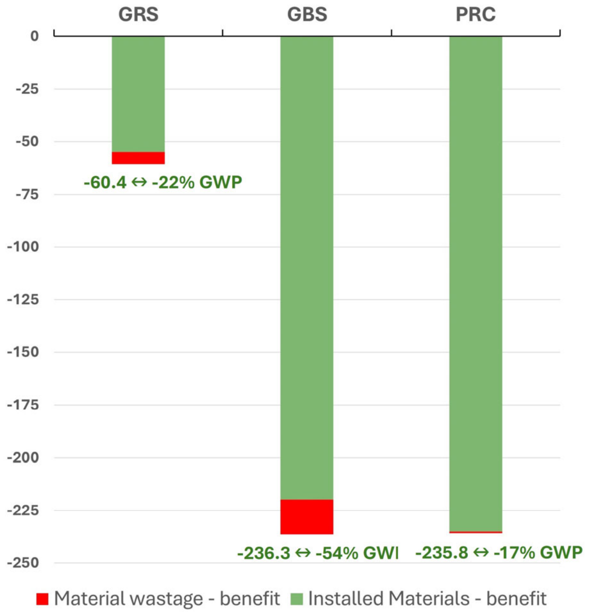

Figure 9. Potential climate change benefits (GWP) from Module D, disaggregated by source: installed materials and construction site wastage.

Ultimately, neither MCI nor Module D results override the main LCA conclusions. However, they provide additional context that helps validate the GRS system's alignment with circular economy principles, while acknowledging the latent recovery potential in more material-intensive alternatives.

3.3 *Economic performance: LCC*

The LCC of the retaining systems was assessed focusing solely on initial implementation costs, encompassing material acquisition, transport, and construction (A1–A5). This simplified scope, while excluding operation and end-of-life phases, is consistent with established practices for passive geotechnical structures, and aligns with the early-phase guidance provided in ISO 15686-5 (International Organization for Standardization, 2017), which supports streamlined LCC methods in preliminary design stages (Gluch & Baumann, 2004; Samuelsson et al., 2023; Dormohamadi et al., 2024; Jelušič et al., 2024).

All values were normalized per functional unit (€/m) and derived from regional cost databases and public procurement sources. Table 3 summarizes the results.

Table 3. Initial life cycle costs (A1–A5) per functional unit of retaining system.

Material	Unit Cost	GRS	GBS	PRC
Reinforcement (HSG)	€/m²	92.5	-	-
Structure	€/m³	-	345.0	346.5
Recycled Aggregate	€/m³	369.6	297.6	326.4
Geotextile-filter	€/m²	9.6	18.6	18.6
Total Initial LCC	€/m	471.7	661.2	691.5

The GRS structure achieved the lowest cost (€471.7/m), despite higher demand for geosynthetic reinforcement due to anchorage and interaction with the selected backfill. This is compensated by efficient use of recycled aggregates and less structural complexity.

The GBS and PRC systems, on the other hand, reached €661.2/m and €691.5/m, respectively. These higher costs are linked primarily to the material-intensive nature of gabion and reinforced concrete units, which serve as self-supporting structural components. Their costs reflect both material and labor intensity, rather than functional complexity.

These results reinforce the notion that material efficiency, constructive modularity, and the strategic use of recycled resources — as offered by the GRS configuration — can translate into tangible economic benefits. Unlike more conventional systems, which tend to rely on costlier and more rigid structural units, the GRS approach leverages mechanical interaction and optimized reinforcement to reduce material intensity without compromising performance. This balance between structural functionality and resource-conscious design not only improves cost-effectiveness but also positions GRS as a strategically favorable solution in projects seeking both technical viability and sustainability gains.

4 CONCLUSIONS

Retaining systems up to about 5 m in height are a familiar sight in urban, transport, and infrastructure projects. They address recurring needs — from stabilising slopes to optimising space — often under tight cost and schedule constraints. Because these applications are so widespread, the choice of structural solution carries weight not just for engineering performance, but also for environmental and economic outcomes over the project's lifetime.

The comparison carried out here shows that this choice matters. Among the three alternatives analysed, the GRS consistently achieved the lowest global warming potential, the highest material circularity score, and the most competitive initial cost. These results held even when the system required a greater quantity of geosynthetic reinforcement — an investment offset by reduced material intensity elsewhere and by the use of recycled aggregates.

The findings reinforce a broader point: sustainability metrics need to be considered early in geotechnical design, when they can still influence key decisions. The GRS configuration demonstrates that it is possible to combine technical performance with lower embodied impacts and reduced cost, without adding construction complexity.

By coupling LCA with a streamlined LCC, this work outlines a practical route towards more circular, resource-efficient retaining systems. The results strengthen the case for recycled backfills and geosynthetics as viable, high-value components in these structures, particularly in contexts where minimising emissions and resource use is a project priority.

While global warming potential is a well-established indicator, the study also shows that other categories — such as acidification, water use, or resource depletion — can diverge significantly between alternatives. In practice, the most "sustainable" choice will depend on which pressures are most critical in a given location or project type. Future work should therefore adapt the weighting of indicators to the local context, and explore longer-term performance data to confirm these trends over a full service life.

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