

Life Cycle Assessment of a CDW-Based Geosynthetic-Reinforced Slope versus a Gabion Retaining Structure

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Abstract. Geotechnical engineering plays a pivotal role in sustainable development by supporting critical infrastructure projects, such as housing, transportation networks, and environmental protection systems. Geosynthetic reinforced structures, essential for creating stable and resilient infrastructures, should also align with principles of sustainability and circular economy to address global environmental and economic challenges. This study evaluates the environmental performance of two functionally equivalent earth-retaining structures: a geosynthetic-reinforced slope (GRS) using recycled construction and demolition waste as backfill, and a conventional gabion retaining structure (GAB) built with natural aggregates. A life cycle assessment (LCA) was conducted following EN 15804 +A2 and ISO 14040/44, covering modules A1–C4. Results show that the GRS achieved reductions of 30 % in global warming potential, 99.8 % in non-renewable primary energy, and 82 % in water use compared with the GAB, confirming the effectiveness of material substitution and design optimisation. Secondary indicators followed the same trend, reinforcing methodological robustness. Beyond the numerical results, the findings show that sustainability in geotechnical design arises from efficiency and circular material flows—not from restricting construction itself. The study concludes that sustainable construction should evolve through intelligent design, where optimisation replaces compensation and performance coexists with environmental responsibility.

1 Introduction

The construction sector remains essential for societal well-being and economic development. Modern cities, sanitation, housing, and transport networks—all fundamental components of quality of life—depend on this sector's capacity to transform natural resources into infrastructure. Although construction is often portrayed as an environmental burden, this view tends to oversimplify the complexity of its role in modern society. Global data indicate that the built environment accounts for approximately 40 % of material consumption and 36 % of energy-related CO₂ emissions [1,2]. These consolidated figures include not only the impacts of material production and construction, but also the emissions associated with building operation—energy demand for heating, cooling, and comfort that sustains modern life. Hence, a substantial share of what is attributed to the construction sector reflects the energy intensity of living itself. The challenge, therefore, is not to restrain construction, but to evolve it—reducing impacts through innovation, design efficiency, and responsible use of materials.

Within this context, geotechnical engineering plays a pivotal role. Foundations, retaining walls, and earthworks are indispensable to the built environment,

yet they contribute substantially to embodied energy and emissions due to the intensive use of concrete, steel, and natural aggregates [3,4]. Improving the sustainability of these systems requires rethinking traditional practices—not only by substituting materials but by optimising how they are used. The integration of recycled construction and demolition waste (CDW) and geosynthetics offers a promising pathway toward lower-carbon and resource-efficient geotechnical structures, coupling mechanical performance with environmental responsibility [5–7].

This study applies a life cycle assessment (LCA) to compare two functionally equivalent earth-retaining structures: a geosynthetic-reinforced slope (GRS) employing recycled CDW as backfill, and a conventional gabion retaining structure (GAB) constructed with natural aggregates. The analysis follows a cradle-to-grave scope (A1–C4) consistent with EN 15804 +A2 [8]. Beyond quantification, the study aims to illustrate a balanced perspective: construction is not the problem—it is the foundation of progress. The real challenge lies in transforming it into a more intelligent, circular, and genuinely sustainable industry, where environmental accountability strengthens, rather than limits, engineering innovation.

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2 Methodology

2.1 Overview

The environmental assessment compared two structurally equivalent earth-retaining structures: a geosynthetic-reinforced slope (GRS) employing recycled CDW as backfill, and a conventional gabion retaining structure (GAB) using natural aggregates. The analysis followed the methodological principles established in ISO 14040 and ISO 14044 [9, 10] and the modular structure defined in EN 15804 +A2 [8], adopting a cradle-to-grave system boundary (A1–C4).

Modelling was performed in One Click LCA (version 2023) [11] using datasets representative of Portuguese and broader European manufacturing conditions. The functional unit was defined as a one-metre cross-section of the retaining structure, corresponding to approximately 10.5 m³ of material, and all results were normalised to this reference to ensure comparability between structures.

The GRS configuration was based on a full-scale experimental embankment constructed using recycled CDW as backfill material within the research project CDW_LongTerm (PTDC/ECI-EGC/30452/2017 - POCI-01-0145-FEDER-030452) [12,13].

Fig. 1 illustrates the experimental structure, which served as the reference for the geometric and material configuration adopted in this study. These sources provided the physical and material reference framework for both design alternatives analysed in this study.



Fig. 1. Full-scale geosynthetic-reinforced slope (GRS) constructed under the CDW_LongTerm research project.

2.2 Case Study Description

The comparative analysis considered two earth-retaining structures designed to meet equivalent geometric and mechanical requirements. Each structure measured 3 m in height, 4 m at the base, and 3 m at the crest, forming a trapezoidal cross-section representative of low- to medium-height earth-retaining structures.

The GRS configuration was developed from the experimental reference model, using CDW as backfill reinforced with polypropylene geogrids (GG) at 0.5 m

vertical spacing and a non-woven geotextile (GTX) acting as a filter at the facing (Fig. 2).

The GAB was designed as a geometrically equivalent alternative composed of galvanised-steel cages filled with natural stone, with a compacted soil layer at the rear interface to reproduce realistic soil–structure interaction and ensure comparable global stability (Fig. 3).

Material quantities and transport assumptions were derived from the experimental data of the GRS and mirrored for the GAB under geometric equivalence to ensure functional comparability [12,13]. Verified environmental product declarations (EPDs) were used where available to represent material impacts in One Click LCA. All inventory data were normalised to the functional unit (FU) defined for this study.

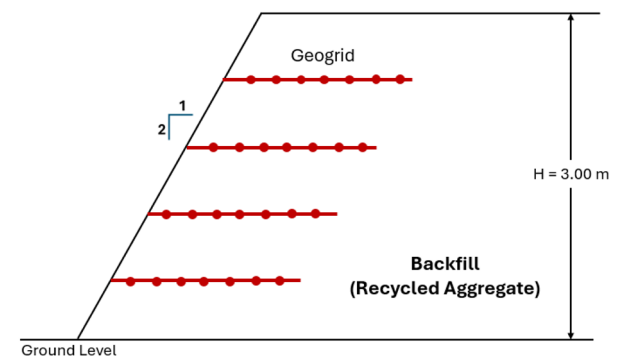


Fig. 2. Schematic configuration of the GRS configured as a steep slope: CDW backfill reinforced with GG.

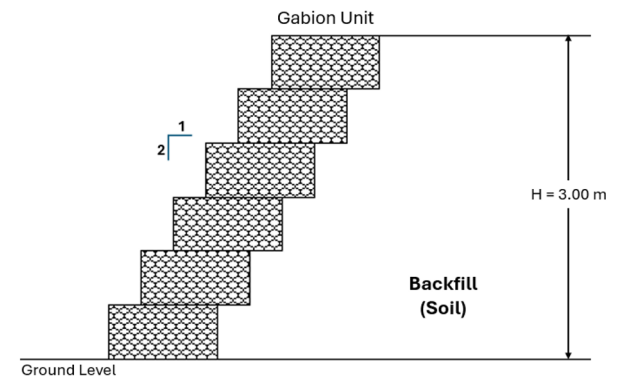


Fig. 3. Schematic configuration of the GAB: galvanised-steel cages with natural-stone infill and compacted soil at the rear interface.

2.3 LCA Modelling Approach

Modelling in One Click LCA followed the data structure defined by the European standard for construction products [8], consistent with the methodological framework established in ISO 14040 and ISO 14044 [9,10]. The system boundary covered modules A1–A5 (product and construction) and C1–C4 (end-of-life), thus representing a cradle-to-grave scope. The use stage (B1–B7) and Module D were excluded, as the earth-retaining structures are passive systems that require no maintenance, reuse, or recycling (Fig. 4).

Both models adopted the same reference service life (RSL), identical system boundaries, transport logic, and data-processing routines, ensuring that differences in

environmental performance stemmed solely from material composition and construction techniques. Environmental impacts were calculated according to the core indicators defined in EN 15804 +A2 [8]. The analysis emphasised global warming potential (GWP-total), non-renewable primary energy use (NRPE), and water use (FW)—the categories most sensitive to material and design variations. Secondary indicators such as acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP) were also quantified for completeness. All results are expressed per functional unit, enabling direct and consistent comparison between the GRS and GAB systems.

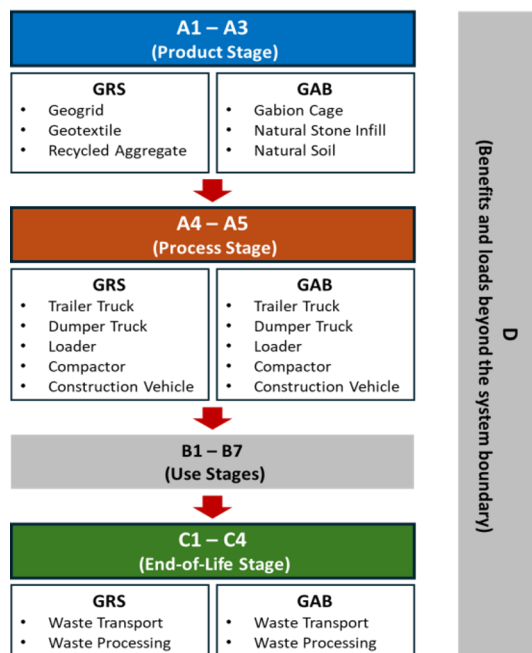


Fig. 4. System boundaries of the life cycle assessment for the GRS and the gabion retaining structure (GAB).

2.4 Inventory and Data Sources

The life cycle inventory (LCI) was developed using primary project data complemented by verified datasets from One Click LCA. The scope covered modules A1–A5 and C1–C4, and all quantities and impacts were normalised to the FU.

For the GRS, material quantities were taken from the documentation and measurements of the full-scale experimental project [12,13]. For the GAB, quantities were derived from a geometrically equivalent configuration designed to ensure comparable mechanical performance. Transport distances, vehicle classes, and waste treatment scenarios followed the default European-average datasets available in One Click LCA, consistent with the data structure of EN 15804 +A2 [8]. When available, supplier EPDs were used to represent specific materials.

Construction activities (A5) were modelled as equipment operating time converted to equivalent diesel consumption, covering excavation, filling, compaction, and handling. End-of-life processes (C1–C4) used default transport and disposal datasets from the same

source, ensuring methodological consistency across all impact indicators. The material inventory for both retaining structures is summarised in Table 1, listing the principal components and corresponding quantities per FU.

Table 1. Material inventory for GRS and GAB per FU.

Material	Unit	Quantity
Geosynthetic-reinforced slope (GRS)		
Backfill material (CDW)	m ³	10.5
Geogrid (GG)	m ²	18.5
Geotextile (GTX)	m ²	15.0
Gabion Retaining Structure (GAB)		
Galvanised-steel cages – GAB	kg	50.0
Natural stone infill – GAB	m ³	3.0
Backfill soil – GAB	m ³	7.5

3 Results and Discussion

3.1 Environmental and Resource Performance

The comparative results presented in Fig. 5 confirm a clear and consistent environmental advantage of the GRS configuration across all major indicators. When normalised to the GAB baseline (100 %), the GRS achieved approximately 70 % of the GWP-total, 0.2 % of the NRPE, and 18 % of the FW, demonstrating significant improvements in carbon, energy, and water performance.

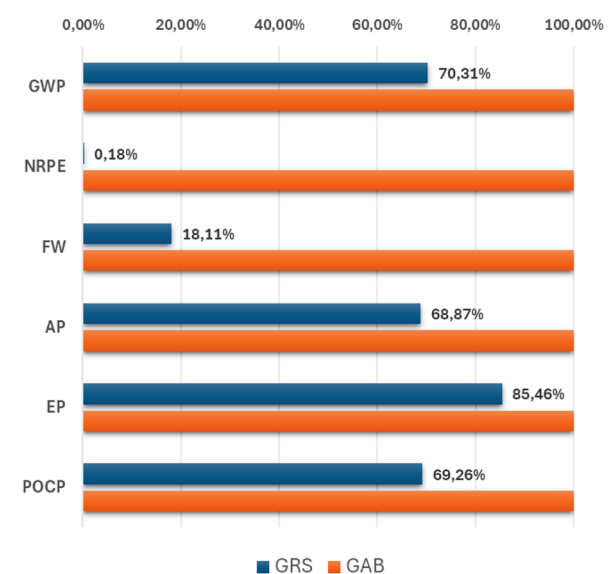


Fig. 5. Comparative life-cycle results for the GRS and GAB systems per functional unit.

The larger relative reduction observed for NRPE compared with GWP reflects the different sensitivities of these indicators to material composition: in the GAB scenario, non-renewable primary energy demand is dominated by fossil-energy-intensive processes associated with galvanised steel production and quarrying of natural aggregates, whereas in the GRS these processes are largely avoided through the use of recycled CDW and low-mass polymeric reinforcements.

In absolute terms, the GWP-total reached 282.7 kg CO₂e/FU for the GAB and 198.8 kg CO₂e/FU for the GRS, corresponding to a 30 % reduction in embodied emissions. This reduction primarily stems from the substitution of energy-intensive components—galvanised-steel cages and natural aggregates—by recycled aggregates (CDW) and polymeric reinforcements (GG, GTX). The reduced overall mass of the GRS, together with shorter expected transport distances (A1–A4), further amplifies the reduction in upstream impacts—those that usually dominate the life-cycle footprint of retaining structures.

As shown in Fig. 6, the GWP of the GAB is mainly driven by the material production (A1–A3) and construction stage (A5), which together define the key hotspots for this system. The A1–A3 module contributes the largest share (≈ 112 kg CO₂e/FU), dominated by the wire-mesh cages (≈ 75 % of the stage impact) and natural aggregates (≈ 21 %).

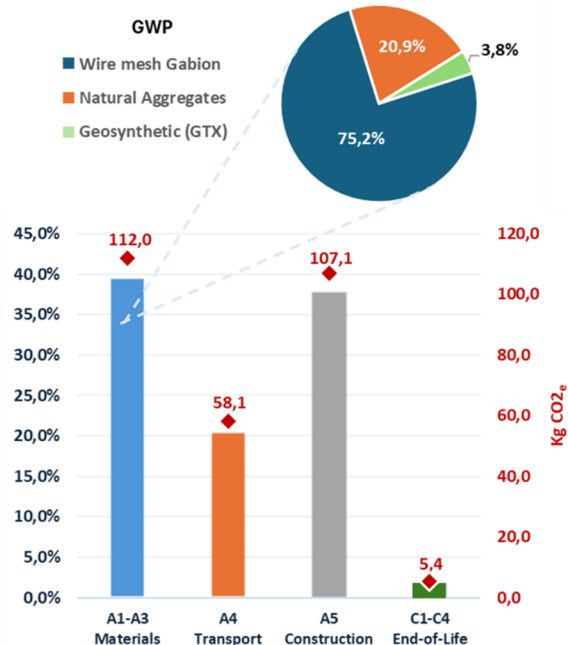


Fig. 6. Contribution of life-cycle stages to GWP for the GAB and breakdown of A1–A3 materials.

The A5 module (≈ 107 kg CO₂e/FU) follows closely, reflecting the intensive fuel use and machinery operation required for stone placement. Transport (A4) has a secondary yet non-negligible role (≈ 58 kg CO₂e/FU), affected by the large mass of both aggregates and metallic components. This pattern confirms that the GAB's footprint is largely driven by material intensity and demanding logistics, both inherent to its conventional design.

The GRS (Fig. 7) presents a notably different balance. The A1–A3 stage decreases substantially (≈ 79 kg CO₂e/FU), dominated by CDW aggregates with low embodied energy and minimal water demand compared to natural sources. As a result, the relative influence of A4 (transport) becomes more relevant (≈ 68 kg CO₂e/FU), highlighting the importance of local sourcing in maintaining the system's performance. The A5 (construction) stage drops to ≈ 40 kg CO₂e/FU, owing to simplified installation procedures and reduced equipment requirements. Within A1–A3, CDW backfill accounts for ≈ 79 % of emissions, while geosynthetics (GG, GTX) contribute only ≈ 21 %, confirming that their low mass offsets the energy intensity of polymer processing. Eliminating steel components removes the main emission hotspot identified in the GAB, resulting in a configuration that is lighter and inherently more efficient.

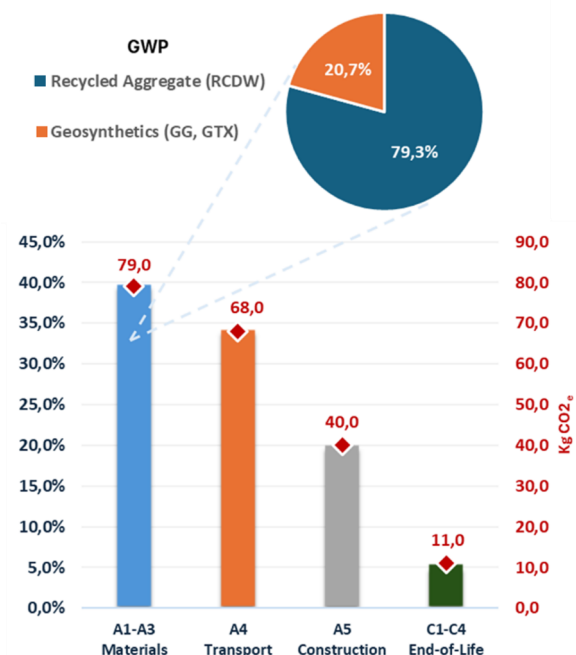


Fig. 7. Contribution of life-cycle stages to GWP for the GRS and breakdown of A1–A3 materials.

The comparative interpretation of Figs. 6–7 shows that, although both retaining structures share a similar stage hierarchy, their dominant mechanisms differ sharply. The GAB concentrates its impacts in energy-intensive material production and construction, whereas the GRS distributes them more evenly, driven by low-intensity recycling and moderate transport. This shift translates into a systemic reduction of energy and water demand, consistent with the observed 99.8 % reduction in NRPE and 82 % in FW.

The environmental indicators in Table 2 corroborate these findings, with reductions from 15 % to 30 % in secondary categories (AP, EP, POCP). The coherence across all indicators reinforces that the GRS's advantage derives from intrinsic design efficiency—mass reduction and resource circularity—rather than from external credits or offsets.

Although the GRS scenario assumes local availability of CDW, this assumption was verified through a sensitivity analysis. Extending the transport

distance of recycled aggregates up to 200 km—representative of critical but realistic conditions in Portugal—did not significantly alter the comparative outcomes. This indicates that the GRS maintains its environmental advantage even under less favourable logistical conditions, confirming the robustness of its performance within a regional supply context.

Taken together, these results reaffirm that the most effective pathway to sustainability in geotechnical design lies in the control of mass, material typology, and transport logistics. The GRS demonstrates that rational, data-supported design choices can deliver substantial environmental benefits without compromising structural performance, aligning with findings by Moncada et al. [5], Fraser et al. [6], and Cunha [14], and consistent with the circular design framework advanced by Araujo Lima et al. [15].

Table 2. Summary of life-cycle impact indicators per FU.

Environmental indicators	GAB	GRS	Δ (%)
GWP-total (kg CO ₂ e)	282.7	198.8	− 30
NRPE (MJ)	2.04E6	3.75E3	− 99.8
FW (m ³)	340.94	61.73	− 82
AP (mol H ⁺ eq)	1.07	0.74	− 30
EP (kg PO ₄ ^{3−} eq)	0.0123	0.0105	− 15
POCP (kg NMVOC eq)	0.96	0.67	− 30

3.2 Contribution and Implications for Circular Geotechnical Design

The contribution analysis clarifies how the reduction mechanisms interact and what they represent for geotechnical design practice. In the GAB, the upstream modules (A1–A3) account for over 90 % of the total impacts, dominated by the production of steel cages and natural aggregates. These materials carry high GWP and NRPE values due to energy-intensive manufacturing, extraction, and transport processes. The GRS, in contrast, reshapes this profile: by replacing these components with CDW and lightweight polymers, the system achieves a notable reduction in mass while nearly eliminating water-intensive production stages.

Although A1–A3 remain the dominant contributors in both retaining structures, their absolute magnitude differs sharply. For the GRS, these stages are substantially lower, while A4 and C remain marginal (< 10 % of total impacts). This pattern confirms that the improvements stem from the inherent configuration of the GRS itself rather than from external compensations such as energy offsets or recycling credits.

These findings align closely with the pioneering work of Inui et al. [3] and Heerten [4], who showed that the largest environmental gains in retaining structures arise not merely from material substitution but from reducing structural mass and optimizing geometry. Inui

et al. reported reductions of roughly 25–40 % in GWP when replacing reinforced-concrete walls with lighter MSE systems, while Heerten documented up to 60 % lower CO₂ emissions through rational geosynthetic design.

Together, these studies established that the embodied impacts of geotechnical structures are governed primarily by the production of concrete and steel—the same materials that dominate the upstream modules here—and that efficiency in design outweighs the influence of downstream credits or compensatory mechanisms.

From a design perspective, the results reaffirm that sustainability in geotechnical engineering is fundamentally a question of mass and distance. The GRS demonstrates that a lighter, locally sourced configuration can achieve equivalent structural performance with far lower environmental cost. Similar reasoning was observed by Fraser et al. [6], who identified material density and transport as the key determinants of embodied impacts in retaining structures. The present analysis also reinforces that adopting circular strategies in geotechnics does not depend on radical technological innovation but on rational, data-supported design decisions. Moncada et al. [5] reached comparable conclusions, showing that incremental optimisation using geosynthetics often yields greater life-cycle benefits than complex end-of-life recovery schemes.

These insights converge with the framework proposed by Araujo Lima et al. [15], who view circular geotechnical design as the coevolution of performance, material efficiency, and resource circularity. The comparison presented here provides empirical evidence that such integration is both technically feasible and environmentally effective, underscoring the role of LCA as a decision-support tool for sustainable geotechnical design.

Although Module D was excluded from the defined cradle-to-grave boundaries, preliminary data suggest that its inclusion could partially adjust the comparative balance. The GAB would likely recover higher recycling credits from steel (≈ -132 kg CO₂e/FU) than the GRS (≈ -86 kg CO₂e/FU). These potential downstream benefits, however, remain outside the present scope and do not offset the dominant advantages of the GRS across the active life-cycle stages (A–C), where most embodied impacts occur. This reinforces the superior efficiency of the GRS in carbon and resource performance, while highlighting the need for future assessments to incorporate recovery and reuse scenarios in geotechnical design, as discussed by Samuelsson et al. [16].

4 Conclusion

The GRS, reinforced with polymeric inclusions and using CDW as backfill, proved substantially more sustainable than the conventional gabion retaining structure. Across modules A1–C4, it achieved reductions of about 30 % in GWP-total, 99.8 % in NRPE, and 82 % in FW. These results derive not from

end-of-life assumptions or methodological artefacts, but from the fundamentals of design itself — a lighter configuration, shorter supply chains, and low-energy material processing. In this sense, the study reaffirms that the environmental efficiency of geotechnical structures depends mainly on mass, material type, and transport distance—rather than on downstream recovery strategies. More broadly, the findings highlight the potential of geotechnical design as a driver of circular construction. When material optimisation and life-cycle evidence are incorporated into ordinary engineering decisions, the outcome is not only a smaller footprint but also greater technical reliability and cost efficiency. The GRS exemplifies this evolution: a move from conventional containment structures toward intelligent, resource-efficient engineering, where sustainability emerges naturally from sound design choices rather than from external pressure or ideology. Ultimately, this work supports a pragmatic vision for the construction sector—acknowledging its indispensable role in development while demonstrating that genuine progress lies in engineering better, not simply building less. By grounding circularity in solid design logic and verifiable data, geotechnical engineering can help lead the transition toward infrastructures that are both resilient and responsible.

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References

1. World Economic Forum, *Circularity in the Built Environment* (2024). Available at: https://reports.weforum.org/docs/WEF_Circularity_in_the_Built_Environment_2024.pdf
2. UN Environment Programme (UNEP) & Global ABC, *Global Status Report for Buildings and Construction 2023* (2024). Available at: <https://www.unep.org/resources/report/global-status-report-buildings-and-construction>
3. T. Inui, C. Chau, K. Soga, D. Nicolson, N. O’Riordan, Embodied energy and gas emissions of retaining wall structures. *J. Geotech. Geoenvironmental. Eng.* 137(10), 958–967 (2011). [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000507](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000507)
4. G. Heerten, Reduction of climate-damaging gases in geotechnical engineering practice using geosynthetics. *Geotextile. Geomembrane.* 30, 43–49 (2012). <https://doi.org/10.1016/j.geotexmem.2011.01.006>
5. A. Moncada, I.P. Damians, S. Olivella, R.J. Bathurst, Study of environmental impact from geosynthetic reinforced soil walls. *E3S Web Conf.* 569, 13001 (2024). <https://doi.org/10.1051/e3sconf/202456913001>
6. I. Fraser, A. Elsing, M. Stucki, S. Büsser, R. Itten, R. Frischknecht, H. Wallbaum, Comparative Life Cycle Assessment of Geosynthetics versus Conventional Construction Materials: Case 4 – Soil Retaining Wall. *Proc. EUROGEO 5*, Valencia (2012). European Association for Geosynthetic Manufacturers (EAGM). Available at: <https://www.eagm.eu/>
7. E.M. Palmeira, The Pacheco Silva Lecture 2024 – Geosynthetics and sustainability: Solutions to preserve the environment and reduce the effects of climate change. *Soils & Rocks* 48(3), e2025011224 (2025). <https://doi.org/10.28927/SR.2025.011224>
8. EN 15804:2019 +A2, Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products. European Committee for Standardization (CEN), Brussels (2019).
9. ISO 14040:2006, Environmental management — Life cycle assessment — Principles and framework. International Organization for Standardization (ISO), Geneva (2006).
10. ISO 14044:2006, Environmental management — Life cycle assessment — Requirements and guidelines. International Organization for Standardization (ISO), Geneva (2006).
11. One Click LCA, *Building LCA software and EPD database* (2023). Available at: <https://www.oneclicklca.com>
12. C.S. Vieira, F.B. Ferreira, P.M. Pereira, M.L. Lopes, A. Topa Gomes, S. Madeira, N. Cristelo, Valorisation of C&D Waste as Backfill Material of Geosynthetic-Reinforced Structures – Study of the Long-Term Behaviour. In: Biondi, B. et al. (eds) *Geosynthetics: Leading the Way to a Resilient Planet*. Taylor & Francis, London (2024). <https://doi.org/10.1201/9781003386889-12>
13. F.B. Ferreira, C.S. Vieira, P.M. Pereira, N. Cristelo, M.L. Lopes, Full-Scale Model of a Geosynthetic-Reinforced Embankment Built with Recycled Construction and Demolition Materials: Construction and Instrumentation. Technical Report, Faculty of Engineering, University of Porto (FEUP), Porto (2020).
14. D.G.C.P. Cunha, Life Cycle Assessment of Geosynthetic Reinforced Soil Structures. MSc Thesis, Faculty of Engineering, University of Porto (FEUP), Porto (2025). Available at: <https://repositorio-aberto.up.pt/>
15. L.P.V. de Araújo Junior, C. Bueno, J.L. da Silva, Life Cycle Assessment and Circularity Indicators of Earth-Retaining Walls and Mechanically Stabilized Earth. *Sustainability* 17, 3769 (2025). <https://doi.org/10.3390/su17093769>
16. L. Samuelsson, J. Larsson, M. Eriksson, Integrating life-cycle environmental impact and costs into geotechnical design. *Sustain. Cities Soc.* 98, 104831 (2023). <https://doi.org/10.1016/j.scs.2023.104831>