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Manuscript title: Assessing the sustainability of composite liner systems for municipal solid waste landfills: a triple bottom line approach

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Abstract

Municipal solid waste landfills require a liner system to prevent the migration of landfill leachate into the surrounding environment. Currently, liner system selection and design processes are primarily based on engineering performance, cost, and ease of construction and rarely consider sustainability. This study assessed the sustainability of four different composite liner systems, considering their technical equivalence through leachate infiltration rates and employing the triple bottom line (TBL) approach, which considers environmental, economic, and social impacts. The four composite liner systems evaluated included: (1) geomembrane (GM) over compacted clay liner (CCL) (denoted as GM/CCL), (2) GM over geosynthetic clay liner (GCL) (denoted as GM/GCL), (3) GM over soil mixed with lime and cement (SA) (denoted as GM/SA), and (4) GM over fly ash mixed with bentonite (FAB) (denoted as GM/FAB). The life cycle stages of each system, including material extraction, construction, monitoring, and disposal were also analyzed. The study was conducted for the DeKalb Landfill in DeKalb, Illinois, USA. Life cycle assessment was performed using the Eco-Indicator and TRACI method in SimaPro 8.0.1 to quantify environmental impacts. The results showed that GM/FAB was the most sustainable liner system in terms of environmental impact and second in economic and social impacts. On the other hand, GM/GCL was deemed the most preferred in terms of economic and social impacts.

Keywords: leachate infiltration; life cycle assessment; landfill liner; economic sustainability; social sustainability

Introduction

Municipal solid waste landfills are required to have a composite liner system with a flexible geomembrane liner at the base and side slope of the landfill underlain by compacted soil liner that is at least 2 feet thick and has a maximum hydraulic conductivity of 1 x 10^{-7} cm/s (Sharma and Reddy, 2004; EPA, 2021). In addition, the liner system must be built to meet the requirements of the local regulatory body by preventing leachate transport into the subsurface environment. The efficiency of landfill liner systems has been studied extensively over the past 20 to 30 years using various low-permeability materials, both natural (e.g., clays) and manufactured (e.g., geosynthetics). In the past few decades, geosynthetic clay liner (GCL) containing bentonite clay sandwiched between layers of geotextile has become increasingly common. This is because GCL has a very low hydraulic conductivity (1 x 10^{-10} m/s) and can be easily installed during the construction of a liner system (Keerthana and Arnepalli, 2022; Kumar and Kumari, 2023).

Most landfill lining systems comprise a 60-mil HDPE geomembrane overlying a 2-ft thick compacted clay liner (CCL). However, securing a sufficient quantity of low-permeable inorganic clay near landfill sites is challenging. Due to rising costs and a shortage of clay, researchers have renewed interest in identifying alternative local materials to reduce clay proportion in MSW landfill liner systems (Keerthana and Arnepalli, 2022; Kumar and Kumari, 2023). Many studies have investigated the hydraulic conductivity and chemical compatibility of liner systems (H*t al.*, 2022). The construction and ease of installation of liner systems relies on the availability of local fine-grained materials (such as clays) and other manufactured geosynthetics closer to the project site.

Recently, the local soils near the site that were deemed inadequate have been modified through the addition of hydrated lime and Portland cement to meet the specifications for the liner (Benson and Daniel, 1994; Francisca and Mozejko, 2022; Liu *et al.*, 2022). It is crucial to implement proper compaction to maintain low hydraulic conductivity (Devapriya and Thyagaraj, 2023; Nath *et al.*, 2023). Fly ash has also been considered as a potential alternative material for landfill liners. Fly ash, a byproduct of burning coal is composed of silt-sized, hollow, spherical particles. Research has shown that pozzolanic fly ash can gradually decrease permeability and can be used as an effective hydraulic barrier (Prashanth, Sivapullaiah and Sridharan, 2001). Pal and Ghosh (2013) suggested employing fly ash and bentonite combination as a liner material after identifying the decrease in permeability of various blends of fly ash and bentonite for variable quantities. The hydraulic conductivity of the mix is also often reduced by compaction conditions (Sankar and Niranjan, 2015). Later, the geotechnical behavior of fly ash bentonite mixes as a liner material was examined with varying proportions of bentonite. It was found that the permeability of the mix decreased to less than 1×10^{-9} m/s with increased bentonite content, indicating the suitability of the mix as a liner material (Kantesaria, Chandra and Sachan, 2021).

Engineering properties such as compaction, hydraulic conductivity, and chemical compatibility issues of alternate liner systems have been addressed well (Prashanth, Sivapullaiah and Sridharan, 2001; Pal and Ghosh, 2013; Sankar and Niranjan, 2015; Kantesaria, Chandra and Sachan, 2021; Nath *et al.*, 2023). However, the assessment of sustainability considerations is often disregarded in evaluations. This has increased international pressure to address the UN’s Sustainable Development Goals (SDGs) for successfully implementing and decommissioning landfill projects. The lack of attention given to TBL sustainability can have significant implications for landfill projects for long-term viability and their impact on the environment and society.

Therefore, sustainability considerations must receive the proper consideration and evaluation they deserve in all critical assessments. The present study aims to evaluate the sustainability of four different landfill liner systems: GM/CCL, GM/GCL, GM/SA (92% soils + 3% hydrated lime + 5% Portland cement), and GM/FAB (20% bentonite + 80% fly ash) based on the TBL sustainability consideration (environmental, economic, and social impacts) over their design life period. The DeKalb County landfill in DeKalb, Illinois, USA, was chosen to assess all these liner systems. The DeKalb County landfill is an engineered landfill designed to meet the Subtitle D requirements of the Resource Conservation and Recovery Act (RCRA). For the TBL sustainability assessment, a one-acre landfill area is considered.

1. Materials and methods

1.1. Liner systems

The present study evaluates four alternative landfill liner systems for a sustainability assessment. Figure 1 is a schematic representation of the different alternative liner systems proposed in our study. These liner systems have been designed to minimize the use of natural soil, which is typically employed as a conventional material in pavement sub-bases. The sub-base thickness in the proposed liner systems remains consistent with conventional sub-bases(Liu *et al.*, 2022; Devapriya and Thyagaraj, 2023). This ensures the pavement structure retains the required load-bearing capacity and structural integrity.

All four of these composite liner systems have liner materials with hydraulic conductivity of approximately of the order 10^{-7} cm/s, meeting the minimum criteria set forth by USEPA regulations for a liner material (EPA, 2021). For GM/SA, 92% of native soil of clayey nature is proposed to be combined with cement and lime. Based on the published literature and our laboratory experiments, the hydraulic conductivity of CCL, GCL, SA, and FAB are taken as $1x10^{-7}$ cm/s, $1x10^{-8}$ cm/s, $1x10^{-7}$ cm/s, and 2.623 $x10^{-7}$ cm/s respectively for the present study. Each material's unit weight and cost estimate are either derived directly or considered typical values reported in the literature. Materials required and transport distances are summarized in Table 1.

2.2 *Equivalence of composite liner systems*

A leachate leakage rate analysis was performed to demonstrate the technical equivalence of the four composite liner systems. As per the recommendations of Giroud and Bonaparte (Giroud and Bonaparte, 1989), the following relation was used for estimating the leachate leakage rate (Q) from a composite liner system:

$$\mathbf{Q = 0.7\, a^{0.1} k_s^{0.88} h_w}$$

where '**a**' is the area of the hole in the geomembrane liner equal to 0.005 in^2 (typical value considered); With good quality assurance and quality control, one hole per acre is recommended to be considered; '$\mathbf{k_s}$' is the hydraulic conductivity of low-permeable CCL, GCL, SA or FAB (cm/s); '$\mathbf{h_w}$' is the leachate head on top of the geomembrane. For this study, 6 inches of leachate head is considered. It is important to mention that the maximum allowable leachate head on the geomembrane liner is 12 inches. The typical thickness of the liner system is 24 inches, and the landfill area equal to 1 acre is considered.

2.3 Sustainability assessment

The triple bottom line, which combines environmental, economic, and social considerations, is the framework used for sustainability assessment (Reddy, Cameselle and Adams, 2019).

Life cycle assessment (LCA) was performed utilizing SimaPro 8.0.1 LCA software, the Ecoinvent 3.0 as a database, and Eco-Indicator 99 and TRACI as impact assessment methodologies once the appropriate materials were selected for all liner systems. The scope (i.e., characterizing the system boundaries from beginning to end life cycle stages consisting of raw material extractions, construction, and monitoring), material assemblies, unit processes, energy inputs, and diesel consumption are used as input parameters. SimaPro has several techniques for assessing the system's environmental impacts; TRACI, Eco-Indicator-99, and BEES are the most often employed. Eco-Indicator-99 and TRACI - Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts - were used in this study to perform the impact assessment. The US Environmental Protection Agency (USEPA) created TRACI, which is a midpoint oriented LCA approach, particularly for the areas of North America utilizing input characteristics that correspond to US regions. While the Eco-indicator 99 technique focuses on three distinct types of environmental damage: to resources, ecosystem quality, and human health. Each damage category has many impact subcategories, measured in kPt (kilo points). The results are analyzed without bias by examining the data independently for each damage category without any subjective weighting.

In addition to the environmental assessment, each liner system is then economically evaluated utilizing the total system costs (such as material and excavation expenses, shipping costs, and expenditures related to compaction, spreading, and mixing/blending of various components). All four liner systems were finally assessed for social sustainability using a semi-qualitative assessment methodology based on the UNEP and SETAC frameworks (Martin *et al.*, 2023; Mattos and Calmon, 2023; Mogos *et al.*, 2023).

2. Results and discussion

2.1. Equivalence of composite liner systems

The leachate leakage rates for all four composite liner systems considered in the present study are estimated as follows:

1. GM/CCL – Fig. 1(a)

$$Q = 0.7\ (0.005)^{0.1}[1\text{x}10^{-7}/2.54]^{0.88}\text{x}6 = 7.53\text{x}10^{-7}\ \text{in}^3/\text{s per acre}$$

2. GM/GCL (Bentomat) – Fig. 1(b)

$$Q = 0.7\ (0.005)^{0.1}[1\text{x}10^{-8}/2.54]^{0.88}\text{x}6 = 9.92\text{x}10^{-8}\ \text{in}^3/\text{s per acre}$$

3. GM/SA – Fig. 1(c)

$$Q = 0.7\ (0.005)^{0.1}[1\text{x}10^{-7}/2.54]^{0.88}\text{x}6 = 7.53\text{x}10^{-7}\ \text{in}^3/\text{s per acre}$$

4. GM/FAB – Fig. 1(d)

$$Q = 0.7\ (0.005)^{0.1}[2.623\text{x}10^{-7}/2.54]^{0.88}\text{x}6 = 1.76\text{x}10^{-6}\ \text{in}^3/\text{s per acre}$$

These results show that all composite liners' leachate leakage rates (Q) are significantly low, of 10^{-6} to 10^{-8} in^3/s per acre. Hence, the liner systems can be considered hydraulically satisfactory and equivalent.

2.2. Environmental sustainability

Eco-Indicator 99 and TRACI methods were used to assess the environmental impacts of all four selected liner systems. Figures 2 and 3 show the single score results and environment impact assessment due to eleven different impact categories using the Eco-Indicator 99 method for all liner systems. Environmental impact scores due to GM/CCL, GM/GCL, GM/SA, and GM/FAB liner systems are 2.40 kPt, 6.40 kPt, 6.0 kPt, and 1.60 kPt, respectively. However, if we reduce the thickness of GM/SA and GM/FAB to 12 inches (Fig. 2) based on the previous case histories reported by Fuleihan and Wissa (Fuleihan and Wissa, 1995) for indicative purposes, the single score reduced to 3.0 kPt and 0.6 kPt, respectively. The larger score indicates a higher environmental impact due to the landfill liner system. Therefore, based on the Eco-Indicator 99 method, it is implied that a liner system consisting of geomembrane overlain by geosynthetic clay liner (GM/GCL) would be the least environmentally sustainable, and GM/FAB is the most environmentally sustainable based on a single score. It is important to note that natural resources are the category most impacted by GM/CCL and GM/GCL, followed by human health. However, for GM/SA, human health is the most impacted category, followed by natural resources.

The adverse effect of each impact subcategory on the environment using the Eco-Indicator 99 method is shown in Fig. 3. Carcinogens, climate change, fossil fuels, ozone layer, and respiratory inorganics are more adverse environmental impacts in the case of GM/SA liners than GM/CCL, GM/GCL, and GM/FAB liner systems.

It is inferred that even though GM/CCL liner is environmentally sustainable in major impact categories (i.e., resp-inorganics, radiation, ecotoxicity, ozone layer, and land use), it could have serious impacts on human health due to the presence of carcinogens and respiratory organics; on ecosystem due to acidification, eutrophication; and on resources due to depletion of minerals and fossil fuels. The carcinogens negatively impact the neighborhood community and workers on the site. High levels of fossil fuels can lead to depletion of energy resources and negative environmental impacts. Regarding GM/FAB liner systems, relatively more affected categories include the ozone layer, radiation, ecotoxicity, and land use than GM/CCL. It has also been found to have a lower level of environmental impact than GM/CCL in other impact categories. If we consider the case of reducing the liner thickness, then GM/FAB (12”) referring to case histories presented by Fuleihan and Wissa (1995), becomes the most environmentally sustainable as per the Eco-Indicator 99 assessment method.

Life cycle assessment results for different landfill liner systems obtained from the TRACI method are shown in Fig. 4. The TRACI method helps identify two more impact categories on different liner systems in detail, such as global warming and smog. The results obtained from TRACI are relatively similar to those obtained by Eco-Indicator 99. In the case of GM/SA liners, global warming, ozone depletion, acidification, eutrophication, carcinogenic, non-carcinogenic, respiratory effects, and smog primarily contribute to the negative environmental impact. This may be due to the emission caused by the production of hydrated lime and Portland cement in the liner system. The materials may cause cation(s) to leach from the liner material mix, thus reducing the pH of the overall soil mixture. Similarly, carcinogenic and fossil fuel depletion were found to harm the environment in the case of the GM/GCL liner system. Based on TRACI results, it is concluded that GM/FAB liner is the most environmentally sustainable system, followed by GM/CCL, GM/GCL, and GM/SA liner systems. The environmental impacts are minimized with the reduced volume of material consumption, as the EIA method assumes a linear relation between input and impact.

2.3. Economic sustainability

An economic evaluation of all four different liner systems was performed by incorporating costs associated with different material assembly (purchase), excavation, material transport to the landfill site, compaction, spreading, and blending. More information regarding necessary material transport and the unit costs are listed in Table 2. The given cost is based on reported literature and consultation with manufacturers and producers.

The cost analysis of liner systems for a unit acre landfill site area revealed that the GM/GCL system was the most cost-effective option at an estimated cost of $17733. The GM/ FAB system was the second most preferred option, costing $24847. The GM/CCL system cost was estimated to be $42282, and the GM/SA system was the least cost-effective option at a cost of $43984. Based on these calculations, it is concluded that the GM/GCL liner system is the most cost-efficient choice, followed by the GM/FAB liner system.

2.4. Social sustainability

Social sustainability is the least definable and most individualized of the three pillars, varying for different projects. As per the Western Australia Council of Social Services (WACOSS), the following characteristics may define social sustainability: fairness, diversity, interrelated cohesiveness, quality of life, democracy, governance, and maturity. The social sustainability chart, created by Benoit-Norris et al. (Benoît-Norris *et al.*, 2011), is used in this study to assess the social sustainability of liner systems. Table 3 displays the sustainability rating chart for each chosen liner system. In this approach, value '0' denotes the absence of adverse societal effects, whereas value '1' denotes harmful effects. As a result, low-scoring assembly methods are seen to be more socially responsible.

The justifications for the assigned ratings are summarized below:

- Workers: Systems like GM/CCL and GM/admixed-soil liners might possibly have detrimental societal effects on problems like child labor, forced labor, unequal working hours, and prejudice against equal opportunity for everyone. All four liner systems, however, might pose health and safety risks to landfill site personnel during excavation, compaction, spreading, and mixing of soils, geosynthetics, and stabilizing chemicals.

- Consumers: All four landfill liner systems might have severe or unfavorable long-term effects, mainly because harmful and corrosive waste leachate can migrate to the environment and then be exposed to the public.
- Local Community: In the local communities, installation of landfill liners might have a severe social impact. The construction of landfills is generally met with resistance from local communities in the Chicago area, as it may result in the relocation of residents and perceived environmental issues. However, installing all liners has the potential for employment to locals, which may benefit the community.
- Society: Due to technological advancements, engineered landfills with liner systems prevent any potential adverse effects, thereby directly or indirectly addressing various societal problems, including violence and corruption.

Overall, social rating points for each system have been provided under different impact categories. The GM/GCL liner system is the most socially viable option, followed by GM/FAB, GM/CCL, and GM/SA liner systems. GM/CCL is the least socially viable option.

3. Conclusions

The construction of engineered landfills necessitates implementing a composite lining system to mitigate the migration of harmful leachate into the underlying subsoil. In this study, a comprehensive sustainability assessment of four landfill composite liner systems, which are technically equivalent in leachate infiltration rate, was performed using the three pillars of sustainability - environmental, economic, and social impacts. Utilizing site-specific data from the DeKalb County Landfill in Illinois, USA, the following composite liner systems were selected for evaluation: geomembrane with compacted clay liner (GM/CCL), geomembrane with geosynthetic clay liner (GM/GCL), geomembrane with soil amended with 3% hydrated lime and 5% Portland cement liner (GM/SA), and geomembrane with fly ash bentonite mix system (GM/FAB).

The analysis revealed that the GM/FAB liner system was the most environmentally sustainable option compared to the other liners from the life cycle assessments. However, the GM/GCL liner was superior in economic and social sustainability. This is because of the costs associated with collecting, transporting, and installing materials like Portland cement and hydrated lime and excavating and compacting natural soils. However, in the case of CCL, these costs are minimal due to using locally available clay material in the liner system. Regarding social sustainability, GM/GCL is superior to GM/FAB as it involves excavating and transporting clay material, which may create work opportunities for residents. Nevertheless, the GM/GCL extensively used low permeable clay, a non-renewable natural resource.

Construction of large landfill lining systems demands thousands of tons of natural clay for lining purposes. Instead, GM/FAB minimized the extensive usage of natural resources and promoted the usage of industrial byproducts like fly ash. This has the following advantages: (1) effective utilization of fly ash, which is currently disposed in ash ponds occupying the valuable land surface area and poses challenging problems like subsurface pollution and dike instability; and (2) minimizes the extensive usage of non-renewable natural resources like clay materials for lining purpose thereby saving the environment and further reduces the cost of excavation and conveyance of material from long distances. Therefore, considering all environmental, economic, and social aspects, the study recommends GM/FAB as the sustainable liner system among all the four types discussed. In specific project conditions where the availability of fly ash resources is too far from the site conditions that involve high transportation costs, it is recommended to use a GM/GCL liner system using locally available geosynthetics vendors/manufacturers.

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Notations

TBL	Triple Bottom Line
GM	Geomembrane
CCL	Compacted Clay Liner
GM/CCL	Geomembrane over Compacted Clay Liner
GCL	Geosynthetic Clay Liner
GM/GCL	Geomembrane over Geosynthetic Clay Liner
SA	Soil mixed with Lime and Cement
GM/SA	Geomembrane over Soil mixed with Lime and Cement
FAB	Fly ash mixed with Bentonite
GM/FAB	Geomembrane over Fly ash mixed with Bentonite
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
EPA	Environmental Protection Agency
HDPE	High Density Polyethylene
MSW	Municipal Solid Waste
SDGs	Sustainable Development Goals
RCRA	Resource Conservation and Recovery Act
USEPA	United States Environmental Protection Agency
LCA	Life Cycle Assessment
WACOSS	Western Australia Council of Social Services

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Tables

Table 1. Material assemblies for various liner systems

Material Specification	Volume (m^3)	Material Density (kg/m^3)	Weight (tons)	Distance (km)	tkm (ton-kilometres
Clay	2,470	1650	4076	0-5	20377.5
60-mil HDPE Geomembrane	6.0705	940	5.71	110	628
GCL (Bentomat)	32.5	800	25.9	65	1683.5
Soil Admixed (92% native soil + 3% Hydrated Lime + 5% Portland Cement)	1231	1450	1783.9	Lime-15 Cement-70	15252.5
Soil Admixed (92% native soil + 3% Hydrated Lime + 5% Portland Cement) (12”)	615.5	1450	891.95	Lime-15 Cement-70	7626.25
FAB (80% Fly ash + 20% Bentonite)	1976 + 494	1467	3623.5 (724.7+2898.8)	Bentonite-20 Fly ash - 80	246398 (14494+231904)
FAB (80% Fly ash +20% Bentonite) (12”)	988 + 247	1467	1811.75 (362.4+1449.4)	Bentonite-20 Fly ash - 80	123226 (7274+115952)

Table 2 Summary of economic analysis of liner materials

Materials	Material Volume / Weight	Location	Distance (km)	Unit cost	Unit cost consideration
Clay	2470 m^3	Available on site	0-5	\$6/yd^3 (purchase) \$6.22/yd^3 (excavation) \$1.32/yd^3 (spreading) \$0.5/yd^3 compacting)	Excavation, transport, spreading, and compaction
Silt, Sand, and Gravel	1643 tons	Available on Site	0-5	\$14/yd^3	Material cost, transport, and spreading
HDPE Geomembrane	6.0705 m^3	MPC Containment, 4834 S Oakley Ave, Chicago IL	110	\$0.45/ft^2	Material and transportation cost
Geosynthetic Clay Liner (Bentomat)	32.5 m^3	AMCOL International Corp., 2870 Forbs Avenue Hoffman Estates, Illinois	65	\$0.52/ft^2	Material cost, transport, and placement
Lime	53.5 tons	EME Midwest Generation, Joliet IL	15	\$132.3/ton	Material cost, transportation, and mixing
Portland Cement	90 tons	Cemex USA, 23462 S. Youngs RdChannahon, IL 60410	70	\$115/ton	Material, transportation, and blending cost
Fly ash	2898.8 tons	Any source available near the site	80	\$0/ton	Transportation

Bentonite	724.7 tons	Source available near the site	65	$14/ton	Material cost, and transportation

Table 3 Social sustainability rating system

Stakeholder Group	Impact Category	GM/CCL Liner	GM/GCL Liner	GM/SA Liner	GM/FAB Liner
Workers	Freedom of Association and Bargaining	0	0	0	0
	Child Labour	1	0	1	1
	Fair Salary	0	0	0	0
	Working Hours	1	0	1	1
	Forced Labour	1	1	1	1
	Equal Opportunities/ Discrimination	0	0	0	0
	Health and Safety	1	1	1	1
	Social Benefits/Social Security	0	0	0	0
Consumers	Health and Safety	1	1	1	1
	Feedback Mechanism	0	0	0	0
	Consumer Privacy	0	0	0	0
	Transparency	1	0	1	0
Local Community	Delocalization and Migration	1	0	1	1
	Safe and Healthy Living Conditions	1	1	1	1
	Access to Material Resources	1	1	0	1
	Local Employment	0	0	0	0
	Secure Living Conditions	1	0	1	0
Society	Public Commitments to Sustainability Issues	0	0	0	0
	Contribution to Economic Development	1	0	0	0
	Prevention and Mitigation of Armed Conflicts	0	0	0	0
	Technology Development Corruption	0	0	0	0
	Total Social Impact Assessment values	11	5	9	8

Figure captions

Figure 1 Schematic representation of four different liner systems considered for sustainability assessment (a) GM/CCL, (b) GM/GCL, (c) GM/SA, and (d) GM/FAB

Figure 2 Environmental impact (single score) for different liner systems based on the Eco Indicator 99 method

Figure 3 Impact characterization of different variables for selected liner systems based on Eco indicator 99

Figure 4 Environmental impacts for different liner systems based on the TRACI method

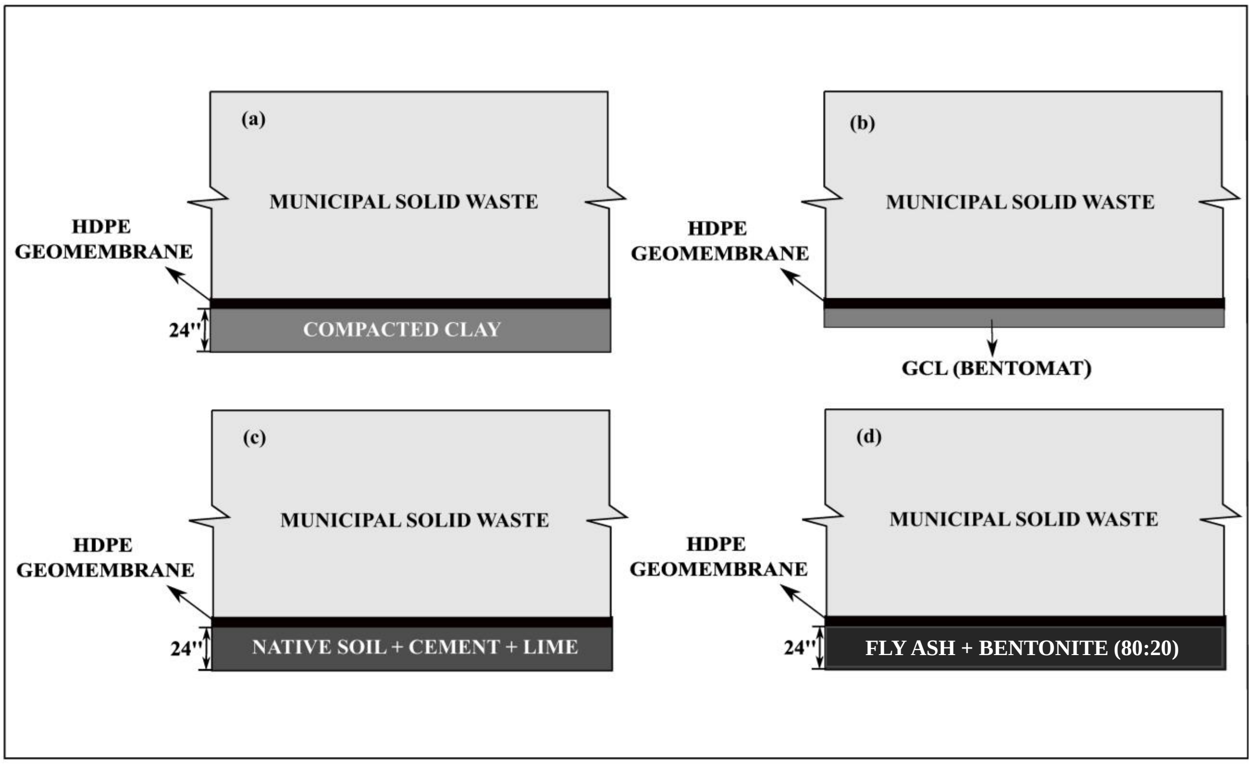

Figure 1

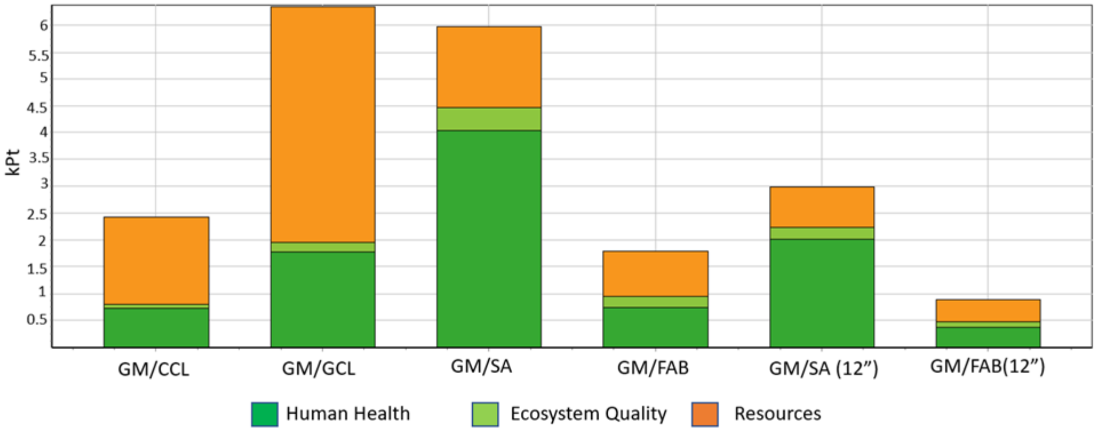

Figure 2

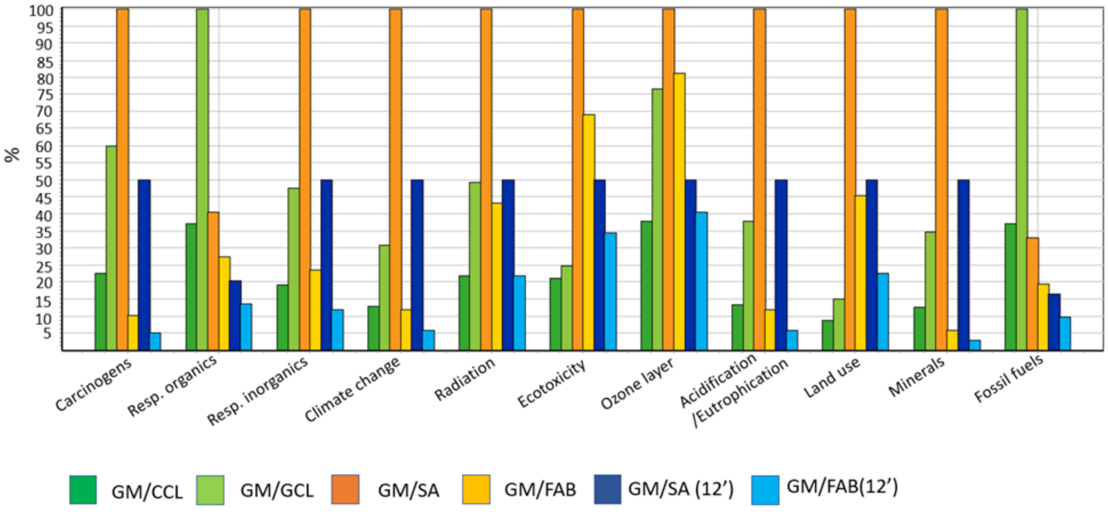

Figure 3

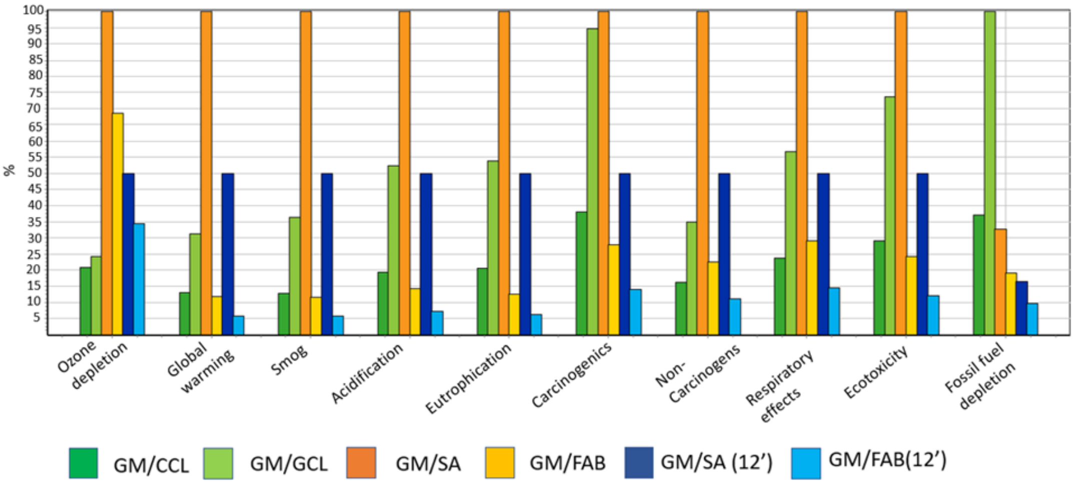

Figure 4