Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-823

Life cycle assessment of innovative biogeochemical cover systems for mitigating landfill gas emissions

Krishna R. Reddy, Gaurav Verma
Department of Civil, Materials, and Environmental Engineering, University of Illinois Chicago, USA, kreddy@uic.edu

ABSTRACT: Municipal solid waste (MSW) landfills are the third-largest source of methane (CH_4) emissions in the U.S., contributing 103.7 million metric tons (MMT) of carbon dioxide (CO_2) equivalent, or 14.4% of total CH_4 emissions. Due to its high global warming potential, over 28 times that of CO_2, fugitive CH_4 emissions are a significant concern. This concern is exacerbated by the CO_2 emissions produced as part of LFG emissions from MSW landfills. While engineered landfills utilize gas collection and soil cover systems, fugitive CH_4 and CO_2 emissions persist. To mitigate these emissions, an innovative biogeochemical cover (BGCC) system was developed, incorporating a CH_4 oxidation layer (MOL) made of biochar-amended soil and a carbon dioxide sequestration layer (CSL) using alkaline industrial byproducts like basic oxygen furnace (BOF) slag or cement kiln dust (CKD). Lab-scale column experiments were conducted to test two BGCC configurations: BGCC-PWBOF (pinewood biochar -MOL with BOF slag -CSL) and BGCC-RHCKD (rice husk biochar -MOL with CKD -CSL). - demonstrated significant potential for mitigating CH_4 and CO_2 emissions. A life cycle assessment (LCA) following ISO 14040 was conducted across two scenarios to compare BGCC systems against conventional soil cover (SC) over a functional unit of one hectare of landfill cover area over 30 years. The two scenarios modeled as part of the LCA include: (1) when materials are sourced locally and (2) when materials are obtained from different distances. Results showed that BGCC-RHCKD achieved a 1.6-fold greater reduction in global warming potential compared to both BGCC-PWBOF and SC across both scenarios. Across the majority of impact categories, BGCC-RHCKD was comparatively the most sustainable system in the locally available scenario, whereas BGCC-PWBOF comparatively outperformed BGCC-RHCKD in the alternative distance scenario. Overall, BGCC systems present a more sustainable alternative to traditional landfill covers, particularly when materials are sourced locally near the landfill site.

KEYWORDS: landfill gas emissions, biogeochemical cover system, methane oxidation; carbon sequestration, life cycle assessment.

1 INTRODUCTION

Municipal solid waste (MSW) landfills are the third-largest source of methane (CH_4) emissions in the U.S., with conservative inventory estimates indicating emissions of approximately 103.7 million metric tons (MMT) of carbon dioxide (CO_2) equivalent, representing about 14.4% of total CH_4 emissions (USEPA, 2024a).. Due to its global warming potential, which is over 28 times greater than that of CO_2, CH_4 emissions are a significant environmental concern (USEPA 2024b). This issue is further compounded by the CO_2 emissions produced as part of landfill gas (LFG) emissions from MSW landfills. LFG emissions consist primarily of equal amounts of CH_4 and CO_2 (around 50% v/v each) (USEPA 2024c), along with trace amounts of other gases. Both CH_4 and CO_2 are potent greenhouse gases that, if not captured, can contribute to severe environmental issues like global warming and climate change. Additionally, CH_4's high combustibility and potential explosiveness when concentrations exceed certain thresholds pose safety risks to life and property near landfill sites (USEPA 2005).

To mitigate fugitive LFG emissions, engineered landfills use either active or passive gas collection systems, with the choice governed primarily by applicable EPA regulatory standards and influenced by factors such as landfill size and waste composition, which determine whether regulatory emission thresholds are exceeded (Sharma and Reddy 2004). These systems are designed to capture LFG, which can either be used for energy recovery or flared to reduce its volume and impact. Furthermore, conventional soil cover (SC) systems are typically placed over MSW landfills to help minimize LFG emissions. These cover systems serve multiple purposes, such as preventing precipitation infiltration and reducing the breeding of rodents and vectors (Sharma and Reddy 2004). However, despite the use of SC and gas collection systems, the challenge of fugitive LFG emissions remains significant. This is partly due to the limited oxidative capacity of SC and partly because the performance of gas collection wells is highly variable, with reported collection efficiencies spanning a wide range depending on site design, operation, and waste conditions. Consequently, a substantial fraction of generated LFG can bypass the collection system and migrate through the cover. Installing gas collection systems at older, abandoned landfills and dumpsites may not always be technically or economically feasible, making the management of fugitive LFG emissions a continued challenge.

To address these fugitive emissions, an innovative biogeochemical cover (BGCC) system was developed by researchers at the University of Illinois Chicago (UIC) (Chetri et al. 2022a, b, Verma et al. 2024a, b, 2025a, b). This cover system includes a CH_4 oxidation layer (MOL) made from biochar-amended soil (BAS) to enhance microbial oxidation of CH_4, as well as a CO_2 sequestration layer (CSL) using alkaline industrial byproducts such as basic oxygen furnace (BOF) slag or cement kiln dust (CKD) to capture CO_2. Laboratory column experiments were conducted to test two BGCC configurations: BGCC-PWBOF (pinewood biochar-MOL with BOF slag-CSL) and BGCC-RHCKD (rice husk biochar-MOL with CKD-CSL). – which demonstrated significant potential for mitigating CH_4 and CO_2 emissions (Verma et al. 2025b). However, the comparative sustainability of these configurations in terms of their lifecycle environmental impacts has not been evaluated yet.

Life Cycle Assessment (LCA) is widely used to quantify the environmental impacts associated with the entire lifecycle of a product, process, or service, from raw material extraction to disposal or recycling. This analysis helps identify opportunities to improve environmental performance, supporting sustainable development and informed decision-making. In this study, a comparative LCA was conducted for two BGCC configurations (BGCC-RHCKD and BGCC-PWBOF) against a SC system to determine the most sustainable cover design for mitigating LFG emissions. The study aims to (1) evaluate the environmental impacts of the BGCC-RHCKD and BGCC-PWBOF systems relative to the SC system when materials are sourced locally, and (2) compare the sustainability of the BGCC-RHCKD, BGCC-PWBOF, and SC systems when materials are obtained from alternative sources in order to evaluate the effect of transportation distances on the environmental sustainability of these cover systems.

2 METHODOLOGY

2.1 *Design of Alternative Cover Systems*

Figure 1 illustrates the schematic designs of the two BGCC configurations (BGCC-RHCKD and BGCC-PWBOF) and the SC system evaluated in the life-cycle impact assessment. All profiles include a 15-cm gas distribution layer (GDL) at the base to ensure uniform gas flow; gravel was assumed for this layer based on on-site availability from the leachate collection system, minimizing transportation impacts. The BGCC-RHCKD system comprises a 45-cm methane oxidation layer (MOL) of rice husk biochar-amended soil (RH-BAS, 10% w/w), overlain by a 30-cm cement kiln dust (CKD) CO_2 sequestration layer (CSL) and a 15-cm vegetative topsoil layer (to control erosion and reduce infiltration). The BGCC-PWBOF system similarly includes a 45-cm MOL of pinewood biochar-amended soil (PW-BAS, 10% w/w), a 30-cm BOF slag CSL, and a 15-cm topsoil layer. The SC profile consists of a 45-cm barrier soil MOL, a 30-cm sand layer (as drainage layer), and a 15-cm topsoil layer. The landfill soil used in all systems was pre-exposed to low CH_4 flux to stimulate methanotrophic activity and is referred to as incubated soil..

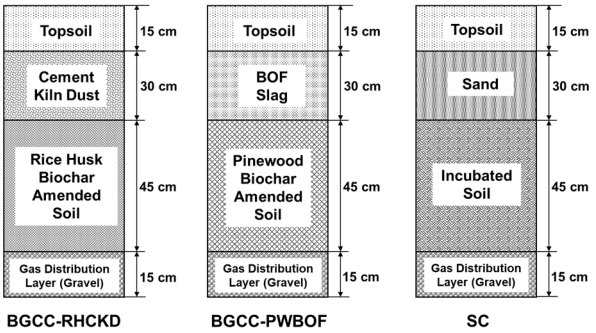

Figure 1. Schematic of the biogeochemical cover (BGCC) and soil cover (SC) profile. Note: BGCC-RHCKD = Biogeochemical cover consisting of rice husk (RH)- biochar-amended soil as MOL and cement kiln dust (CKD) layer as CSL; BGCC-PWBOF = Biogeochemical cover consisting of pinewood (PW)-biochar-amended soil as MOL and basic oxygen furnace slag layer as CSL; SC = Soil cover consisting of incubated soil as MOL and sand layer

2.2 *Methane Emission Analysis using CALMIM*

In this study, the mitigation of surface CH_4 emissions through microbial oxidation in each landfill cover system was simulated using the California Landfill Methane Inventory Model (CALMIM), developed by Spokas et al. (2011). This JAVA-based, field-verified tool is designed to model CH_4 emissions from landfill covers using a one-dimensional diffusion method to calculate annual, site-specific emissions. CALMIM incorporates several factors such as the surface area, properties of cover materials, the extent of engineered gas recovery systems, and climatic conditions affecting seasonal CH_4 oxidation. Unlike models that rely on first-order kinetic approaches for CH_4 generation, CALMIM estimates CH_4 emissions primarily based on concentration gradients, making it a practical tool for screening landfill CH_4 emissions and evaluating cover performance. However, CALMIM does not explicitly account for pressure-driven transport, which can become important under barometric or wind-induced pumping and in cover systems that incorporate gas recovery. In this analysis, gas recovery was intentionally set to zero, meaning the results represent a conservative scenario and this assumption may be considered a study limitation. Gas recovery was excluded to isolate the CH_4 oxidation and attenuation capacity of each cover profile, ensuring that performance differences reflect the intrinsic behavior of the cover materials rather than variations in gas recovery efficiency.

To simulate surface CH_4 emissions from all three cover systems, a 1-hectare landfill site near city of Chicago was chosen for this study. Table 1 outlines the input parameters used in the CALMIM model to analyze CH_4 emissions, including site and cover characteristics. This cover area was selected based on the functional unit defined in the LCA, which will be discussed further in a later section of this paper. Maximum CH_4 oxidation rates were set at 1580 µg/g-day for RH-BAS of the BGCC-RHCKD, 460 µg/g-day for PW-BAS of the BGCC-PWBOF, and 360 µg/g-day for the barrier layer of SC, based on previous laboratory batch incubation experiments (Verma et al. 2025b).

Table 1. Input used for methane (CH_4) emissions analysis using CALMIM Model.

Inputs	Parameters	Values
Site	Latitude	42.48236908
	Longitude	-87.86830258
	Waste footprint	1 hectare
Cover characteristics	Coverage	100% of waste
	Organic matter	Low for SC Medium for BGCC
	Vegetation	0
	Gas recovery	No
Cover type final	Temperature: upper	Default
	Temperature: lower	Default
	CH_4: upper	2 ppm
	CH_4: lower	55%
	O_2: upper	20%
	O_2: lower	0%
	Maximum CH_4 oxidation rate	
	…..10% RH-BAS	1580 µg/g-day
	…..10% PW-BAS	460 µg/g-day
	…..Soil cover	360 µg/g-day

After defining site and cover characteristics, including maximum CH_4 oxidation rates, soil textures consistent with the BGCC-RHCKD, BGCC-PWBOF, and SC laboratory simulations were selected. Table 2 summarizes the soil textures and corresponding layer thicknesses for each cover profile.

Table 2. Properties of materials in different cover systems used in CALMIM model for methane (CH_4) analysis.

Cover Profiles	Layer	Material	Thickness (cm)
BGCC-RHCKD	Topsoil layer	Silty clay	15
	CKD	Low plastic silt	30
	10% RH-BAS	Silty clay RH-biochar	45
	GDL	Gravel	15
BGCC-PWBOF	Topsoil layer	Silty clay	15
	BOF slag	Sand	30
	10% PW-BAS	Silty clay PW-biochar	45
	GDL	Gravel	15
SC	Topsoil layer	Silty clay	15
	Sand	Sand	30
	Barrier soil	Silty clay	45
	GDL	Gravel	15

In this study, CALMIM was used to estimate annual reductions in surface CH_4 emissions resulting from microbial oxidation in the cover systems. The resulting outputs were used as inputs for environmental impact assessment in SimaPro. In contrast, the CO_2 mitigation potential of each cover system was directly incorporated into the life-cycle assessment in SimaPro through material-specific sequestration benefits; therefore, no additional CO_2 modeling was required.

2.3 *Life Cycle Assessment (LCA)*

Two LCA scenarios were evaluated: a locally available scenario and an alternative distance scenario. The locally available scenario assumes all materials for the three cover

systems are sourced near the landfill, while the alternative distance scenario retains the same inventory except for transportation distances. For the latter, material supply locations were identified and distances to the landfill were calculated using Google Maps and incorporated into the LCA inventory. Details of the transportation distances for both scenarios are provided in the following sections. This comparison assesses the influence of transportation on environmental impacts, which can significantly affect multiple impact categories (da S. Trentin et al., 2019). Similar studies evaluating the sustainability assessment and the role of transportation in BGCC-based cover systems were previously conducted by Verma and Reddy (2026a, b), however the objective of those studies was different.

2.3.1 *Goal, Scope and System Boundary*

The LCA was conducted in accordance with the guidelines established by the International Organization for Standardization (ISO 14040). The objective of this study was to evaluate and compare the environmental impacts of the BGCC-RHCKD and BGCC-PWBOF systems with the SC system under both the locally available and alternative distance scenarios. The analysis was based on a functional unit of 1 hectare (10,000 m²) of landfill cover for a post-closure period of 30 years. Figure 2 illustrates the system boundaries used in the LCA, which encompassed processes such as material processing, transportation to the landfill site, equipment mobilization, and onsite cover placement.

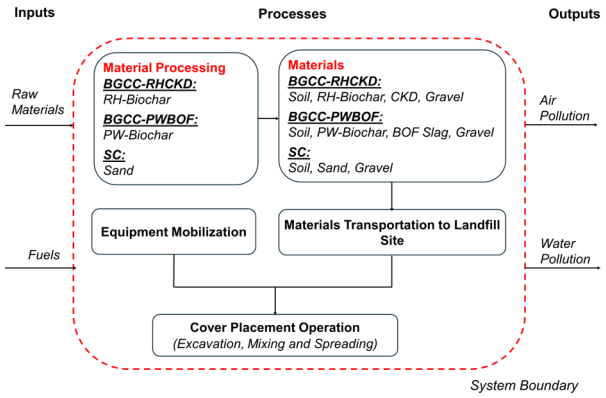

Figure 2. System boundaries for the cover systems analyzed.

Notably, the production processes of CKD and BOF slag were excluded from the study scope, as both are byproducts of cement and steel production and were treated as waste materials in both scenarios. Although biochar is often considered a byproduct of biogas production, feedstock-specific sourcing can be challenging; therefore, biochar production was included in the LCA to accurately capture its environmental impacts. Biochar production was assumed to occur at the feedstock source to minimize transportation impacts, which is important given that biochar feedstock requirements are typically 3.2–5 times the mass of the final product. Transporting this large volume of feedstock to the landfill would substantially increase emissions and overall environmental impacts. Waste disposal scenarios were also excluded from the system boundaries. Although rice is not grown locally in Illinois, rice husk biochar was selected due to its favorable properties and availability through U.S. suppliers, while pinewood biochar was used as a locally available and regionally common feedstock.

2.3.2 *Life Cycle Inventory Analysis*

The database incorporated in SimaPro v 9.0 was used for the inventory. Ecoinvent global (GLO) databases v3.5 were used most, however, US databases were used wherever available. Data for rice husk–derived biochar were partially obtained from the supplier, while remaining inputs, including propane required for pyrolysis initiation, were sourced from Puettmann et al. (2020). Data for pinewood-derived biochar were fully adopted from Puettmann et al. (2020). Biochar production using air-curtain burners was assumed. Table 3 summarizes the material inventories for biochar production used in the LCA.

Table 3. Materials inventory for production of biochars for LCIA

Input	RH-Biochar	PW-Biochar
Feedstock (kg)	5000	5000
Biochar yield (%)	31.25	20
Natural gas (L)	441	441
Water (for Quenching) (L)	5.91	2000
Biochar yield (kg)	1562.5	1000
Fixed Carbon (%)	39.27	89

Table 4 presents the quantities of materials, and the operations involved in applying all three cover types over a one-hectare landfill area, based on the technical design previously discussed (see Figure 1). A hydraulic digger, referenced in the ecoinvent database, was employed for cover placement operations.

Table 4. Quantities of materials and construction operations for different cover systems over an area of 1 hectare of landfill.

Materials	Cover Profiles		
	BGCC-RHCKD	BGCC-PWBOF	SC
Topsoil Layer (t)	2,220	2,145	2,070
CKD/BOF Slag/Sand (t)	3,420	6,780	5,640
Barrier Soil (t)	6,230.9	5,103	6,435
Biochar (t)	692.3	567	-
Gas Distribution Layer (Gravel) (t)	2,550	2,550	2,550
Operations involved			
Placement of Topsoil Layer (m^3)	1,500	1,500	1,500
Placement of CKD/BOF Slag/Sand (m^3)	3,000	3,000	3,000
Placement of Biochar Amended Soil/Barrier Soil (m^3)	4,500	4,500	4,500
Placement of Gravel (m^3)	1,500	1,500	1,500

*t - tonnes

Table 5 summarizes the input parameters for transportation distances used in both the locally available and alternative distance scenarios.

Table 5. Inventory for transportation distances used during different landfill scenarios.

Transportation Distance	Locally Available Scenario	Alternative distance Scenario
CKD to Landfill Site (km)	50	218
BOF Slag to Landfill Site (km)	50	128
Sand to Landfill Site (km)	50	70
RH-Biochar to Landfill Site (km)	50	677.5
PW-Biochar to Landfill Site (km)	50	217
Soil to Landfill Site (km)	1	1
Gravel to Landfill Site (km)	1	1

In the locally available scenario, a comparative LCA of BGCC-RHCKD and BGCC-PWBOF against the SC system assumed transportation distances of 50 km for CKD, BOF slag, RH- and PW-biochar, and sand, reflecting local sourcing, while soil and gravel were assumed to be sourced on-site (1 km). CH_4 oxidation rates and CO_2 sequestration capacities were obtained from Verma et al. (2025b), and corresponding surface CH_4 emission mitigation was estimated using CALMIM. In addition, fixed carbon stored in biochar was included in SimaPro during LCA. Transportation was modeled using a

diesel-powered single-unit truck from the US database in SimaPro v9.0. For the alternative distance scenario, all inventory inputs remained unchanged except for transportation distances, which are summarized in Table 5.

2.3.3 *Impact Assessment*

LCA for both scenarios was conducted using the TRACI 2.1/US2008 impact assessment method implemented in SimaPro v9.0. Developed by the U.S. EPA, TRACI is a midpoint-based method tailored to U.S. conditions and evaluates 10 impact categories: ozone depletion, global warming, smog, acidification, eutrophication, carcinogenic and non-carcinogenic effects, respiratory effects, ecotoxicity, and fossil fuel depletion.

3 RESULTS AND DISCUSSION

As discussed above, LCA of all three cover systems (BGCC-RHCKD, BGCC-PWBOF and SC) were evaluated for two scenarios in order to evaluate the effect of transportation distances on their environmental sustainability.

3.1 *Landfill (IL, USA): Locally available scenario*

Under this LCA scenario, it was assumed that the materials utilized during the construction of all three cover systems were sourced locally at a distance nearby landfill site. Figure 3 presents a relative comparison of the environmental impacts for the BGCC-RHCKD, BGCC-PWBOF, and SC systems in a locally available scenario.

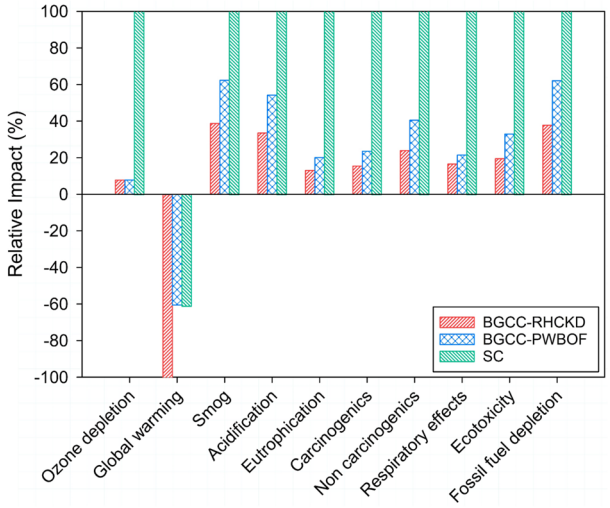

Figure 3. Relative environmental impact of BGCC-RHCKD, BGCC-PWBOF and SC system during locally available scenario

Overall, the SC system demonstrated the highest environmental burdens, followed by the BGCC-PWBOF and BGCC-RHCKD systems. Significant differences in environmental impacts were observed across all categories between the BGCC-RHCKD and SC systems, with the SC system exhibiting impacts 2.5 to 7.7 times greater across all categories. A detailed analysis indicated that the SC system's most significant negative impacts were in smog, ecotoxicity, and fossil fuel depletion. For instance, the smog impact for the SC system was 23,441.39 kg O_3 eq, compared to 9,068.05 kg O_3 eq for the BGCC-RHCKD system. The SC system's ecotoxicity impact was 610,539.46 CTUe, which was 5.1 times higher than the BGCC-RHCKD system's 118,923.62 CTUe. Additionally, fossil fuel depletion impacts for the SC system were 2.6 times higher, at 237,623.75 MJ, compared to 89,777.68 MJ for the BGCC-RHCKD system. The SC system also had a eutrophication impact of 159.28 kg N eq, nearly 7.7 times higher than the BGCC-RHCKD system's 20.74 kg N eq. Eutrophication impacts mainly result from excess nutrient deposition into the environment. In the BGCC-RHCKD system, these impacts were primarily due to emissions from transportation activities, as shown in Figure 4.

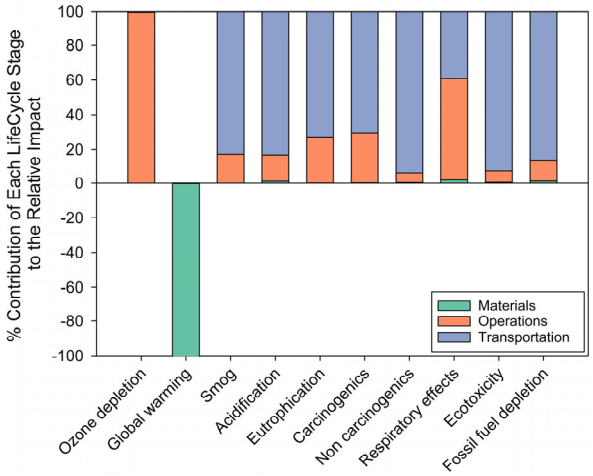

Figure 4. Relative environmental impact of each life cycle stage of BGCC-RHCKD system during locally available scenario.

For the SC system, the sand processing (including quarrying and mining) likely contributed to these emissions. As the system boundary for the SC system considers soil as a waste material, its extraction and processing are excluded from this analysis. Therefore, any environmental impact associated with the SC system's material lifecycle in the locally available scenarios is attributed solely to sand. Smog impacts primarily result from pollutants like VOCs, NOx, and particulate matter emissions, while fossil fuel depletion impacts arise from non-renewable energy use. In the BGCC-RHCKD locally available scenario, smog and fossil fuel depletion impacts were largely due to emissions from diesel-powered trucks used in transportation (shown in Figure 4). For the SC system, emissions from sand extraction and processing, in addition to transportation-related emissions, contributed to these impacts. On comparing the environmental impacts exhibited by BGCC-RHCKD and BGCC-PWBOF system, BGCC-PWBOF system demonstrated slightly higher environmental burden across all impact categories as shown in Figure 3.

In the global warming impact category, all three cover systems contributed positively by mitigating greenhouse gases (CH_4 and CO_2), thereby benefiting the climate. A comparative analysis reveals that the BGCC-RHCKD system demonstrated 1.63–1.65 times greater potential for reducing global warming impacts compared to the SC and BGCC-PWBOF systems. Specifically, the BGCC-RHCKD system achieved a global warming impact of -72,556,819.69 kg CO_2 eq, while the SC and BGCC-PWBOF systems recorded impacts of -44,441,182.66 kg CO_2 eq and -43,934,531.91 kg CO_2 eq, respectively, which were nearly identical. This indicates that the BGCC-RHCKD system sequestered approximately 1.6 times more CO_2 during the passage of fugitive LFG through the cover. The enhanced performance of the BGCC-RHCKD system in reducing global warming is attributed to the high CH_4 oxidation potential (1580 µg/g-day) of RH-BAS (MOL) and the CO_2 sequestration capacity (225 g/kg) of the CKD layer incorporated into the system. In contrast, the SC and BGCC-PWBOF systems showed lower effectiveness due to their lower CH_4 oxidation potentials (360 and 460 µg/g-day, respectively).

Figure 4 presents the relative environmental impacts of the BGCC-RHCKD system during locally available scenario across various life cycle stages, including materials processing, operation, and transportation. It is important to note that the materials life-cycle stage accounts for impacts from material production and processing (specifically biochar), along with material-specific mitigation benefits (CH_4 oxidation and CO_2 sequestration), while the operations life-cycle stage includes impacts from on-site cover construction activities and

associated fuel use. The analysis indicated that transportation related activity (RH-biochar and CKD) predominantly contributed to negative impacts across most of the impact categories, except for respiratory effect, where operation exhibited the highest negative impacts (7.25 kg PM2.5 eq). In the global warming impact category, the BGCC-RHCKD system demonstrated a significant positive contribution (-72,605,776.66 kg CO_2 eq), primarily driven by microbial CH_4 oxidation in the RH-BAS layer and the CO_2 sequestration capacity of the CKD layer. In contrast, the environmental impacts from operational activities (5,798.73 kg CO_2 eq) and transportation (43,158.46 kg CO_2 eq) were negative but minimal compared to the positive impacts offered by CH_4 oxidation and CO_2 sequestration. Among the different stages, material use caused the least environmental harm (Figure 4). This was largely because many materials in the BGCC-RHCKD system, such as CKD and clay soil, were considered waste materials (modeled as dummy inventory in SimaPro) and therefore did not contribute to environmental degradation, with the exception of biochar production. Consequently, the minimal environmental impact associated with materials in the BGCC-RHCKD system can be attributed exclusively to the biochar production process.

3.2 *Landfill (IL, USA): Alternative Distance Scenario*

In this LCA scenario, it was assumed that the materials used in the construction of all three cover systems were sourced from different distances from the landfill site. Figure 5 presents a comparison of the environmental impacts for the BGCC-RHCKD, BGCC-PWBOF, and SC systems.

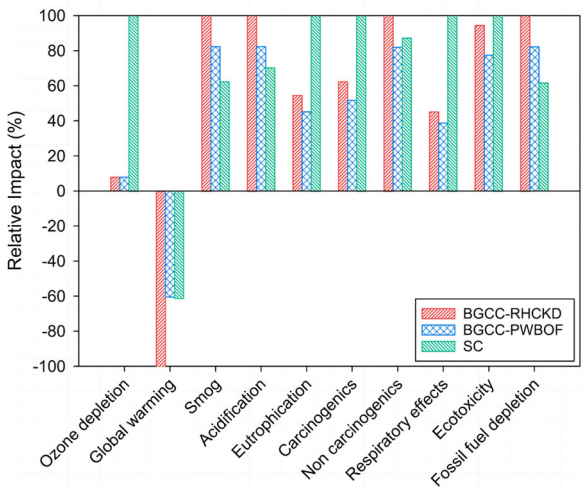

Figure 5. Relative environmental impact of BGCC-RHCKD, BGCC-PWBOF and SC system during alternative distance scenario.

Unlike the previous scenario, the environmental burden of the cover systems showed mixed results. Out of the nine impact categories assessed (excluding global warming), the BGCC-RHCKD system demonstrated lower environmental impacts in four categories-eutrophication, carcinogenicity, respiratory effects, and ecotoxicity-compared to the SC system. However, when compared to the BGCC-PWBOF system, the BGCC-RHCKD system exhibited slightly higher environmental impacts across all categories. For example, the eutrophication impact for the SC system was 167.13 kg N eq, compared to 90.95 kg N eq for the BGCC-RHCKD system. The SC system's respiratory impact was 76.6 kg PM2.5 eq, which was 2.2 times higher than the BGCC-RHCKD system's 34.56 kg PM2.5 eq. Additionally, ecotoxicity for the SC system were 1.1 times higher, at 667,725.9 CTUe, compared to 63.0455.4 CTUe for the BGCC-RHCKD system. In the BGCC-RHCKD system, majority of the impact categories were primarily due to emissions from transportation activities, as shown in Figure 6.

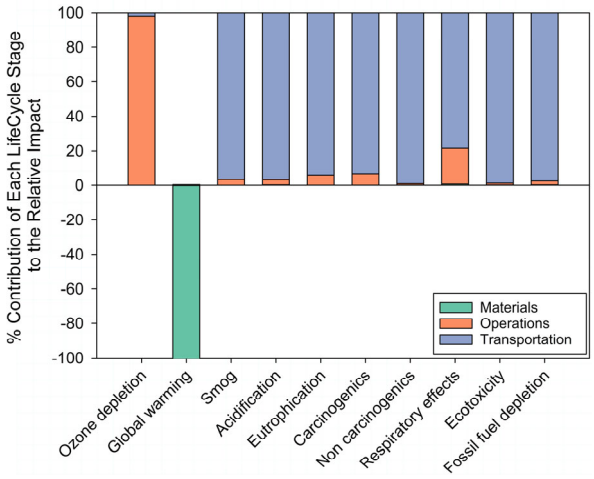

Figure 6. Relative environmental impact of each life cycle stage of BGCC-RHCKD system during alternative distance scenario

In the global warming impact category, similar to the previous scenario, all three cover systems effectively contributed to mitigating greenhouse gases (CH_4 and CO_2). A comparative analysis shows that the BGCC-RHCKD system achieved 1.63 - 1.65 times greater potential in reducing global warming impacts compared to both the SC and BGCC-PWBOF systems. This suggests that the positive impact of all three systems on global warming remains consistent. Therefore, it can be concluded that variations in the transportation distances of the materials do not significantly influence the global warming impact of any of the cover systems.

Figure 6 illustrates the relative environmental impacts of the BGCC-RHCKD system during the alternative distance scenario across various life cycle stages, including material processing, operation, and transportation. The analysis revealed that emissions from transportation activities (related to RH-biochar and CKD) were the primary contributors to negative impacts across all impact categories. Among the different stages, material use caused relatively minor environmental harm (Figure 4) compared to transportation. However, the operation life cycle stage resulted in a notable impact on respiratory effects, with the operation stage contributing to 7.25 kg PM2.5 eq, compared to 27.08 kg PM2.5 eq during transportation.

A comparison of the results from both LCA scenarios for the three cover systems revealed that increasing the transportation distance between the material suppliers and the landfill site compromises the environmental sustainability of the cover systems. For instance, in the locally available scenario, where the transportation distance for CKD and RH-biochar suppliers was 50 km each, the BGCC-RHCKD system demonstrated the lowest environmental impact among all three cover systems. However, when these transportation distances were increased to 218 km for CKD and 677.5 km for RH-biochar, the environmental impacts showed mixed responses. In the second alternative distance scenario, the BGCC-PWBOF system was found to be more environmentally sustainable than the BGCC-RHCKD. Therefore, it is recommended to source materials locally in order to minimize the environmental impacts associated with transportation during the life cycle stages. In terms of practicality, it is important to note that complete localization of materials may not always be feasible due to site-specific, regulatory, and availability constraints. However, it is recommended in practice, that landfill operators should source cover materials from nearby or regional suppliers to minimize costs and logistical challenges. Even partial reductions in transportation distances can lead to measurable environmental benefits.

4 LIMITATION OF THE STUDY

The primary objective of this study was to evaluate and compare the sustainability of BGCC-RHCKD and BGCC-PWBOF systems with the SC system under two scenarios. The CALMIM model was used to analyze CH_4 emissions, applying a distinct constant value for the maximum CH_4 oxidation rate for each cover system. This enabled estimation of annual CH_4 emissions with and without oxidation and the calculation of peak annual mitigation capacity. However, it is important to acknowledge the limitations of this approach. In real-world landfill scenarios, CH_4 emissions are subject to significant temporal and spatial variations due to changes in waste composition, climatic conditions, and landfill operational practices. As a result, there may be periods when actual emissions are lower or higher than the estimated mitigation efficiency. This could lead to an overestimation or underestimation of the mitigation capabilities derived from the CALMIM model in this study. Therefore, the results presented here in this study does not convey the realistic scenario, rather it represents idealistic scenario. Nevertheless, the primary aim of this research was not to establish absolute emission reduction values but rather to provide a comparative assessment of the performance of different landfill cover systems. By focusing on the relative performance of BGCCs and SC systems, the study sought to highlight their maximum potential in mitigating CH_4 emissions under idealized conditions. Thus, the global warming reduction impacts reported for each cover system represent their maximum mitigation capabilities when implemented optimally as landfill cover systems.

5 CONCLUSIONS

This study aims to evaluate and compare the environmental impacts of the different landfill cover system which includes biogeochemical cover comprising rice husk biochar-amended soil and cement kiln dust (BGCC-RHCKD) and biogeochemical cover comprising pinewood biochar-amended soil and basic oxygen furnace slag (BGCC-PWBOF) systems relative to the soil cover (SC) system across two scenarios modeled as a part of LCA. These scenarios include (1) locally available scenario - in which the materials utilized for construction of the cover system were sourced locally nearby the location of the landfill site; (2) alternative distance scenario - in which different distances of material supplier form landfill site were used. Based on the analysis conducted to fulfill the above objectives, the following conclusions were drawn:

(1) Locally available scenario-: The BGCC-RHCKD system stands out as relatively most sustainable option among the three cover systems, demonstrating lower environmental impacts across all categories. Furthermore, all three systems contributed positively to the reduction of global warming impacts, with the BGCC-RHCKD system showing 1.63-1.65 times greater potential for mitigating global warming compared to the SC and BGCC-PWBOF systems. This enhanced performance is primarily due to the higher microbial methane (CH_4) oxidation capacity of the RH-biochar-amended soil (RH-BAS) layer and the CO_2 sequestration ability of the CKD layer in the RH-BGCC system. In contrast, the BGCC-PWBOF and SC systems rely on relatively lower microbial CH_4 oxidation in their barrier soil layers.

(2) Alternative distance scenario: In contrast to the previous scenario, the environmental burden of the cover systems in this case showed mixed results. In some impact categories, the BGCC-RHCKD system exhibited lower environmental impacts compared to the SC system. Moreover, in this scenario, the BGCC-PWBOF system was found to be relatively more environmentally sustainable than the BGCC-RHCKD system.

Overall, it was concluded that the material should be sourced locally for the cover system in order to minimize the environmental impacts associated with transportation during the life cycle stages. Failing to do so may compromise the environmental sustainability of the cover system.

6 REFERENCES

Chetri, J.K., Reddy, K.R., Grubb, D.G., and Green, S.J., 2022a. Biogeochemical versus conventional landfill soil covers: Analysis of gas flow profiles, microbial communities, and mineralogy. Journal of Hazardous, Toxic, and Radioactive Waste, 26(3), 04022022.

Chetri, J.K., Reddy, K.R., and Grubb, D.G., 2022b. Investigation of different biogeochemical cover configurations for mitigation of landfill gas emissions: Laboratory column experiments. Acta Geotechnica, 17(12), 5481–5498.

da S Trentin, A.W., Reddy, K.R., Kumar, G., Chetri, J.K., and Thomé, A., 2019. Quantitative assessment of life cycle sustainability (QUALICS): Framework and its application to assess electrokinetic remediation. Chemosphere, 230, 92–106.

Puettmann, M., Sahoo, K., Wilson, K., and Oneil, E., 2020. Life cycle assessment of biochar produced from forest residues using portable systems. Journal of Cleaner Production, 250, 119564.

Sharma, H.D., and Reddy, K.R., 2004. Geoenvironmental engineering: Site remediation, waste containment, and emerging waste management technologies. Hoboken, NJ: John Wiley & Sons.

Spokas, K., Bogner, J., and Chanton, J., 2011. A process-based inventory model for landfill CH_4 emissions inclusive of seasonal soil microclimate and CH_4 oxidation. Journal of Geophysical Research: Biogeosciences, 116(G4).

USEPA, 2005. Guidance for evaluating landfill gas emissions from closed or abandoned facilities. EPA-600/R-05/123a. Washington, DC: USEPA. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi/P1000BRN.PDF?Dockey=P1000BRN.PDF [Accessed 7 Jan. 2024].

USEPA, 2024a. Basic information about landfill gas. Available at: https://www.epa.gov/lmop/basic-information-about-landfill-gas [Accessed 7 Jan. 2024].

USEPA, 2024b. Importance of methane. Available at: https://www.epa.gov/gmi/importance-methane [Accessed 7 Jan. 2024].

USEPA, 2024c. Basic information about landfill gas. Available at: https://www.epa.gov/lmop/basic-information-about-landfill-gas [Accessed 7 Jan. 2024].

Verma, G., Chetri, J.K., and Reddy, K.R., 2024a. Spatial variation of methane oxidation and carbon dioxide sequestration in landfill biogeochemical cover. Environmental Technology, pp.1–17.

Verma, G., Chetri, J.K., and Reddy, K.R., 2024b. Evaluating the efficacy of biogeochemical cover system in mitigating landfill gas emissions: A large-scale laboratory simulation. Environmental Science and Pollution Research, 31(38), pp.50782–50803.

Verma, G., Chetri, J.K., Reddy, K.R., and Green, S.J., 2025a. Large-scale testing to assess the performance of biogeochemical and soil cover systems for landfill gas mitigation. Acta Geotechnica, pp.1–24.

Verma, G., Reddy, K.R., and Green, S.J., 2025b. Investigation of biogeochemical landfill covers incorporating different biochars and alkaline industrial byproducts for landfill gas mitigation: A column experiment study. *Science of The Total Environment*, *974*, p.179192.

Verma, G., and Reddy, K.R., 2026a. Life cycle assessment of biogeochemical versus conventional soil landfill cover: Sensitivity and uncertainty analyses. Journal of Hazardous, Toxic, and Radioactive Waste, 30(1), p.04025037.

Verma, G., and Reddy, K.R., 2026b. Integrated resiliency and sustainability assessment of biogeochemical cover system to mitigate landfill gas emissions. Waste Management, 209, p.115200.