Chapter-8

Sustainability Analysis of Study

8.1. Introduction to the Chapter

Building In the previous chapter, the geotechnical performance of untreated and treated Municipal Solid Waste Fines (MSWF) was thoroughly assessed, focusing on their application in pavement and foundation engineering. The mechanical properties, including the load-bearing capacity and compressibility of the treated MSWF, were analyzed to evaluate the potential for reuse in infrastructure projects. These assessments provided a foundation for understanding the structural viability of MSWF when stabilized with various materials (Smith et al., 2017). The findings highlighted the need for further exploration into the environmental sustainability of these stabilization techniques, particularly considering the increasing importance of reducing carbon footprints and enhancing the resilience of construction materials in line with circular economy principles (Geissdoerfer et al., 2017). This chapter shifts focus to a comprehensive sustainability analysis of different MSWF stabilization methods, specifically comparing Xanthan Gum (XG), Agar Gum (AG), and traditional cement stabilization. The assessment includes an evaluation of the carbon emissions associated with each method, financial implications, and broader environmental impacts. By integrating Environmental, Social, and Governance (ESG) criteria into the analysis, the chapter aims to provide a holistic view of the long-term viability of these materials, considering not only their immediate geotechnical performance but also their potential contributions to sustainable development and resilient infrastructure (Baumgartner, 2014; Berardi, 2013). This approach ensures that the recommendations derived from this study are grounded in both technical rigor and environmental responsibility, aligning with the evolving demands of modern civil engineering practices.

8.2. Material and Method

The study investigates the stabilization of Municipal Solid Waste Fines (MSWF) through a comprehensive sustainability assessment, utilizing both bio-based stabilizers, Agar Gum (AG) and Xanthan Gum (XG), as well as a conventional stabilizer, lime. This assessment encompasses multiple dimensions, including carbon footprint, economic viability, ESG (Environmental, Social, and Governance) impact, and overall suitability for various applications, as aligned with sustainable development goals (SDGs) (Nations 2023).

I. **Sustainability Initiatives:** The study is divided into two primary approaches. The first approach focuses on utilizing MSWF in place of fresh soil for geotechnical applications, while the second explores the stabilization of MSWF using biopolymers (XG/AG) instead of traditional cement or lime.

II. **Carbon Footprint Analysis:** Emission factors from previous studies were used to calculate the carbon footprints associated with each stabilizer. The analysis focused on the emissions from raw material production, transportation, and application, with lime exhibiting significantly higher emissions compared to bio-based alternatives like AG and XG.

III. **Economic Analysis:** The cost analysis was performed by calculating the expenses associated with raw materials, transportation, and application. Special consideration was given to the potential financial benefits of carbon credits, particularly for AG, which is carbon-negative.

IV. **ESG Analysis:** The environmental, social, and governance impacts of each stabilizer were evaluated, following the Global Reporting Initiative (GRI) framework. This included assessing the environmental footprint, occupational health and safety, and governance challenges associated with each stabilization method.

V. **Resiliency Analysis:** A multidimensional resiliency analysis was conducted, taking into account the durability of stabilization, environmental impact, adaptability for future land use, and compliance with relevant regulations. The analysis demonstrated that AG and XG offer durable stabilization while preserving soil integrity and contributing to long-term environmental resilience, making them suitable for a wide range of geotechnical applications.

VI. **SDG Alignment Analysis:** For both Initiatives as discussed, the alignment of these approaches with SDGs 9, 11, 12, 13, and 15 was examined. This analysis emphasizes the contribution of MSWF utilization to sustainable infrastructure, urban development, resource efficiency, climate action, and biodiversity protection.

This comprehensive methodology (Ref flowchart given in Figure 50) ensures that the study's findings are robust, addressing both immediate geotechnical performance and broader sustainability objectives, thereby providing a holistic view of the viability of MSWF stabilization methods.

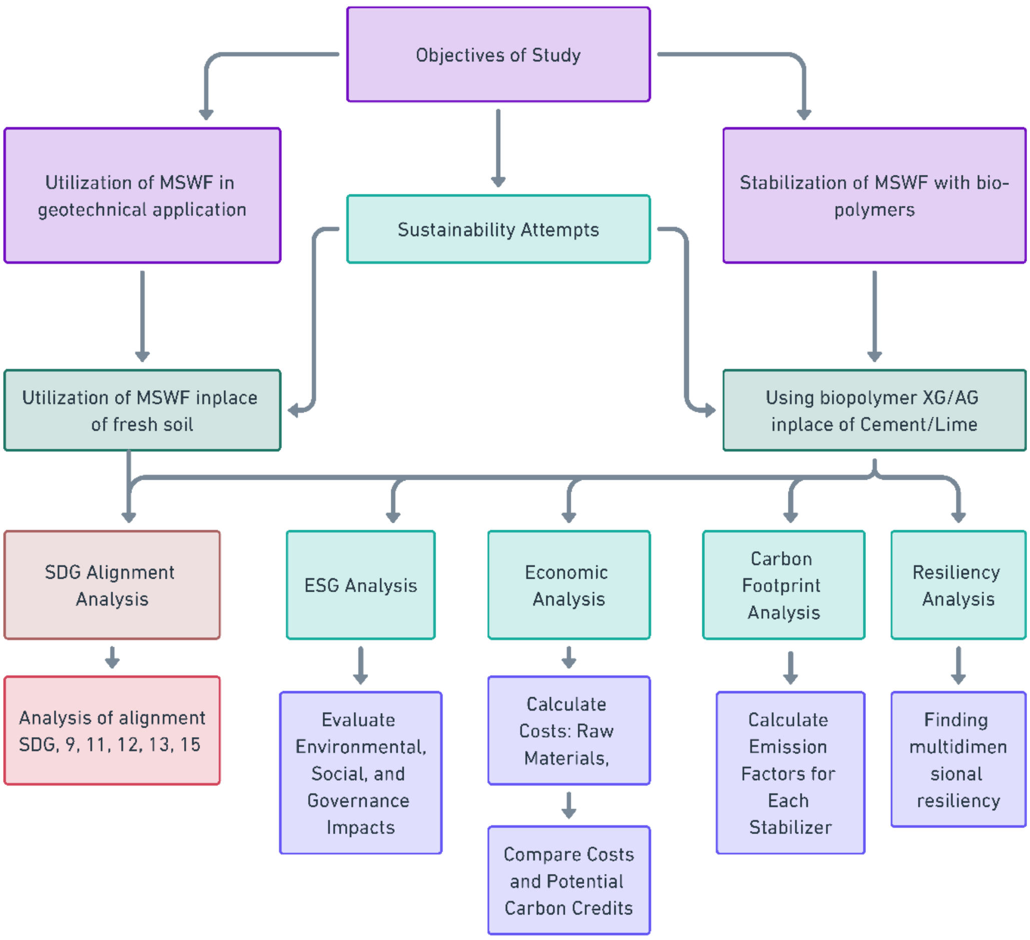


Figure 50: Flowchart of the methodology analysis of the sustainability analysis

8.3. Result and Discussion

8.3.1. Carbon footprint analysis

In this study, Xanthan Gum (XG) and Agar Gum (AG) were utilized to stabilize Municipal Solid Waste Fines (MSWF). The carbon footprint analysis was conducted per metric ton of stabilization. For simplification, factors such as the transportation of materials, the stabilization process, and other related aspects were assumed to be similar across all methods. Therefore, the analysis focused solely on the CO_2e emissions generated during the material manufacturing process. The CO_2e emission factors were derived from previous studies and are summarized in Table 19.

The term CO_2e (Carbon Dioxide Equivalent) represents the global warming potential (GWP) of different greenhouse gases expressed in terms of the equivalent amount of CO_2. The 'e' stands for equivalent, meaning that various gases (such as methane and nitrous oxide) are converted into the amount of CO_2 that would have the same warming effect over a specific time period, typically 100 years.

For comparison purposes, lime was also considered, which is also considered a convention material for soil stabilization, with the quantity adjusted to match the properties of the MSWF stabilized with 1.5% XG or AG. Through experimentation, it was found that 8.5% quick lime by weight of MSWF induced similar properties, with variation less than 2.5%. The Optimum Moisture Content (OMC) was maintained as described in Chapter 5 during the preparation of the samples.

Table 19: CO2e Emission Factors for Different Stabilization Methods

Stabilizer	CO2e Emission Factor (kg CO2e per kg stabilizer)	Source & Justification
Lime	1.2	The CO_2e emission factor for lime is based on the calcination process in lime production, where significant CO_2 is released. (Laveglia et al. 2022)
Xanthan Gum (XG)	7.79	The emission factor for XG is derived from CarbonCloud's assessments, which outline the energy-intensive production process involving microbial fermentation and subsequent processing (CarbonCloud 2024).
Agar Gum (AG)	-1.11	The CO_2e factor for AG is based on life cycle assessments (LCA) of agar production from seaweed, particularly considering the carbon sequestration during seaweed cultivation. This data is supported by studies focusing on the environmental impact of bio-based products, as

detailed in the "Life Cycle Assessment of Agar Production" (Zhang et al. 2024).

Calculations:

- OMC (Optimum Moisture Content): 15.2% for MSWF.
- Water Required: 15.2% of 1 ton (1000 kg) = 152 kg (or liters) of water.
- Binder (AG or XG) Requirement: 1.5% of 152 kg water = 2.28 kg of binder.

1. Lime Stabilization:

Amount of Lime Used: 8.5% of 1 ton (1000 kg) = 85 kg of lime.

CO_2e Emissions from Lime Production:

$$85kg \times 1.2kg\ CO_2e/kg = 102kg\ CO_2e$$

Total CO_2e for Lime Stabilization: 102 kg CO_2e.

2. Xanthan Gum (XG) Stabilization:

Amount of XG Used: 1.5% of 152 kg = 2.28 kg of XG.

CO_2e Emissions from XG Production:

$$2.28kg \times 7.79kg\ CO_2e/kg = 17.76kg\ CO_2e$$

Total CO_2e for XG Stabilization: 17.76 kg CO_2e.

3. Agar Gum (AG) Stabilization:

- Amount of AG Used: 1.5% of 152 kg = 2.28 kg of AG.
- CO_2e Emissions from AG Production:

$$2.28kg \times (-1.11) kg\ CO_2e/kg = -2.53kg\ CO_2e$$

- Total CO_2e for AG Stabilization: −2.53kg CO_2e

Summary of CO2e for Stabilizing 1 Ton of MSWF:

- **Lime Stabilization: 102 kg CO_2e**.
- **Xanthan Gum Stabilization: 17.76 kg CO_2e**.
- **Agar Gum Stabilization: −2.53kg CO_2e.**

8.3.2. Financial Analysis

To ensure an accurate financial comparison of the stabilizers, the average market rates were gathered from reliable online sources (Ref Figure 51), with specific considerations for the intended application in soil stabilization. Given that Xanthan Gum and Agar Gum are typically produced for food or laboratory use, their production processes are more stringent and costly. Therefore, a reasonable normalization was applied to reflect the reduced purity and manufacturing requirements when used for geotechnical applications, resulting in cost reductions for these materials. (Ref Table 20)

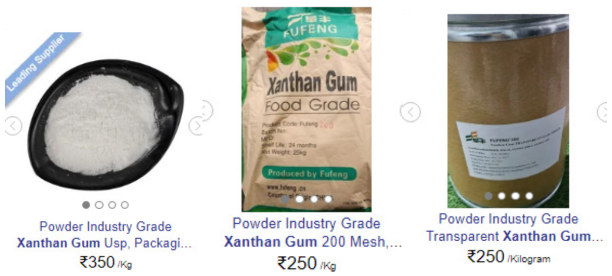
Table 20: Financial Analysis of XG, AG and Lime

Stabilizer	Average rate (At available grade) (INR)	Reasonable normalisation	Normalised Rate (INR)	Quantity required	Total amount (INR)
Quick Lime (Powder form)	6.08	For **Quick Lime** (Powder form), no normalization is needed as the cost reflects typical large-scale industrial use.	6.08	85	516.8
Xanthan Gum	283.3	For **Xanthan Gum**, a 20% cost reduction is applied because the manufacturing process for soil stabilization is less	226.6	2.28	516.6

		complex than for food or cosmetic uses, requiring lower purity levels.			
Agar Gum	1466.6	For **Agar Gum**, a 35% cost reduction is assumed, reflecting the use of a less pure form suitable for soil stabilization, which lowers production and maintenance costs compared to its food and laboratory-grade counterparts.	953.3	2.28	2073.5

* Assumptions are based on potential cost reductions due to lower purity and less stringent manufacturing requirements for soil stabilization applications

(a) Quick Lime: The average price for 1 kg is ₹6.08



(b) Xanthan Gum: Average price (industrial-grade) before normalization is ₹283.3 per kg.

(c) Agar Gum: Average price (food/laboratory grade) before normalization is ₹1466.6 per kg.

Figure 51: Market Prices of Stabilizers for MSWF Stabilization (source: indiamart.com)

8.3.3. Financial Analysis in Terms of "Carbon Credit 'CCT' & Offsetting"

As discussed earlier, the per-ton stabilization cost of MSWF using Lime and Xanthan Gum (XG) is nearly identical, while Agar Gum (AG) remains significantly more expensive. However, the environmental impact in terms of carbon emissions differs substantially: AG not only offsets 2.53 kg of CO_2 but also results in a carbon-negative footprint, whereas XG emits 17.76 kg of CO_2—still relatively low. Lime, on the other hand, contributes 102 kg of CO_2 per ton of MSWF stabilized.

For projects aiming to achieve carbon neutrality, offsetting carbon emissions becomes a crucial consideration. In countries like India, where the carbon market is still developing, carbon credits typically range between \$2 to \$10 per ton of CO_2e (Dev and Krishnamurthy 2023). This variability in carbon credit prices can significantly influence the overall financial viability of a project.

For instance, in a scenario where a project in the European Union (Current CCT in EU as on 16 Aug 2024 1300 IST is €72.44 i.e., ~6,678.01 INR, 162) aims to be carbon-neutral, using Lime as a stabilizer would incur substantial additional costs due to the high carbon credit prices in the region. The cost of offsetting Lime's higher emissions could make the project less financially viable compared to using XG or AG, which have lower or negative carbon footprints. In this case, XG emerges as a more cost-effective option due to its relatively low emissions and moderate base cost, making it favourable across various carbon markets.

Ultimately, while AG provides the most significant environmental benefit by being carbon-negative, the choice of stabilizer will depend on the specific financial and environmental goals of the project, as well as the prevailing carbon credit prices in the region where the project is being implemented (Rasheed et al. 2023). Projects that prioritize sustainability and operate in regions with high carbon credit values may find AG or XG to be more attractive options despite their higher initial costs.

8.3.4. ESG Analysis- Aligned to the Global Reporting Initiative (GRI) Framework

This ESG analysis is conducted using the **Global Reporting Initiative (GRI)** framework, which is widely recognized for its comprehensive guidelines on environmental, social, and governance factors. By aligning with GRI standards, a standardized and transparent evaluation of Municipal Solid Waste Fines (MSWF) stabilization methods is ensured, allowing for meaningful comparisons across different techniques. This approach provides a detailed, quantifiable assessment of the environmental, social, and governance impacts of Lime, Xanthan Gum (XG), and Agar Gum (AG) stabilization, supporting informed decision-making in sustainable development.

This analysis (Given below in Table 21) complements the technical and financial evaluations in the thesis, offering a holistic view of the sustainability and long-term viability of these methods. This inclusion is appropriate for a thesis where ESG considerations are part of the broader research context, enhancing the depth and relevance of the study.

Table 21: ESG analysis aligned to GRI framework

Aspect	**Lime Stabilization**	**Xanthan Gum (XG) Stabilization**	**Agar Gum (AG) Stabilization**
Environmental Impact (GRI 305: Emissions)	**CO2 Emissions:** 102 kg CO2/ton MSWF **Impact:** High emissions reported under GRI 305-1.	**CO2 Emissions:** 17.76 kg CO2/ton MSWF **Impact:** Low emissions reported under GRI 305-1.	**CO2 Emissions:** -2.53 kg CO2/ton MSWF **Impact:** Carbon-negative, reported under GRI 305-4.
Social Impact (GRI 403: Occupational Health and Safety)	**Health Risks:** High exposure to dust/chemicals. **Impact:** Report incidents and mitigation under GRI 403-2.	**Health Risks:** Minimal occupational hazards. **Impact:** Low incidents, reported under GRI 403-2.	**Health Risks:** Moderate physical labor risks. **Impact:** Reported under GRI 403-2 with focus on safety.
Governance Impact (GRI	**Governance Challenges:** High regulatory compliance needs.	**Governance Challenges:** Moderate, focused on compliance.	**Governance Challenges:** Requires sustainable sourcing and biodiversity

102: General Disclosures)	**Impact:** Disclosed under GRI 102-15.	**Impact:** Disclosed under GRI 102-15.	management. **Impact:** Disclosed under GRI 102-15.

This ESG analysis evaluates the environmental, social, and governance impacts of three stabilization methods—Lime, Xanthan Gum (XG), and Agar Gum (AG)—for Municipal Solid Waste Fines (MSWF).

Lime stabilization is associated with high CO_2 emissions, significant health risks for workers, and stringent governance requirements, making it less favorable from an ESG perspective. **Xanthan Gum** presents a lower environmental impact and minimal social risks, with moderate governance challenges, positioning it as a more sustainable option. **Agar Gum**, despite its higher cost, offers the best environmental benefits with carbon-negative emissions and aligns strongly with sustainability goals, though it requires careful governance to ensure responsible sourcing.

This analysis, aligned with GRI standards, provides a quantitative and standardized reflection of the ESG performance of each stabilization method, guiding sustainable decision-making.

8.3.5. Resiliency cum Suitability Analysis of Stabilizers

To assess the overall suitability of the stabilizers for MSWF, a resiliency cum suitability analysis was conducted, given in Table 22, following established geotechnical and environmental criteria. This analysis considered multiple factors, including strength, setting time, durability, soil chemistry, environmental impact, and economic considerations, to ensure a comprehensive evaluation of each stabilizer's long-term performance and adaptability. The analysis aligns with industry standards for sustainable construction and environmental resilience, providing a detailed comparison to guide material selection.

Table 22: Resiliency and Suitability Analysis of Stabilizers

	Resiliency and Suitability		
Aspect	**Lime**	**Xanthan Gum (XG)**	**Agar Gum (AG)**
Strength & Setting Time	High immediate strength provides short-term resilience in urgent projects, but high emissions reduce long-term environmental resilience.	Delayed strength development may pose short-term challenges, but low emissions enhance long-term environmental resilience.	Combines quick strength with zero emissions, offering strong short-term and long-term resilience.
Durability & Soil Chemistry	Durable in structure but changes soil chemistry, potentially limiting soil's future adaptability and resilience.	Less durable in wet conditions, which may affect short-term resilience, but maintains soil's chemical integrity, preserving long-term adaptability.	Durable and stable without altering soil chemistry, maintaining both immediate and future resilience of the soil for diverse uses.
Environmental Impact	High carbon emissions undermine environmental resilience, requiring mitigation through carbon offsets.	Low carbon emissions contribute to greater environmental resilience by reducing the need for offsets and lowering the project's overall carbon footprint.	Carbon-negative impact bolsters environmental resilience, potentially providing long-term benefits through carbon sequestration.
Economic Considerations	Cost-effective in the short term, but long-term economic resilience is compromised by future costs related to environmental impact and carbon offsets.	Higher initial costs are offset by long-term savings on carbon offsets and lower environmental impact, enhancing economic resilience.	High upfront costs may challenge short-term financial resilience, but long-term sustainability and potential carbon credits improve economic resilience over time.

Suitability for Future Land Use	Alters soil permanently, reducing adaptability and future resilience of the land for other uses.	Preserves soil quality, supporting the land's long-term resilience and adaptability for future agricultural or developmental uses.	Maintains soil integrity, offering the highest long-term resilience for future land use, ensuring that the soil remains adaptable and environmentally healthy.

- **Lime**: Provides immediate structural resiliency but compromises long-term environmental and economic resilience due to high emissions and permanent changes to soil chemistry.
- **Xanthan Gum (XG)**: Offers balanced resilience, with some short-term challenges but strong long-term environmental and economic resilience due to low emissions and preservation of soil integrity.
- **Agar Gum (AG)**: Delivers comprehensive resiliency with both immediate and long-term benefits. It combines structural durability, zero emissions, and the preservation of soil chemistry, making it ideal for projects prioritizing sustainability and future adaptability.

8.3.6. SDG Goal Alignment Analysis of Study (of Sustainability Initiatives)

The SDG alignment analysis was conducted to evaluate how the two sustainability initiatives—using bio-mined MSWF instead of fresh soil, and using biopolymers instead of lime/cement—contribute to the achievement of specific Sustainable Development Goals (SDGs). Each attempt was systematically assessed against relevant SDGs, focusing on their potential to support sustainable infrastructure, enhance urban sustainability, promote responsible consumption, mitigate climate change, and protect biodiversity. This analysis which is given in Table 23, ensures that the overall study's recommendations are aligned with global sustainability objectives.

Table 23: SDG Alignment of Sustainability Initiatives

SDG Goal	**Attempt 1: Using Bio-Mined MSWF Instead of Fresh Soil**	**Attempt 2: Using Biopolymer Instead of Lime/Cement**
SDG 9: Industry, Innovation, and Infrastructure 	Supports sustainable infrastructure by reusing materials, reducing the need for fresh soil excavation, and promoting innovative waste management practices.	Fosters sustainable infrastructure by using low-emission biopolymers, reducing the environmental impact of construction, and encouraging innovation in material science.
SDG 11: Sustainable Cities and Communities 	Reduces landfill use and environmental degradation by repurposing bio-mined MSWF, contributing to more sustainable urban development.	Enhances urban sustainability by reducing pollution and environmental impact, promoting healthier urban environments.
SDG 12: Responsible Consumption and Production 	Encourages a circular economy by turning waste into a resource, reducing the demand for virgin materials, and supporting resource efficiency.	Promotes responsible consumption by replacing non-renewable, high-impact materials with renewable, biodegradable options, supporting sustainable production patterns.
SDG 13: Climate Action	Helps mitigate climate change by lowering emissions associated with soil extraction and waste management.	Significantly reduces CO_2 emissions by using biopolymers instead of high-emission stabilizers like lime and cement,

		contributing to climate action.
SDG 15: Life on Land	Protects biodiversity and ecosystems by minimizing the environmental impact of soil excavation and landfill expansion.	Minimizes ecological harm by using biodegradable, renewable materials, protecting land-based ecosystems and biodiversity.

Both Initiatives align with **SDG 9, SDG 11, SDG 12, SDG 13, and SDG 15** by promoting sustainability and reducing environmental impacts. **Scenario 1** focuses on resource efficiency and reducing waste, particularly through the repurposing of bio-mined MSWF, which prevents additional soil excavation and landfill use. **Scenario 2** emphasizes the environmental benefits of biopolymers, including lower emissions and the use of renewable resources, which reduce the carbon footprint and protect biodiversity.

8.4. Key takeaways and Way forward

- Lime stabilization results in 102 kg CO_2e per ton of MSWF, while Xanthan Gum (XG) emits 17.76 kg CO_2e, and Agar Gum (AG) is carbon-negative at -2.53 kg CO_2e per ton.
- Agar Gum, despite its higher cost of ₹2073.5 per ton, offers potential financial benefits through carbon credits due to its carbon-negative footprint. Xanthan Gum, at ₹516.6 per ton, effectively balances cost and environmental impact.
- Lime is cost-effective at ₹516.8 per ton but carries significant long-term environmental costs, making it less sustainable.

- From an ESG perspective, Agar Gum is the most sustainable, followed by Xanthan Gum, with Lime having the highest negative impact and posing greater health risks to workers.
- Agar Gum and Xanthan Gum face fewer governance challenges than Lime. Agar Gum is ideal for projects prioritizing sustainability, while Lime is more suited for quick, cost-effective stabilization.
- Both Agar Gum and Xanthan Gum align well with sustainable development goals, contributing positively to sustainable infrastructure, climate action, and responsible consumption.

In the next and final chapter, overall findings of the study will be collated and the conclusions will be drawn of the study with this the future recommendations will also be discussed.