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Sustainability Analysis of Landfill Cover System Constructed Using Recycled Waste Materials by Life Cycle Assessment

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ABSTRACT

The sustainability of using industrial by-products for the construction of landfill cover was determined using Life Cycle Assessment (LCA). LCA was carried out on four materials: sand- bentonite mix, red earth- bentonite mix (amended soil), Waste Foundry Sand (WFS)-Bentonite mix, and WFS- marine clay mix. The former two are commonly used cover soils and the latter two are alternative materials proposed. Environmental impacts based on the extraction of resources, processing, transportation to the site, and site preparation were considered using the 'cradle to site' approach. Analysis was carried out in OpenLCA software using the ReCiPe (H) Midpoint method of impact assessment. Required data for analysis was taken from the Ecoinvent database supplemented with inputs from a field survey. The use of WFS in landfill cover systems was found to be sustainable using LCA studies when compared to conventional materials.

INTRODUCTION

Waste management lags behind the advancements in other fields of technology in developing countries. This, coupled with rapid and unplanned urbanization, consumerism, and industrial production, the pressure mounts on existing systems. In recent times, methods such as incinerating, composting, and recycling have been dominating research space and academia, but landfilling remains the most favored solid waste disposal method globally (Nanda & Berruti 2021, Avarand 2023). An engineered landfill effectively isolates the waste from its surroundings and ensures its safety from failure in the future. The composite-engineered layer employed for this is known as a cover system (Ujaczki et al. 2016).

Although landfill cover is widely discussed as a single unit, it is a complex multi-layered engineering construction, with each sublayer complying with specific requirements in terms of functionality, material composition, and engineering properties (Charles et al. 2019). A typical multi-layered cover system, as shown in Fig. 1, has a gas collection layer, barrier layer, drainage layer, and top soil, with each layer separated by specific geosynthetics. The most important layer in terms of functionality is the barrier layer, which prevents the ingression of fluids from outside the landfill as well as the escape of fluids (gas and liquids) from the landfill (Yamsani et al. 2016). Other layers effectively protect the barrier layer from operational damage and aid the latter in isolating disposed waste and its derivatives. In this investigation barrier layer is considered for sustainability analysis as the other layers remain the same in all the cases considered.

Materials selected for the construction of the barrier layer should satisfy the requirements specified by the Environmental Protection Agency (EPA), the most important of which is that hydraulic conductivity should not exceed 10^{-9} $m.s^{-1}$. Traditionally, sand-bentonite mixtures are commonly used for barrier construction due to their superior performance in terms of hydraulic conductivity and strength. However, the unavailability and high cost of sand inhibit it from being used in landfill construction, but it is still considered a reference material for the barrier layer. Locally available lateritic soil mixed with bentonite clay (to reduce hydraulic conductivity to 10^{-9} $m.s^{-1}$) is a widely used, inexpensive alternative to sand bentonite mix, commonly known as amended soils.

Alternatives to sand bentonite mixture and amended soils using industrial by-products are discussed in this paper. Waste Foundry Sand (WFS) is a by-product of metal casting industries. After several repeated cycles of using and reusing, foundry sand eventually ends up as a waste material with limited use in concrete and pavement construction (Siddique & Singh 2011). With over 60 million tonnes of WFS produced worldwide annually (Sandhu & Siddique

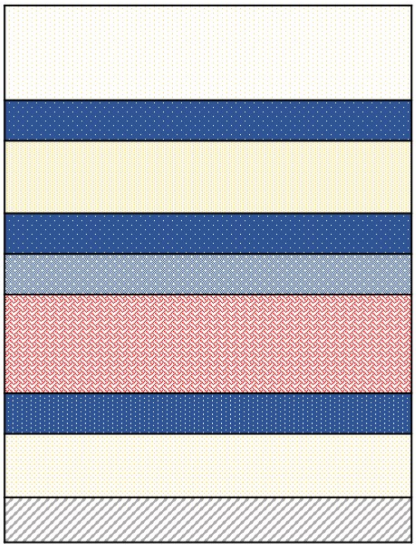


Fig. 1: Typical cross-section of Landfill cover system.

2022), there would be a continuous supply of WFS. WFS does not readily satisfy EPA norms and has to be modified with suitable clay. Bentonite, which is a commonly used clay for barrier soil, and marine clay, which is a naturally occurring clay, is selected for this amendment. Marine clay is a by-product of pile-driving operations in coastal regions. Due to their mineralogical structure, they cannot be used in kilns and hence have limited applications. The use of waste foundry sand and marine clay as landfill cover materials has several benefits, including reducing the need for virgin materials, conserving natural resources, and reducing the amount of waste generated.

Recycling and reusing waste materials for construction purposes promotes resource recovery and thereby contributes to sustainability. However, the allied and dependent processes involved in the same may have greater invisible environmental implications due to the consumption of resources and energy as well as emissions (Cirrincione et al. 2022). Hence, sustainability assessment is very important when a new system or production procedure is proposed. Life Cycle Assessment (LCA) is a method used to qualify, quantify, and evaluate impacts associated with connected processes and product systems. The type and level of impact of each product system can be evaluated, and solutions can be proposed to mitigate negative impacts. The United Nations Organization has stipulated several goals for sustainable development to ensure that the benefits of development are not limited to economic indicators (United Nations 2015).

The broader objective of this study is to ensure sustainability in infrastructure development and waste disposal. The compliance of alternate landfill cover materials with these goals is essential to ascertain the sustainability of the former. The paper aims to assess the sustainability of using WFS and marine clay in the construction of landfill cover systems in comparison with commonly used construction materials for the same.

MATERIALS AND METHODS

Four combinations of soils for barrier construction are considered in this paper, namely sand-bentonite mix, amended soil (red earth-bentonite mix), WFS-bentonite mix, and WFS-marine clay mix. Hence, the basic materials considered for this study were Bentonite, Marine Clay, Red Earth, Waste Foundry Sand, and River Sand. The sand-bentonite mixture is a commonly used reference material for the barrier layer, and the combination used was sand mixed with 20% bentonite, as in available literature (Sivapullaiah et al. 2000, Komine & Ogata 1999).

WFS was collected from the industrial area in Kochi, Kerala, India, and marine clay was collected from a piling site near Kochi coast, from a depth of 8-10 m. Red earth was collected from the locality of Uyogamandal Industrial area, Kochi where an operational engineered landfill exists. Commercially available bentonite was purchased, which was sourced from the North-Western part of India, approximately 1400 km from the site considered. Whereas WFS, red earth, and marine clay were available within a 30 km radius.

Laboratory tests were conducted to check the suitability of using RE- RE-bentonite mix, WFS-bentonite mix, and WFS-marine clay mix as cover materials as per specifications. The test results are shown in Table 1. From these results, the

Table 1: Geotechnical properties of soil mixes used for landfill cover.

Combination	γ_{dmax} [kN.m^{-3}]	OMC [%]	Liquid Limit [%]	Plasticity Index [%]	Corrected Activity Parameter, A_c	Hydraulic Conductivity [m.s^{-1}]	Volumetric Shrinkage [%]	Free Swell Ratio
WFS	17.66	11.70	-	-	-	2.21×10^{-06}	0	1.30
WFS + 5% B	17.80	13.27	41	19	3.29	2.36×10^{-10}	1.31	2.54
WFS + 10% B	17.95	13.68	52	22	2.19	1.08×10^{-11}	2.44	3.88
WFS + 15% B	17.46	14.59	64	30	2.09	3.57×10^{-11}	3.03	4.66
WFS + 20% B	17.01	16.9	67	32	1.72	1.95×10^{-11}	6.11	5.80
RE	17.63	18.00	51	22	1.29	3.24×10^{-08}	1.24	1.11
RE + 3% B	16.69	20.52	55	23	1.20	9.02×10^{-10}	3.07	1.75
RE + 6% B	16.51	21.13	60	26	1.23	8.22×10^{-11}	3.91	1.90
RE + 9% B	15.9	21.86	62	27	1.16	5.61×10^{-11}	6.76	2.12
RE + 12% B	15.49	23.07	67	30	1.18	3.76×10^{-11}	10.90	2.18
WFS + 25% MC	17.83	14.6	19	9	0.65	5.02×10^{-08}	3.97	1.34
WFS + 33% MC	17.46	16.2	23	8	0.45	7.19×10^{-10}	3.93	1.40
WFS + 50% MC	17.17	17.5	29	12	0.46	8.88×10^{-11}	1.93	1.43
MC	14.52	24.00	68	40	0.78	7.00×10^{-11}	16.51	1.50

optimum mixes of soils selected were RE + 6% bentonite, WFS + 10% bentonite, and WFS + 50% marine clay.

Life Cycle Assessment (LCA) method was used for the assessment and comparison of sustainability associated with different materials used in landfill cover construction (ISO 14040 2006, ISO 14044 2006). In simple terms, LCA involves a comparative study based on the functionality of product systems, even though they are made of entirely different materials. Hence, a 'functional unit' is the basic analysis unit (Anh et al. 2022). The sustainability of the Life Cycle Assessment is carried out in a four-stage framework, which includes goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation.

Goal and Scope

The paper covers the utilization of LCA to calculate and analyze the environmental impacts of landfill cover construction using conventional materials and recycled materials with respect to Kochi, India. The functional unit selected for the analysis was 1 acre of landfill cover with a thickness of 0.6 m.

System Boundary

'Cradle to site' approach, which includes material extraction, transportation to site, and site installation, as depicted in Fig. 2. For WFS and marine clay, material extraction was not considered since they are waste materials, and only transportation to site and site installation was considered.

Inventory Analysis

LCA is heavily dependent on the data used for analysis, and it is a laborious process. Ecoinvent database is a global database for materials, energy flows, and emissions and provides data on the environmental impacts of various processes and products. Most data were taken from the Ecoinvent database. Still, some modifications were made

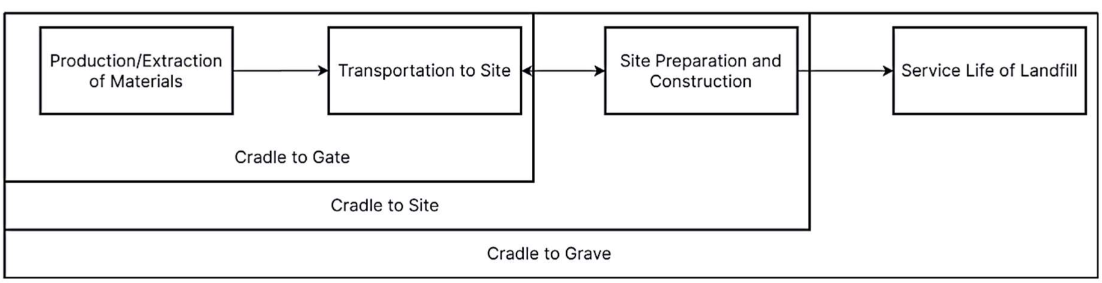


Fig. 2: System Boundary Definition: Cradle to Site.

Table 2: Field data for unit processes (from questionnaire survey).

Unit Process	Rate of Work	Fuel Efficiency
Tipper (Brand – Daimler)	16 m^3 soil per load	2 km.l^{-1} (full load)
Road Roller	2 km.h^{-1}	5 L.h^{-1}
Excavator	15 m^3.h^{-1}	6 L.h^{-1}
Soil laying	20 min per tipper load	-
Crusher	150 t.h^{-1}	25 L.h^{-1}

Table 3: Impact categories relevant to the study.

Impact category	Reference unit
Climate change	kg CO2-Eq
Marine Eutrophication	kg N-Eq
Particulate Matter Formation	kg PM10-Eq
Photochemical Oxidant Formation	kg NMVOC
Terrestrial Acidification	kg SO2-Eq

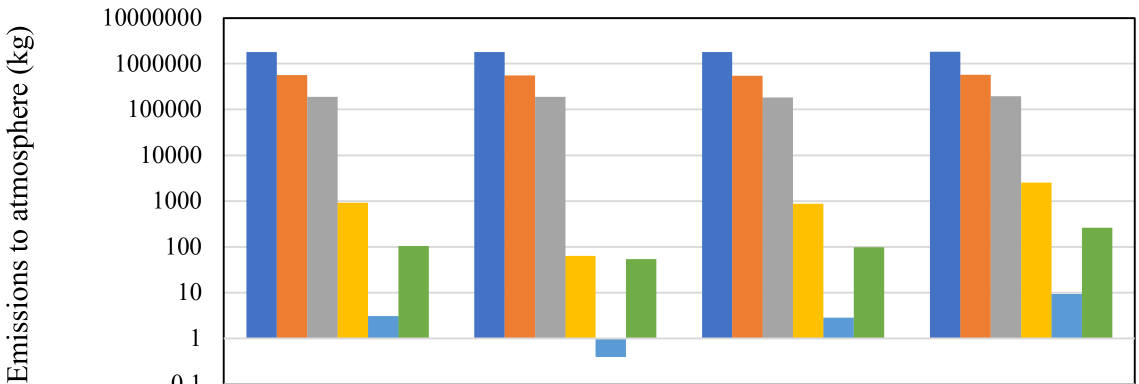
to suit the data in the Indian context since the database is largely based on data from Europe and the Americas. Table 2 shows the unit processes that were modified based on a questionnaire survey in construction sites. A distance of 30 km was fixed for the transport of materials except bentonite. All vehicles were assumed to be complying with BS-IV emission standards. Also, the emissions rates of modified unit processes were calculated on permitted emissions from diesel vehicles as per BS-IV regulations (The Gazette of India 2015).

Life Cycle Impact Assessment

The calculation of the environmental impacts of the landfill cover system was carried out using an impact assessment method called ReCiPe (H) Midpoint method (also known as the CML 2001 method). The production of bentonite involves the quarrying of clay, refining, packaging, and transportation. River sand production involves the use of dredging equipment, motor boats, and transportation. Red earth is excavated using excavators and transported to the site. The production process of WFS and marine clay was not considered since they are byproducts from another industry. However, transportation of the same using diesel lorries was considered. The results of the assessment are presented as environmental impact categories. The impact categories relevant to the study (with > 1% value) are shown in Table 3.

RESULTS AND DISCUSSION

Fig. 3 shows the values of emissions corresponding to carbon dioxide, carbon monoxide, unburned hydrocarbons, nitrogen oxides, particulate matter, and sulfur dioxide. Here, the sand-bentonite mix is considered as base mix, and the results are presented in comparison with the same. In all parameters evaluated, emissions to the atmosphere and values of impact categories were found to be maximum for sand-bentonite mix, followed by RE-bentonite mix, WFS-bentonite mix, and WFS-marine clay mix, respectively.



	RE+B (kg)	WFS+MC (kg)	WFS+B (kg)	Sand+B (kg)
Carbon dioxide	1791470	1777537.5	1789678.53	1837506
Carbon monoxide	561807.5	557554.375	550571.35	575481
Hydrocarbons	190744.25	189068.75	185021.9225	195867.6
Nitrogen oxides	922.0736	63.3986	866.749184	2532.7736
Particulates	3.0871	0.3896	2.840132	9.2576
Sulfur dioxide	104.219	53.669	97.96586	264.524

Fig. 3: Emissions from various soil mixes considered during their life cycle.

The life cycle of sand bentonite mix accounts for the production and transportation of sand from the river bed, along with the processes associated with bentonite production and transportation. Hence the maximum values of emission are associated with sand-bondonite mix. Excavation of red earth involves less machinery and fuel compared to sand mining and thus, its emissions are lesser than sand bentonite mix but greater than WFS-bentonite mix. This is due to the fact that the back process of WFS production is not accounted for. WFS-marine clay mix has the least emission values since both WFS and marine clay are byproducts, and the impact of their production was not considered.

Fig. 4 shows the reduction in emissions for RE-bentonite mix, WFS-bentonite mix, and WFS-marine clay mix with respect to sand-bentonite mix. The production of WFS was not considered for assessment since it is a waste product but quarrying operation involving machinery and humans is considered for red earth. RE-bentonite mix and WFS-bentonite mix show a similar range in reduction of emissions even though the impact of transportation of WFS is smaller than that of the multi-stage production and transportation of red earth. This trend indicates the high impact of bentonite in the product system in terms of emissions. It is more evident from the emission values of the WFS- marine clay mix, which has a remarkable 30% less emissions compared to the WFS-marine clay mix. Additionally, the reduction in greenhouse emissions is of lower magnitude compared to NO_x, SO_2, and particulates. This could be attributed to the fact that electricity production in India is predominantly using coal energy (Tiewsoh et al. 2019) and bentonite production consumes a high amount of electricity.

The total energy consumption for each soil mix is shown

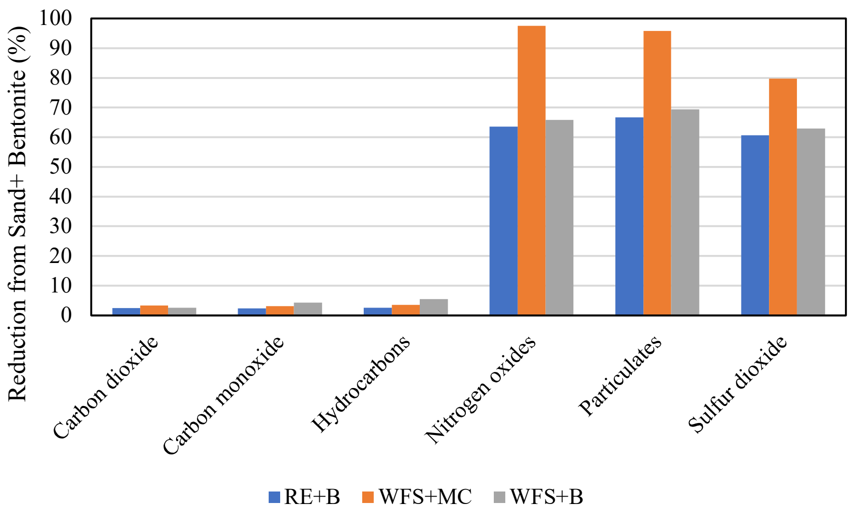


Fig. 4: Reduction in emission values compared to sand-bentonite mix.

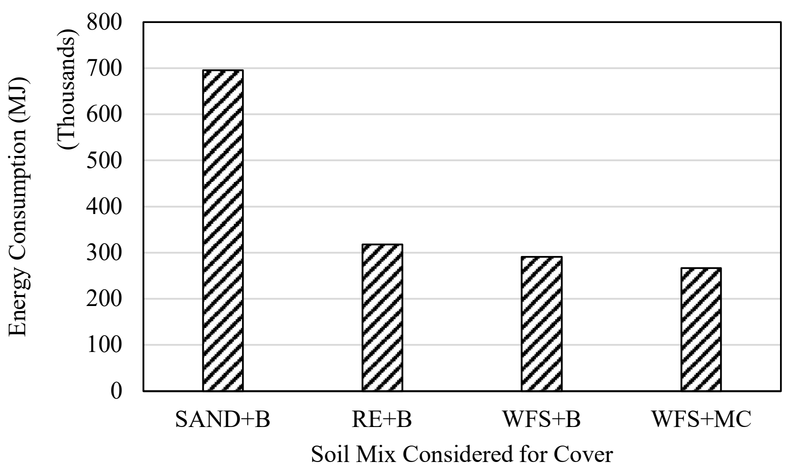


Fig. 5: Energy consumption for soil mixes considered.

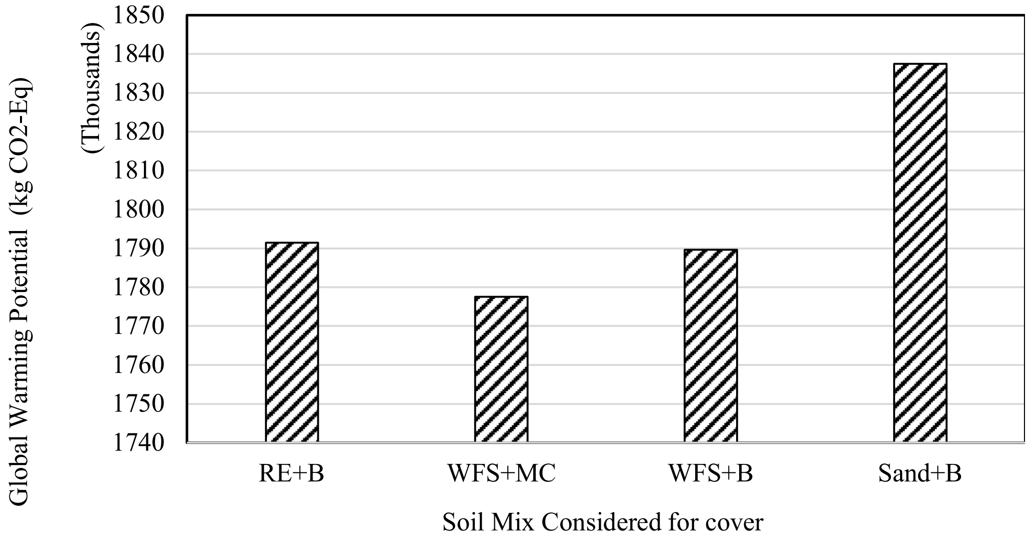


Fig. 6 a: Global warming potential for soil mixes considered.

in Fig. 5. The production of sand-bentonite mix consumes more than two times the energy when compared with all other mixes. River sand mining involves marine equipment and boats which consume higher quantities of fuel and work at a slower pace compared to land types of equipment. This increases the embedded energy associated with river sand considerably. The variation in energy consumption of the other three mixes is in the range of 10%. This modest difference is because diesel consumption for transportation is considerably higher than other energy requirements. Additionally, the WFS+ marine clay mix, which ought to have significantly lower energy consumption, also exhibited only a 10% reduction compared to the WFS+ bentonite mix. The laying of marine clay at the site takes more time compared to other soils, which results in higher fuel consumption.

Figs. 6a to 6e show the variation of impact parameters for soil mixes. Parameters with significant (>1%) contributions are Global Warming Potential (GWP), Marine Eutrophication, Particulate Matter Formation, Photochemical Oxidant Formation, and Terrestrial acidification. Impact parameters are dependent on the indicators represented in Fig. 3. Carbon dioxide and methane in the form of unburned hydrocarbons from diesel exhaust are the prominent greenhouse gases contributing to global warming potential. Among them, methane has 28 times more global warming potential compared to carbon dioxide (Ou et al. 2022). In agreement with the emission values of greenhouse gases and energy consumption, the sand-bentonite mix has the highest contribution to the global warming potential, and the remaining mixes vary by a narrow margin.

Marine eutrophication and photochemical oxidant formation are caused by the release of oxides of Nitrogen (NO_x). Dissolution of NO_x in water bodies may cause eutrophication, which leads to oxygen deficiency in water bodies (Zhou et al. 2019). This leads to the depletion of aquatic life and reduces the self-cleansing capacity of water bodies. Sunlight-sensitive oxides of nitrogen form photochemical oxidants that affect the respiratory system of terrestrial beings and deplete vegetation (Weitekamp et al. 2020). It is evident from Fig. 6b and 6c that reduction in these parameters is remarkably high when substituting sand with WFS and bentonite with marine clay.

Particulate matter or suspended solid particles are released into the atmosphere by diesel exhaust from automobiles and coal-based thermal power plants. Hence, they are directly correlated to the combustion of diesel and coal. River sand mining is found to be the largest contributor to particulate matter formation. Fig. 6d shows that the sand-bentonite mix produces three times the particulate matter compared to the WFS-bentonite mix and RE-bentonite mix.

Terrestrial acidification is caused by SO_2 gas released during the combustion of fossil fuels, which gets dissolved in water to form sulphuric acid. The combustion of coal releases a greater quantity of SO_2 into the atmosphere compared to diesel exhausts (Bhanarkar et al. 2005). It is evident from Fig. 6 e that terrestrial acidification is comparable for all three combinations using bentonite and appreciably less for WFS-marine clay mix, which could be due to the higher electricity consumption associated with bentonite production.

The different impact categories of life cycle assessment show that the WFS- bentonite and WFS- marine clay mixes used for landfill cover construction have an outstandingly low impact with respect to every indicator considered. These mixes also exhibit much lower LCI compared to sand-

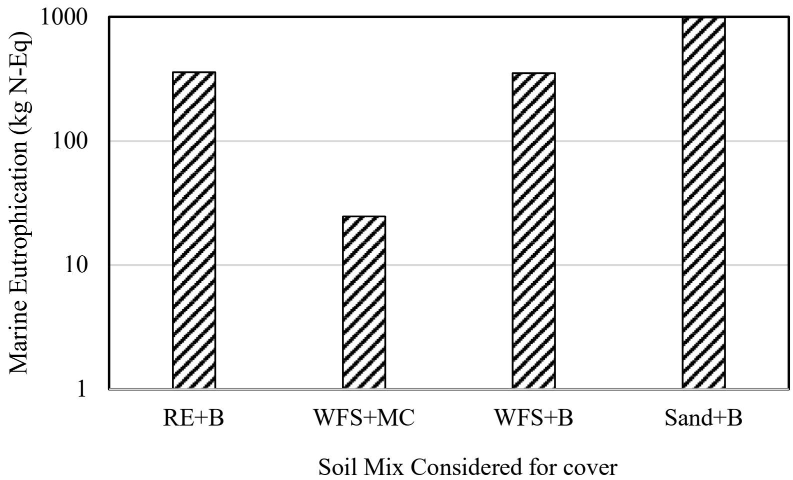


Fig. 6 b: Marine Eutrophication for soil mixes considered.

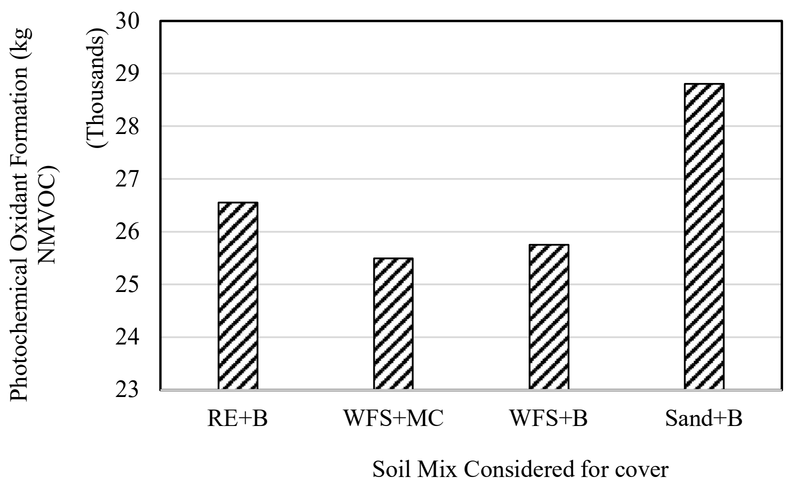


Fig. 6 c: Photochemical oxidant formation for soil mixes considered.

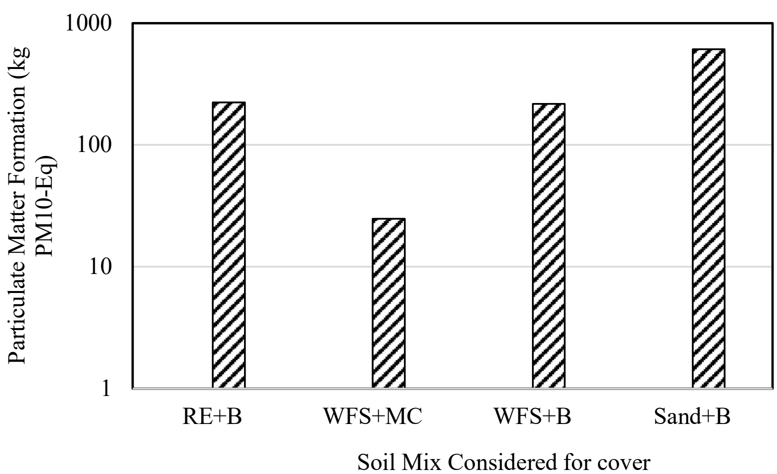


Fig. 6 d: Particulate matter formation for soil mixes considered.

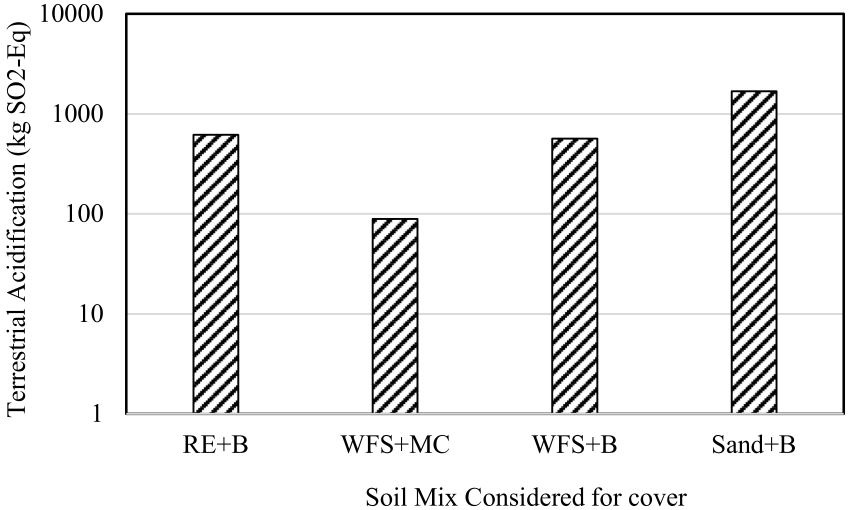


Fig. 6 e: Terrestrial Acidification for soil mixes considered.

bentonite mixes. However, the emission and impact values of WFS-bentonite were similar to those of the red-earth bentonite mix. Hence, both WFS-bentonite and WFS-marine clay mixes may be recommended as sustainable alternatives to landfill cover soil, with the latter proving to be most sustainable with respect to LCA.

The proposed use of industrial by-products like waste foundry sand (WFS) and waste marine clay from the piling industry satisfies criteria SDG-6, SDG-8, SDG-9, SDG-11, SDG-12, SDG-13, SDG-14 and SDG-15 of the UN sustainable development goals. Fulfillment of criteria like clean water and sanitation, climate action, life below water, and life on land was directly attained in the analysis results discussed. Responsible consumption and production are achieved when a waste material is reused as a construction material and further depletion of resources is curtailed. By scaling this concept to industry, innovation and infrastructure development can be achieved. With contribution to waste management and urban growth, possibilities for decent work and economic growth are facilitated and thus lead to sustainable cities and communities.

CONCLUSIONS

The sustainability of replacing sand-bentonite mix and red-earth bentonite mix with industrial by-products such as waste foundry sand and marine clay in landfill cover construction was assessed using Life Cycle Assessment. The following conclusions have been drawn from the study.

- WFS mixed with 10% bentonite and WFS mixed with 50% marine clay were found to be suitable replacements for sand-bentonite and red earth-bentonite mixes.
- WFS- marine clay mix was found to be the most sustainable, with a 60% to 90% reduction in emission values compared to other soil mixes.
- The sustainability of WFS-bentonite was compared to RE- RE-bentonite mix with a 2% to 6% reduction in emission values from the latter. This indicates that bentonite production and transportation are having more impact on the unit processes considered.
- Sand-bentonite mix was found to have 90% more emission compared to WFS-marine clay and 60% compared to WFS-bentonite and RE-bentonite.

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