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RESEARCH ARTICLE

Assessing the Carbon Footprint of Wrap-Faced Retaining Walls: A Comprehensive Life-Cycle Evaluation in Bangladesh

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ABSTRACT

In the field of geotechnical engineering, there's a growing emphasis on climate-friendly and sustainable approaches, leading to a heightened demand for solutions that integrate technical, ecological, and aesthetic considerations. In response, life cycle assessment (LCA) has become increasingly important as a method for assessing the environmental effects of geotechnical engineering projects. This paper focuses on a soil and water soil and water bioengineering construction project that utilizes geotextile to construct a wrap-faced retaining wall. The objective is to evaluate the wall's contribution to global warming potential (GWP) by evaluating its CO2 emissions. The results highlight the significant environmental advantages of soil and water soil and water bioengineering compared to conventional approaches, especially in terms of global warming potential (GWP). The selection of materials is crucial in determining this benefit, as wrap-faced walls exhibit significantly reduced carbon footprints in comparison to conventional alternatives such as reinforced concrete (RC) walls and mechanically stabilized earth (MSE) walls. The carbon footprint of soil and water soil and water bioengineering constructions is estimated to be nine times lower than RC walls and three times lower than MSE walls, indicating a notable reduction in emissions associated with their construction and utilization. This comprehensive approach ensures a thorough examination of the environmental impact throughout the entire lifecycle of soil and water soil and water bioengineering projects, facilitating informed decision-making and sustainable practices in construction and bioengineering.

Keywords: sustainable construction; bioengineering; life cycle analysis (LCA); CO2 emission; global warming potential (GWP); wrap-faced retaining wall

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1. Introduction

In recent years, there has been a trend towards adopting more sustainable and environmentally friendly construction techniques, is driven by the need to mitigate environmental impacts[1-4]. This concern extends beyond conventional building construction to include geo-environmental engineering, where innovative approaches such as soil and water bioengineering are gaining attention[5]. Soil and water bioengineering applications offer an environmental alternative, that aims to achieve the same objectives as conventional civil engineering structures while prioritizing environmental sustainability, aligns with the overarching goal of reducing carbon dioxide (CO_2) emissions associated with construction activities[1]. The imperative to reduce CO_2 emissions arises from the recognition of the construction industry's substantial contribution to global greenhouse gas emissions, with cement production accounting for approximately 5% of global CO_2 emissions[3,4,6-8]. This concern is global, with regions like India attributing around 17% of greenhouse gas emissions to the construction sector, and Western Europe contributing between 8% and 12%[9-13]. Efficient environmental design and materials, including low-CO_2 cements[14,15] and soil and water bioengineering technology[5], play crucial roles in reducing CO_2 emissions. Researchers have explored the cost of CO_2 reduction in building construction[9], and proposed modified life-cycle assessment methods for evaluating CO_2 emissions in new bridge designs[16-21].

Over the past decade, Life Cycle Assessment (LCA) has seen significant application within the construction and civil engineering sector[22-24]. In civil engineering, LCA-based case studies have explored various aspects such as soil and water bioengineering [1], RCC retaining wall structures[25-27], ground improvement works[28,29], soil stabilization[30], and excavation on construction sites [31]. Similarly, in building construction, studies have predominantly focused on foundations, including sustainability indicators for pile foundations, assessment of deep foundations for high-rise buildings, and the global warming potential of pile foundation construction[32-34]. Despite these advancements, there has been a notable gap in the literature specifically examining the applications of LCA to geotechnical construction works[35-38], considering innovative soil and water soil and water bioengineering techniques, particularly for wrap-faced retaining walls using geotextile to estimate the global warming potential (CO_2) emissions and comparing them with conventional structures.

The primary aim of this study is to conduct a life-cycle assessment (LCA) of wrap-faced retaining walls, incorporating geotextile, to evaluate their environmental impact. This assessment will encompass various stages, including material production, transportation, construction, and demolition at the end of the structure's lifespan. The key focus will be on quantifying the carbon footprint associated with each of these stages. Furthermore, the study intends to compare the environmental impact of wrap-faced retaining walls with that of conventional Mechanically Stabilized Earth (MSE) and reinforced concrete retaining wall. By systematically analyzing the LCA of both types of structures.

2. Methodology, materials and site characteristics

2.1. Methodology

The LCA standards referenced in this study include ISO 14040:2006 and ISO 14044:2006 for LCA methodology, along with European standard EN 15978:2011 for assessing the environmental performance of construction applications (specially buildings). It aims to clarify the system boundaries used in construction LCAs, distinguishing between cradle-to-grave, cradle-to-gate, and gate-to-gate approaches. For assessing the environmental impact of geotechnical soil and water bioengineering construction sites, the system boundary is defined as cradle-to-gate, focusing on material acquisition and construction. A cradle-to-gate scope is

appropriate when the primary focus is on the production phase of a product, especially when the majority of environmental impacts occur during this stage and when data for the use and disposal phases may be limited or less relevant. This approach allows for a more straightforward analysis and comparison of different production processes or materials. In this case, the decision to focus solely on Global Warming Potential (GWP) while ignoring other impact categories may be driven by the significance of greenhouse gas emissions, regulatory requirements, or the need to simplify the assessment for stakeholders primarily concerned with climate change. Additionally, constraints in time, budget, or data availability might lead to a narrowed focus on GWP, making it the most practical and relevant impact category to assess in this context. Within this framework, Global Warming Potential (GWP) is chosen as the relevant impact category, measured in kilograms of CO_2-equivalent. The study's main objective is to identify processes within the geo-environmental engineering system that have the most significant environmental impacts, providing insights for reducing these impacts. The functional unit in this case study is defined as "60 meters of wrap-faced retaining wall using geotextile with a width of 3 meters and 4.5 m of height, designed to protect the chocolate factory building."

2.2. Inventory analysis

The inventory analysis for the current case study, a wrap-faced retaining wall using geotextile with consideration of soil and water soil and water bioengineering applications, involved thorough data collection, including site visits with detailed documentation and analysis of construction reports. The objective was to identify all relevant inputs for the project. **Table 1** provides a summary of key aspects, encompassing both on-site and off-site transports, the transport of site engineers and workers, material usage, as well as machinery utilization at the construction site. Transport distances for trucks are summarized, considering the return journey to the production site when empty. The system boundary is defined to exclude manpower, following the standard practice of life cycle assessment (LCA), as well as smaller tools without power consumption. Additionally, the analysis excludes the power consumption of certain infrastructure elements, such as the building container and mobile sanitary system, primarily due to a lack of available data.

Table 1. The inventory data of the wrap-faced retaining wall with soil and water soil and water bioengineering technique.

Stage	Property	Value	Unit
Materials	Sand	810	m^3
	Non-woven Geotextile	445	m^2
	Geo-Jute	277	m^2
	Live-stake		-
Transportations	Truck (Materilas)	2990	km
	Passenger car (Site Eng. & workers)	530	km
Construction equipment	Power saw	12	h
	JCB	145	h

2.3. Material and site characteristics

The construction project, centered around the establishment of a chocolate factory adjacent to a large pond, required a solution that prioritized environmental preservation while addressing slope failure near the factory building. The designated section for this case study, located at Rupgang, Dhaka, Bangladesh (coordinates: 23.7931°N 90.5167°E), is depicted in **Figure 1**. Emphasizing aesthetic appeal, environmental sensitivity, and sustainability, the construction process carefully considered these factors. The primary structural element is a wrap-faced geotextile. Locally sourced Sylhet sand serves as the backfill material,

chosen for its availability and suitability. The USCS soil classification system reveals key characteristics such as a fineness modulus (FM) of 2.61, a friction angle of 31 degrees, and a relative density (Dr) of 48%.

The properties of geotextile: the woven polypropylene multifilament geotextile, specifically DF50, is a versatile material used in studies that is commonly used in civil engineering and construction for soil reinforcement, filtration, separation, and erosion control. Made from polypropylene, a durable and chemically resistant thermoplastic polymer, DF50 is woven using multifilament yarns, which provide high tensile strength and stability, essential for reinforcing applications. The woven structure also ensures controlled permeability, allowing water to pass through while preventing soil particle migration, making it ideal for filtration and drainage. DF50's chemical resistance to acids, alkalis, and salts ensures long-term durability, while UV stabilizers protect it from degradation in exposed conditions. Its durability contributes to a long service life, minimizing environmental impact, and polypropylene's recyclability adds an eco-friendly aspect. Additionally, the exact specifications of DF50, such as tensile strength and aperture size, are included in the wrap-faced retaining wall design[39].

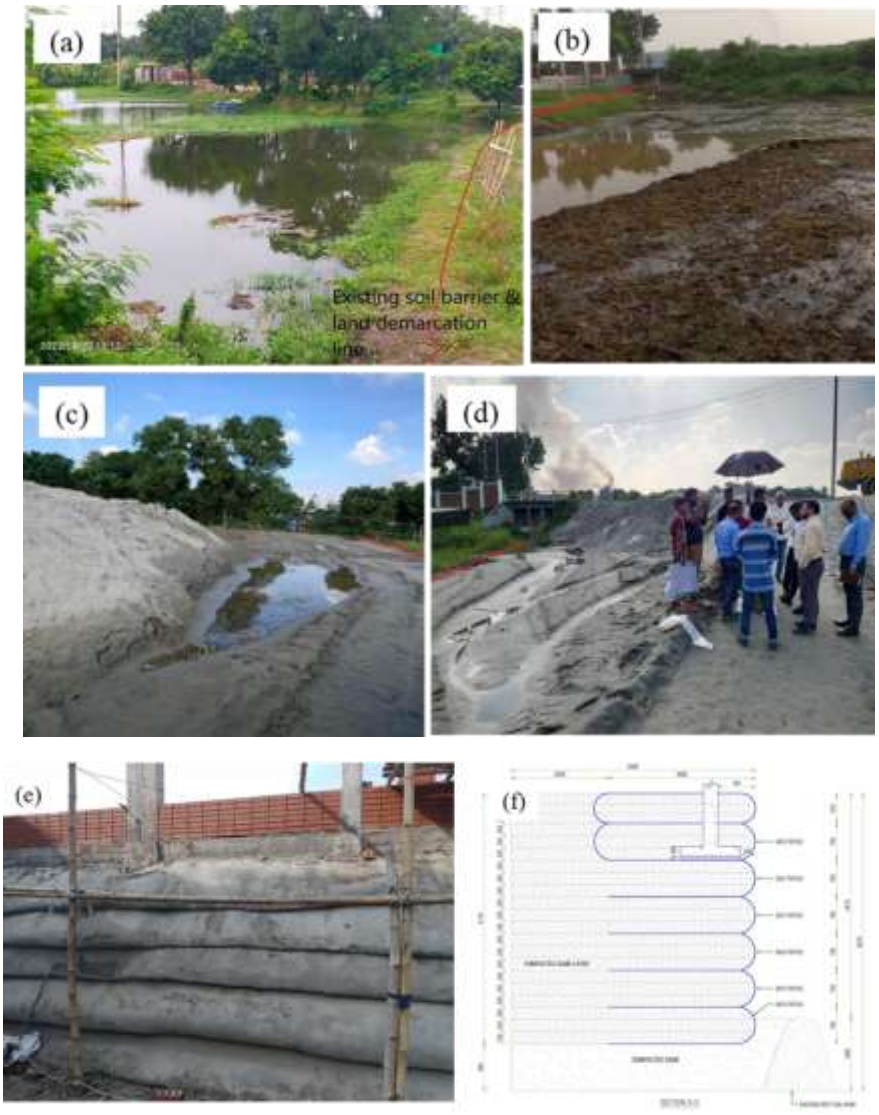


Figure 1. The wrap-faced retaining wall using geotextile: (a) Phase 1: Submerged with water at geotextile site (opposite side of culvert); (b) Phase 2: after dewatering at geotextile site (along culvert); (c & d) Phase 3: after filling sand at geotextile site; (e) After construction work; (f) Cross section of wall.

2.4. Comparison to a conventional alternative—MSE and RCC retaining wall

The Materials and Methods should be described with sufficient details to allow others to replicate and build on the published results. Please note that the publication of your manuscript implicates that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited. **Table 2** shows the inventory data of the mechanically stabilized earth (MSE) retaining wall.

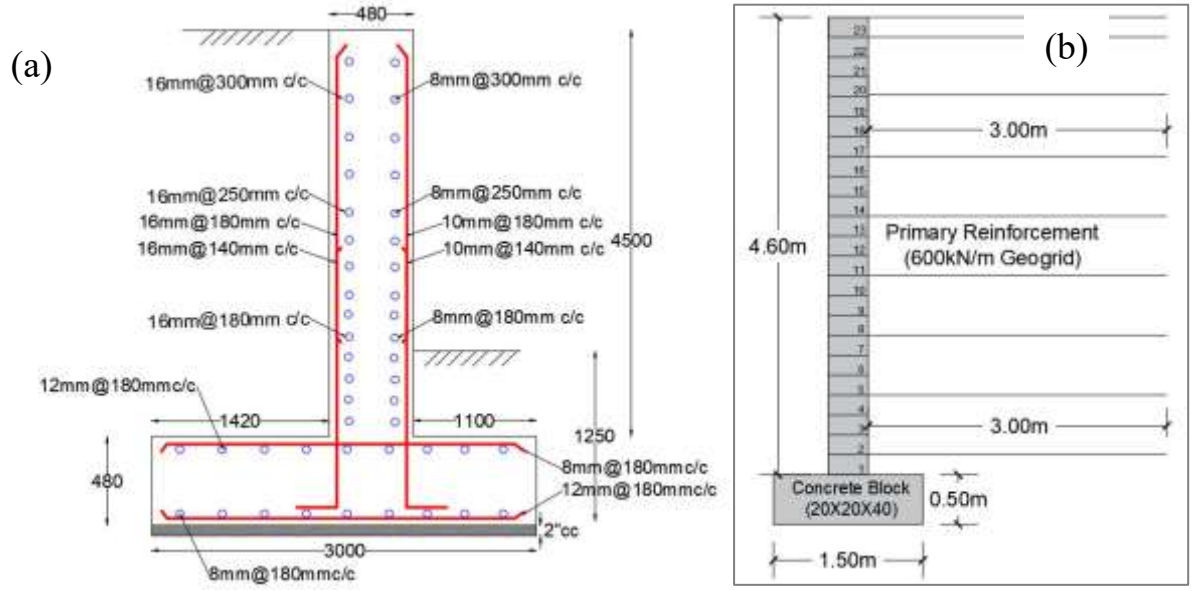


Figure 2. the conventional alternative structure: (a) Reinforce concrete retaining wall; and (b) MSE wall.

Table 2. The inventory data of the mechanically stabilized earth (MSE) retaining wall.

Stage	Property	Value	Unit
Materials	Sand	810	m^3
	Geo-grid	1260	m^2
	Concrete block	5400	pcs
	Concrete	12	m^3
	Earth removal	58	m^3
	Formwork	60	m^2
Transportations	Truck (Materilas)	6770	km
	Passenger car (Site Eng. & workers)	3600	km
Construction Equipment	Power saw	8	h
	JCB	165	h

The comparison between conventional retaining walls (mechanically stabilized earth, MSE, or reinforced concrete, RC, retaining walls, as shown in **Figure 2**) and soil and water bioengineering (wrap-faced wall using geotextile) systems reveals significant differences in global warming potential (GWP) impact analysis, as well as environmental benefits, aesthetic appeal, and construction volume. In this

scenario, the project owner's requirement was to construct a retaining structure without disrupting the surrounding ecology, particularly the adjacent large pond, while also considering environmental benefits and aesthetic appeal in comparison to conventional soil and water bioengineering structures. One significant factor contributing to this preference is the extensive soil excavation necessary for the foundational structures of MSE or RC walls, followed by backfilling, because a conventional (MSE or RC) retaining wall is more or less a 3D construction. These excavation and backfilling processes demand the use of heavy machinery, resulting in heightened greenhouse gas emissions, energy consumption, and increased costs compared to the soil and water bioengineering technique. **Tables 3** likely contain hypothetical inventory data, including information on construction site equipment, preparatory work, and the machinery essential for the construction of the conventional alternative (MSE or RC) retaining wall. This study uses the typical 20 cm by 20 cm by 40 cm concrete blocks to calculate the materials and their impact on global warming (GWP) for MSE wall, which require about 21.31 MJ of energy per block during fabrication. The processes of raw material extraction, mixing, molding, and curing consume this energy. The typical CO_2 emissions for these blocks are approximately 2.1 kg CO_2 per block (cradle-to-gate), reflecting the environmental impact associated with the production process [40]. When considering the entire lifecycle (cradle-to-grave), including transportation, construction, and disposal, CO_2 emissions can increase to 150 to 250 kg CO_2 per cubic meter. To achieve the desired compressive strength and durability, 25 MPa concrete for reinforced concrete (RC) retaining wall is prepared by combining cement, water, and aggregates in specific proportions. The entire lifecycle, encompassing transportation, construction, and disposal, results in CO_2 emissions per cubic meter.

Table 3. The inventory data of the reinforce concrete (RC) retaining wall.

Stage	Property	Value	Unit
Materials	Sand	810	m^3
	Reinforcement	7656	kg
	Concrete	240	m^3
	Eaarth removal	115	m^3
	Formwork	545	m^2
	Weir	26	kg
Transportations	Truck (Materilas)	7880	km
	Passenger car (Site Eng. & workers)	3600	km
Construction equipment	Power saw	8	h
	JCB	100	h

2.5. Emission factor

In the study, the assessment of global warming potential (GWP) incorporates data from diverse sources to calculate the CO_2 emission factor. These sources include existing databases, insights from local manufacturers obtained through personal interviews conducted by the authors, and relevant literature. For instance, data on sand and earth removal were sourced from studies by von der Thannen et al.[1], Yepes et al.[3], Hammond et al.[40] and the Catalonia Institute of Construction Technology[41]. Similarly, information on geotextile materials was drawn from research by Raja et al.[42] and Dixon, Neil, et al.[43]. Formwork data came from studies by Yepes et al.[3] and the Catalonia Institute of Construction Technology[41], while concrete-related data were sourced from studies by Jotisankasa et al.[5], Hammond et al.[40] and Sukontasukkul[44]. Concrete block data were obtained from studies by De Almeida and Oliveira et al.[45, 46] and geogrid data from studies by Hammond et al.[40] and Berg, R. R., et al.[47]. Additionally, transportation-related data, both on-site and

off-site, including passenger car emissions, were sourced from studies by Jotisankasa et al.[5], Sukontasukkul[44], Spielmann[48], while reinforcement data came from studies by Yepes et al.[3], and Hammond et al.[40]. This diverse range of sources ensures a comprehensive and reliable foundation for determining the CO_2 emission factor used in the analysis. By drawing upon various sources, the study aims to capture a nuanced understanding of the environmental impact associated with the soil and water soil and water bioengineering construction project under scrutiny.

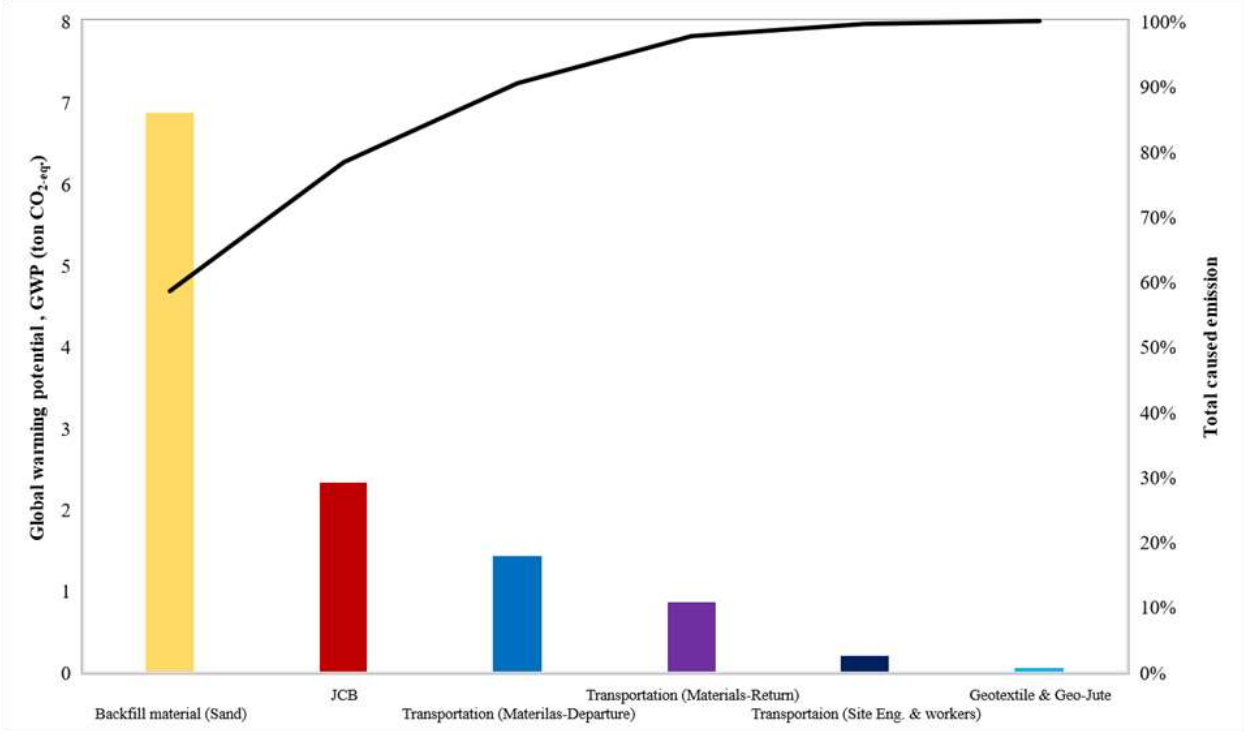


Figure 3. Total emissions caused by each process, and the cumulative percentage.

In the geo-environmental engineering case study of the wrap-faced retaining wall in Rupgong, Dhaka, Bangladesh, the investigation into global warming potential (GWP) provides significant findings. **Figure 3**, which illustrates the impact of GWP, highlights that the majority of emissions originate from the materials used on-site. The backfill sand and geotextile are the primary contributors, with emissions totaling 8770 kg CO_2−eq., accounting for about 65% of the overall emissions. Despite its common perception as a neutral material, sand—being the principal building material—is not CO_2 neutral due to the energy consumption and emissions involved in its supply chain processes, as noted by Hammond et al.[40]. Transportation of materials also plays a substantial role, contributing 2501.03 kg CO_2−eq., which represents approximately 18% of the total emissions. In contrast, the emissions generated by construction machinery are relatively lower, amounting to 2331.60 kg CO_2−eq., or about 17% of the total emissions.

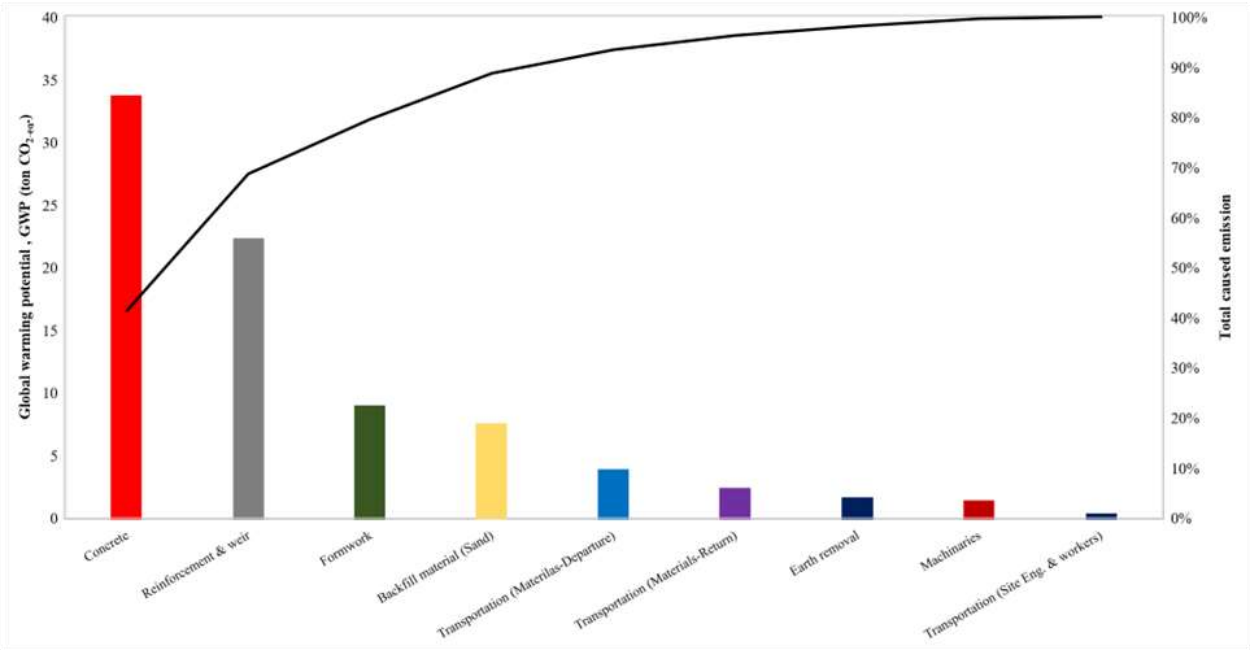


Figure 4. Total emissions caused by each process, as well as the cumulative percentage from the conventional alternative structure: RC retaining wall.

The results depicted in Figure 6 illustrate that the conventional alternative MSE and RC retaining walls generated a total of 35,106.68 and 100,090.93 kg $CO_{2\text{-equivalents}}$ ($CO2\text{-eq.}$), respectively, whereas the soil and water bioengineering method produced 13,602.01 kg $CO_{2\text{-eq.}}$ in total. This indicates that the MSE wall emits nearly three times as much, and the RC wall emits around nine times as much, in terms of global warming potential (GWP), compared to the soil and water bioengineering wrap-faced wall. Regarding transportation, the findings show that the emissions from the conventional RC and MSE walls (6,683.2 and 5,610.44 kg $CO_{2\text{-eq.}}$, respectively) are at least twice as high as those from the water soil and water bioengineering measures (2,501.03 kg $CO_{2\text{-eq.}}$). The difference in material-related emissions is larger. Specifically, the materials utilized for constructing the conventional measures resulted in emissions of 93,407.72 and 26,843.03 kg $CO_{2\text{-eq.}}$ for the RC wall and MSE wall, respectively, while the soil and water bioengineering measure caused emissions of 8,769.38 kg $CO_{2\text{-eq.}}$ (**Figure 4 & 5**). In terms of cumulative percentage lines, the transport required for soil water bioengineering (wrap-faced wall) construction contributed to 18% of total emissions, whereas for conventional construction, it accounted for nearly 16% and 8.4% for MSE and RC walls, respectively. When adding the percentage of emissions from machinery on the construction site, the soil and water bioengineering measure reached approximately 17% of total emissions, while the conventional structure accounted for nearly 7% and 9% for RC and MSE walls, respectively. Consequently, the materials used in soil and water bioengineering construction accounted for nearly 65% of total emissions, whereas those in the conventional measures contributed to around 72% and 76% for RC and MSE walls, respectively (see **Figure 4 & 5**).

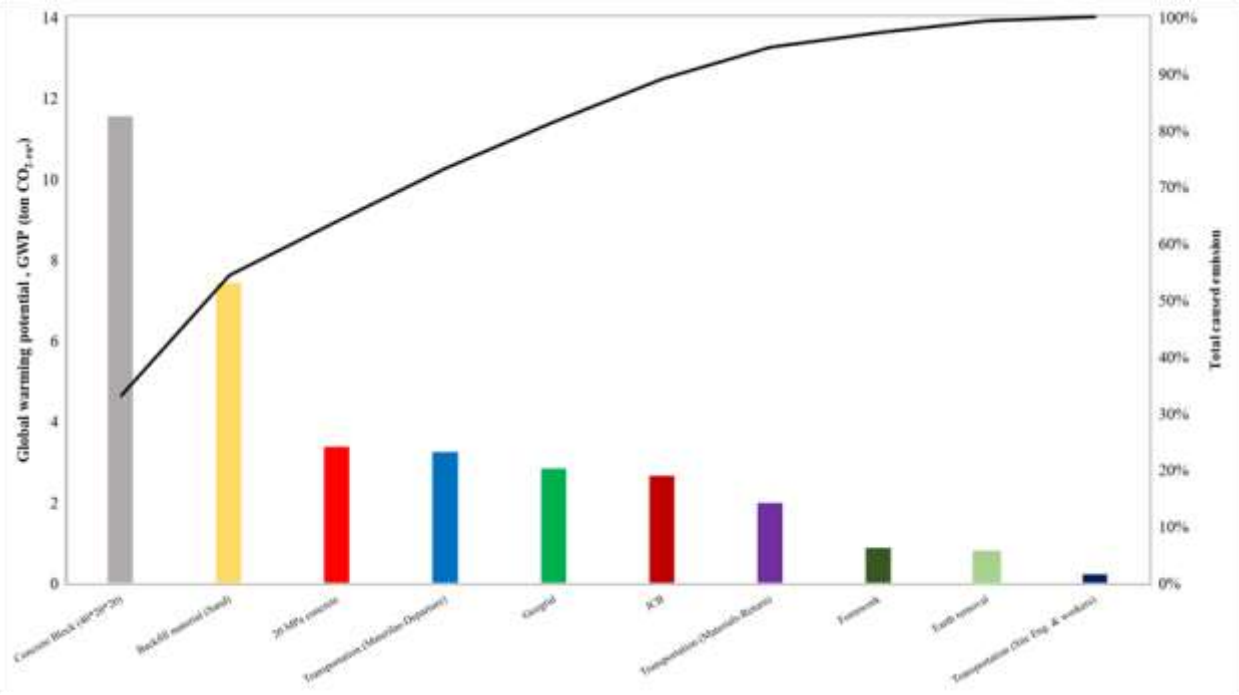


Figure 5. Total emissions caused by each process, as well as the cumulative percentage from the conventional alternative structure: MSE wall.

3. Discussion and Recommendations

This paper presents a specific case study that demonstrates the application of soil and water bioengineering principles in the field of geotechnical engineering. It provides valuable insights into the benefits of using life cycle assessment (LCA) approaches. Unlike many hypothetical case studies prevalent in literature, this study benefits from detailed documentation of an actual construction site, allowing for the monitoring of project progress and subsequent post-calculation of implemented structures. By employing LCA on a tangible soil and water bioengineering project, the paper showcases the practical utility of this methodology in assessing the environmental impact of construction practices. The utilization of real-world data enhances the credibility and applicability of the findings, providing valuable insights for future projects in similar contexts. Moreover, analyzing the environmental implications of genuine construction processes and material selections enables a deeper understanding of the intricacies and challenges associated with soil and water bioengineering endeavors.

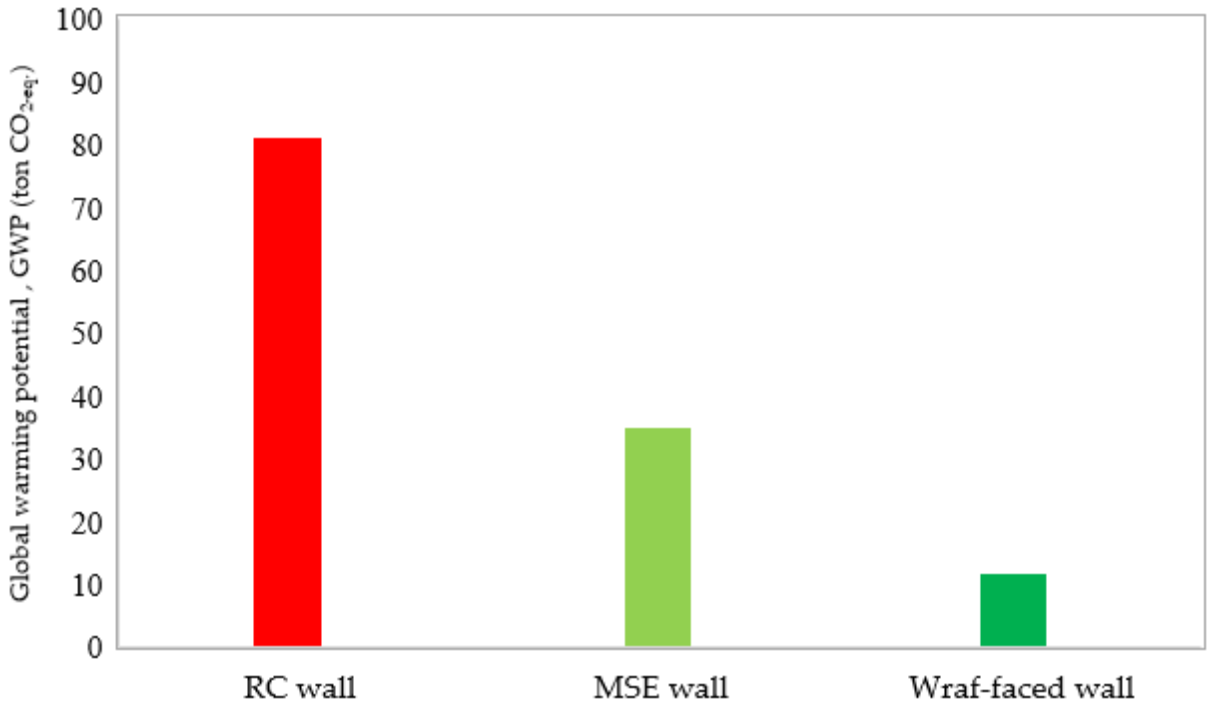


Figure 6. Comparison between conventional (RC and MSE wall) and soil and water soil and water bioengineering (wrap-faced wall) methods for $CO_{2\text{-}eq}$. Emission.

The comparative analysis of global warming potential (GWP) for different retaining wall construction methods highlights the significant environmental benefits of soil and water bioengineering over conventional MSE and RC walls. While the bioengineering approach produces far fewer CO_2-equivalent emissions, particularly in terms of material use and transportation, the study's findings are context-sensitive and may not be universally applicable. The results depend heavily on specific input parameters, such as emission factors and transportation distances, which can vary widely across different regions. Additionally, there is uncertainty in the results due to the reliance on generalized assumptions and the absence of formal sensitivity analyses. Although the study strongly advocates for bioengineering in the specific context of Rupgong, its broader applicability to other projects with different environmental conditions and construction requirements remains uncertain. Future research should address these limitations by exploring the scalability and long-term performance of bioengineering methods, as well as by conducting more comprehensive analyses that include a wider range of environmental impacts and project contexts, like habitat creation and biodiversity promotion, and their potential negative effects during construction, such as emissions and ecosystem disruption. Surprisingly, these negative impacts haven't been adequately studied, highlighting the need for future research and practical recommendations. In our case study, we omitted additional impact categories related to biodiversity due to methodological gaps and challenges. Moreover, we conducted construction solely from the factory side to avoid disturbing ecology of pond's habitats, emphasizing the importance of conscientious ecological consideration throughout soil and water bioengineering projects.

4. Conclusion

This study investigated the effects of the global warming potential (GWP), particularly CO_2 emissions, associated with a wrap-faced retaining wall using geotextile in comparison to conventional alternatives like MSE and RC retaining walls, considering the soil and water bioengineering applications. The following conclusions can be drawn based on the findings of this study:

- The comprehensive lifecycle assessment (LCA) of soil and water bioengineering techniques has highlighted significant environmental advantages over conventional methods. Notably, soil and water bioengineering constructions, such as wrap-faced walls with geotextiles, have significantly lower carbon footprints (based on the assumed emission factor). Compared to reinforced concrete (RC) walls, their carbon footprint is nine times lower and three times lower than mechanically stabilized earth (MSE) walls. These results emphasize the potential of soil and water bioengineering to mitigate global warming by reducing their global warming potential (GWP).

- In order to achieve environmentally friendly and sustainable structures, it's essential to develop construction methods that offer environmental benefits, aesthetic appeal, and sustainability, especially in countries like Bangladesh. Soil and water bioengineering approaches, such as the implementation of wrap-faced retaining walls utilizing geotextiles, are employed to stabilize terrain while simultaneously reducing ecological impact and achieved the engineering goal. The research highlights the importance of developing specialized Life Cycle Inventory (LCI) databases for geo-environmental engineering works, specifically focusing on materials used in soil and water bioengineering structures. This is in response to the introduction of a comprehensive life cycle assessment (LCA) for soil and water bioengineering structures. Moreover, it supports future research efforts focused on mitigating construction-related environmental effects using Life Cycle Impact Assessment (LCIA) and establishing thorough protocols for conducting Life Cycle Assessments (LCA) in the construction and civil engineering industries.

Conflict of Interest

The authors declare no conflicts of interest.

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