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Life Cycle Assessment of Substitutive Building Materials for Landfill Capping Systems in Vietnam

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Abstract: The growing population and urbanization rates in developing countries causes huge pressure on the construction sector to aid the equivalent infrastructure growth. Natural resources are essential to attain the required infrastructure needs. The demand in the construction sector for materials causes significant environmental effects due to the higher consumption rate of finite natural resources. To address such an issue, the study focuses on the landfill capping application demand in Vietnam, based on its extensive landfill presence in its current state and their need to be closed in the years ahead. The study considers utilization of secondary raw materials arising from industrial or anthropogenic waste as an alternative material as a landfill mineral sealing layer, to replace the dependence on conventional clay and bentonite. The selected alternative materials were tested to satisfy the permeability conditions for the landfill sealing layer standards, where results indicated very low permeability values for the mixtures, meeting German quality requirements which require $k \leq 5 \times 10^{-9}$ m/s for landfill class I (landfills without further environmental requirements) and $k \leq 5 \times 10^{-10}$ m/s for class II (conventional landfill for non-hazardous waste) for sealing layers of landfills. Further, the various mixes of alternative mineral layers in a life cycle analysis for a functional unit of one hectare landfill mineral sealing layer resulted in lower environmental footprints than the conventional layer. The results of the mineral sealing layer showed that the higher bentonite composition of about 20% in the mix ratio and transport distance of 65 km for the ashes increased the overall environmental footprint of the mix. In this case, mix 6 and mix 7, having 20% bentonite, tended to possess higher impacts, despite the alternative ashes holding zero allocation, along with the 65 km transportation distance associated with ashes. The avoidance factor over the alternative mixes has an effective approximate 25–50% Global Warming Potential (GWP) impact reduction. There was a significant mineral resource scarcity impact reduction on the use of secondary raw materials.

Keywords: substitutive building materials; soil mechanics; life cycle assessment; landfill capping; mineral sealing layer

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1. Introduction

Municipal solid waste management remains a huge challenge in developing countries, along with rapid economic growth and increasing population in urban centres, waste generation, high costs associated with management, and the containment systems' structure [1]. In recent decades, recycling, incineration, and composting have increasingly contributed to solid waste management, but landfilling still remains a common way of waste handling worldwide [2]. Although several management methods have been deployed to reduce the solid waste burden, landfills remain among the most common techniques applied in controlling municipal waste in many countries [3]. In urban clusters, Solid waste generated from domestic, industrial, and construction sectors is collected and disposed of in Municipal Solid Waste landfills [1,4]. A properly designed sanitary landfill isolates waste materials from the surroundings. A sanitary landfill might experience long term failure in its liner system efficacy due to long-term environmental effects [5,6]. Therefore, landfill sealing technologies comprise low hydraulic conductivity engineered layers as part of the covers and bottom liners, for which clays and geosynthetic materials are conventionally used. However, in the last few decades, landfill designers around the world have faced an increasing scarcity of feasible primary raw materials for landfill construction, particularly in terms of the sealing layer with its special technical requirements. Therefore, an increasing number of mixed wastes have been suggested as alternative landfill barrier materials. The general sources of secondary mineral materials might be: (a) residues of agricultural activities, like ashes from agro-waste [7,8]; (b) metallurgical or mineral waste [7,9]; and (c) mining waste, for instance tailings' sediments. However, tailings' sediments are excluded due to quality reasons, in case they contain too high metal contents or flocculation agents, as described in [10].

Moreover, for landfill applications, particularly the sealing layer, it is necessary to utilize waste streams with constant availability and suitable soil mechanical properties. Secondary waste materials which are often involved in landfill construction include slag, fly ash, brick waste, construction and demolition waste, glass waste, rice husk ash, mining waste, incineration residues etc., [7,9,11,12]. Construction demolition waste (CDW) occurs due to road maintenance, construction, repairing, upgrading, renovation, excavation, and demolition activities. It is widely used in landfill construction operations [13,14]. The construction waste is usually generated as a mixture of concrete, brick, ceramic, natural aggregates, glass, and other materials. The construction waste undergoes processing which generally involves sorting, crushing, milling, and grading according to the application and based on the materials such as concrete and brick, etc. as well [15]. The slag usually remains as a by-product of the mineral extraction, which involves quenching or cooling processing and further milling. The other large quantity of industrial waste is fly ash, which remains stored in ash ponds in large quantities, or is utilised in cement manufacturing [16]. Fly ash might need processing for pollutant reduction or pH neutralisation based on its physical and chemical properties [12,17,18]. Recent research developments focus on replacing river sand with mineral ore sand, which is a type of co-product or by-product of mineral ores that could be further processed to achieve sand properties [19]. In general, recycling the wastes requires energy inputs, which helps to convert the waste into aggregates for utilising in construction applications replacing energy-intensive natural aggregates. After reuse or recycling, municipal solid waste and other types of waste have their endpoint at the landfill. Waste landfilling over a longer period often triggers the biological, chemical, and physical processes in the waste body, resulting in the release of pollutants that may reach the aquifer system by leachate infiltration [20,21].

The landfill design structure on top of the ground involves a special design of multi-layers, which has a specific lifecycle. The multi-layers usually consists of a combination of geological barrier (hydrological), technical barriers (basal liner and capping), and the waste body [22]. It is proposed [23] that a landfill must be designed so that the protection barriers satisfy the requirements for a long duration, at least 30 years while in operation, and at least 30 years after closure. The landfill layer's design during its lifecycle should give unchanged quality protection. A landfill cover is a multi-layered construction system (Figure 1) that reduces water percolation to deposited waste and minimises leachate production and the uncontrolled release of landfill gas into the atmosphere [20]. One of the most important parameters considered for the performance of landfill capping layers is the hydraulic conductivity (k-value) of materials used in the construction of a hydraulic barrier in waste containment facilities [7]. A mineral sealing layer is an important section in the landfill layer covering the landfill base and sides at the bottom and top cover. The thickness of the layer needs to be designed based on a choice of material, such that the permeability of the mineral sealing layer has to be at least equivalent to $k \leq 1.0 \times 10^{-9}$ m/s for the effective protection of soil, groundwater, and surface water [24]. Therefore, a mineral sealing layer requires pre-laboratory testing to establish its permeability. The design and the layer thickness determination must be adapted to the location-dependent water balance and the physical properties of the utilised material. The commonly used mineral sealing layer materials are natural clay, compacted clay, and bentonite-based mixes [25]. The proper removal of leachate represents an important factor in the successful functioning of a landfill facility. The drainage layer forms an integral part of the leachate collection system, comprising of inert material with high permeability along with drain pipes to collect infiltrating water and prevent leachate. The drainage layer lies below the recultivation layer and above the mineral sealing layer [26]. The commonly used drainage layer materials are sand or gravel and geosynthetics [27]. The recultivation layer usually lies above the drainage layer of the landfill, forming a top part of the landfill capping system acting as vegetation and lateral drainage layer [23]. To meet the basic requirements, a recultivation layer should consist of sandy/loamy materials supporting plant growth at least 1 m thickness and should have a hydraulic conductivity of at least 7.2×10^{-6} m/s [28]. The commonly used recultivation layer material is locally available topsoil [29].

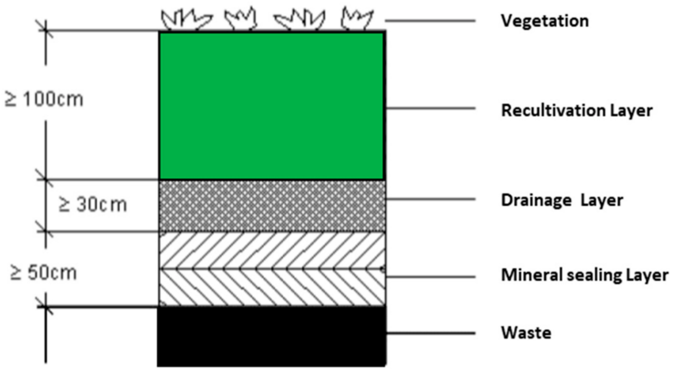


Figure 1. Different layers involved in landfill capping—Landfill Class I Germany (Adapted source: [30]).

The paper presents the result of the research project 033R212C (SAND!), funded by Germany's Federal Ministry of Education and Research (BMBF), that is focusing on mitigating the scarcity of primary raw materials as building materials through the feasibility assessment of secondary raw materials. Among other building applications, the need for mineral resources in landfill construction was addressed in the framework of the assessment of potential substitutive materials. The landfill sealing layer is a compartment of the capping system with particular low permeability requirements. The availability of primary materials that meet the requirements, like clay, is usually limited, especially in the Vietnamese context. For that reason, an environmental assessment was performed using the Life Cycle Assessment (LCA) method to identify feasible options for substitutive building materials to construct the landfill, as well as the environmental benefits. LCA is a rapidly evolving tool used to determine the impacts of products or systems for relevant environmental and resource aspects.

Vietnam is geographically located in Southeast Asia, along the Indochina peninsula, with a total area of 329,566 square kilometres. Due to the considerable north-south extension, the climate is divided into northern and southern climate zones. The north of Vietnam is characterised by a winter-dry subtropical climate. In the south of the country, the tropical climate prevails throughout the year and is also described as variable humidity [31]. The climate of Vietnam overall is tropical typhoon and monsoon, with abundant rainfall and humidity up to 80–90%. The northern part of the country receives annual precipitation of about 1700 mm, while the southern region receives 2000 mm on average [32]. Vietnam's population was estimated to be 96.4 million people in 2019, including an urban population of 32.8 million people [33]. The Vietnamese population is expected to increase by

100 million by 2025 [34]. According to the Vietnam Urban Development Vision of 2020–2025, the urban population is expected to grow from 45% by 2020 to 50% by 2025 [35]. Since the 1986 “Doi Moi” reform, Vietnam has undergone rapid development and urban growth.

Owing to the increasing population and urbanisation, the municipal solid waste (MSW) volume is increasing. The MSW generation rate is estimated to rise yearly by 10–16%, with sources including households, restaurants, markets, municipal activities, and businesses [36,37]. Vietnam generates more than 27.8 mil tons/year of waste from various sources such as municipal, agricultural, and industrial waste [38]. According to [39], in municipal areas, the ratio of solid waste disposed of in landfills was approximately 34%, recycled waste accounts for approximately 42%, and the remaining other disposal processes comprise about 24%. On average, Vietnam’s waste generation was 0.7 kg/cap/day in urban areas and 0.4 kg/cap/day in rural areas [40]. According to [41], about 63% of collected waste ends up in landfills and 22% goes to various treatment facilities. Vietnam has approximately 660 landfills, among which 204 were sanitary landfill and 456 were the non-sanitary type. Table 1 elaborates the distribution of landfills and their capacity across Vietnam.

Table 1. Distribution of landfills and their capacity in Vietnam.

Landfills (LF)	Total LF	Sanitary LF	Non-Sanitary LF	Dumpsite Waste Received (t/Year)	>20 Hectare	1–20 Hectare	<1 Hectare
Western North	39	12	27	224,325	1	30	8
Western North	85	34	51	559,525	7	44	34
Economic Zone Northern	118	33	85	1,810,029	4	27	87
Economic Zone of Red River Delta	72	23	49	472,693	3	49	20
Economic Zone of Central	91	50	41	694,310	7	69	15
Economic Zone of Eastern South, Highland	113	21	92	1,008,488	5	81	27
Economic Zone of Southern	33	13	20	1,793,503	8	16	9
Mekong River	109	18	91	821,828	3	75	31
Total	660	204	456	7,384,701	38	391	231

Huge potential for landfill closure remains within Vietnam, requiring the consumption of vast natural resources like sand, clay, and aggregates, because of the current scenario of there being less aftercare of landfills in Vietnam. This scenario could be used to utilise secondary waste materials in the landfill closure construction process. Particular waste streams that could be involved in the landfill capping construction at various layers were brick waste (BW), construction demolition waste (CDW), fly ash (FA), rice husk ash (RHA), glass waste (GW), and manufactured sand (M-sand/MS). Among the waste-based alternatives, it would be important to identify sustainable, low global warming potential and low environmental footprint carrying materials, considering the climate change situation. Vietnam is one of the world’s largest rice-producing countries, which produced 42.8 million tons in 2017. Based on its production, in 2017 Vietnam had generated approx. 15 million tons of rice husk [42]. The study [43] suggested that utilising rice husk ash combined with lateritic soil decreased the liquid limit percentage and increased the plastic limit to some extent. Also, rice husk ash exhibits inert characteristics, which makes it a safe waste for secondary applications [7,44]. With a rising population of 100 million and a rapidly growing economy with annual GDP growth of around 7%, Vietnam has forecasted that the power generation will rise from the current 47,000 megawatts (MW) to 60,000 MW by 2020 and 129,500 MW by 2030 [45]. At present, the power stations in Vietnam produce about 13 million tonnes of fly ash and plaster per year. Among these, only 38.9% were being used as raw material. The primary product utilizing coal fly ash in Vietnam is gypsum boarding, used in civil construction [46]. Fly ash is composed of fine particle residue emitted from the boiler along with flue gases in the plant as non-combustible, which are captured by electrostatic precipitators or particle capture units before the chimney discharge. It is probably the most studied waste as an alternative material for the construction of landfill liners and covers [47–49]. Research studies indicated that fly ash as a single material could not be used as a liner to achieve a k < 10^{-9} m/s [50,51]. According to [52], waste brick with mortar and concrete waste forms a major share of about 51% of Vietnam's construction sector waste. These waste materials could be used as a partial or complete substitute for capping layers such as drainage, mineral sealing, and recultivation. The study [53] highlights that construction and demolition waste is not yet a relevant waste flow that can be used in Vietnamese cities, as it will increase in volume substantially only starting in 2040. Considering this delayed material recovery, it would be a viable opportunity to consider other waste streams as well in the coming years, before utilizing the construction and demolition waste intensively post-2040.

In general, recycling the secondary waste requires energy inputs, which helps to convert the waste into aggregates for utilising in construction applications replacing energy-intensive natural aggregates. Waste material utilisation could provide environmental benefits [54]. Thus, the scope of the study was to identify feasible substitutive building materials in Vietnam to replace primary raw materials for the sealing layer and to subject potentially suitable materials to a pre-feasibility test and environmental assessment through Life Cycle Assessment (LCA). This study remains one of its kind based on the non-availability of similar studies with relevance to the region and the application as well.

2. Materials and Methods

Figure 2 summarizes the approach for the study on different mineral sealing layer alternatives. The details are described hereafter.

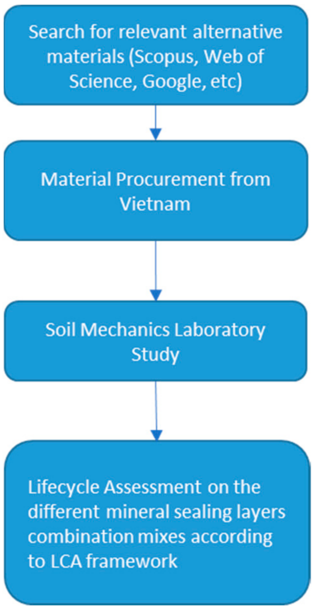


Figure 2. Structured approach for the study on different mineral sealing layers' alternatives.

The study used primary as well as secondary data for the assessment of the environmental effects of secondary building materials as sealing layers for landfills. Primary data were obtained from soil mechanical lab studies while secondary data were obtained from literature, as well as from using the LCA database. While the LCA assessment of fly ash used mainly literature data, the pre-feasibility assessment of milled brick and rice husk ash was based on lab tests as there was no literature source yet that determined the relevant soil mechanical data, particularly in material mixtures as well as for landfill sealing layers.

2.1. Prefeasibility Analysis: Soil Mechanical Test

Geotechnics includes soil mechanics, rock mechanics, and engineering geology [55]. From the engineering aspect, soil is considered to be any loose sedimentary deposit, such as gravel, sand, silt, clay, or a mixture of these materials [56]. The scope of the investigation was to identify feasible materials or material mixes that can be used as substitutive building materials for the sealing layer of the landfill capping system. Regarding the legal requirements for the landfill sealing layers, the demands of the German Landfill Act (Dep V, 2009) [57] were considered. According to that legislation, landfills were divided into classes, depending on their hazard potential. Class I refers to "Above-ground landfill for moderately contaminated excavated earth and rubble and comparable mineral commercial waste". Class II refers to waste with a higher level of pollutants that also has a higher biological content than that in landfill class I. Higher landfill classes refer to hazardous waste landfills that are anyhow excluded from the implementation of substitutive building materials.

The general approach to the pre-feasibility assessment of the substitutive building materials comprised the following steps:

- Selection of potential materials that are available in large amounts in Vietnam and are considered residues based on literature research;
- Procurement of these materials and performance of a general soil mechanical characterisation of the pure materials;
- Development of mixture scenarios for the materials based on their properties and existing experiences;
- Soil mechanical investigations for several mixture scenarios to assess feasible mixtures that meet the requirements of the existing legislation on landfill sealing layers;
- Those mixtures that met the legal requirements for landfill sealing layers in terms of hydraulic conductivity have been considered for potential implementation and, in this regard, for the LCA.

The key parameter for the assessment of leachate formation through a sealing system or component is the hydraulic conductivity of the sealing material. It describes the gravitational flow rate at which water seeps into the ground through interconnected voids of materials, described in hydrology through the permeability coefficient kf [58]. The German legislation for surface sealing systems requires kf $\leq 5 \times 10^{-9}$ m/s for landfill class I (simple landfills for construction rubble) and kf $\leq 5 \times 10^{-10}$ m/s for class II (pre-treated municipal waste landfill). The investigations have been performed according to the existing German (Deutsches Institut für Normung) DIN norms, summarized in Table 2.

Table 2. DIN norms applied for the soil mechanical lab tests.

Parameter	Methodology	According to Norm
Water content	The water content was determined based on DIN 18121 Part 1 by oven drying. The sample in its natural state was weighed and then dried together with a pan in the Memmert drying oven at 105 °C. After cooling, the sample was weighed again. The mass difference corresponds to the amount of pore water evaporated by oven drying.	DIN EN ISO 17892-1
Grain density	The test procedure for determining the grain density using a helium pycnometer is regulated by DIN 66137-2: Gas pycnometry.	DIN 66137-2 (analogue to ASTM D854)
Grain size distribution	The grain size distribution was determined using a combined dry sieving with a sieving machine (mesh size (mm): 8, 4, 2, 1, 0.5, 0.25, 0.125, and 0.063) and areometer (elutriation) to classify very fine fraction.	DIN 18123 (analogue to Particle-Size Analysis of Soils ASTM D422)

Table 2. *Cont.*

Parameter	Methodology	According to Norm
Hydraulic permeability	The hydraulic permeability was determined through falling pressure height in a triaxial cell, as given in the procedure of DIN 18130. In parallel, the hydraulic conductivity was estimated from the grain size distribution for validation.	DIN 18130
Loosest layering	The loosest storage was determined with a trowel. The result was calculated as the mean of 5 individual tests.	DIN 18126 (analogue to ASTM D4254)
Densest layering	The impact fork test was carried out. The result was calculated as the mean of 3 individual tests.	DIN 18126 (analogue to ASTM D4253)
Retention curve (contains information on field capacity, welting point, and air capacity)	The retention curve was determined according to DIN EN ISO 11274:2019. A kaolin box was used to determine the degree of saturation at a pressure of 1.8 pF and 2.5 pF. The pressure plate extractor was used to determine the degree of saturation at a pressure of 4.2 pF. To determine the retention curve, the samples were installed with a dry density of 0.175 g/cm^3.	DIN EN ISO 11274

For the lab study, the selected materials were Asian rice husk ash and milled brick waste. Moreover, fly ash was taken into consideration as a potential sealing layer, based on wide relevance and usage among similar construction applications that had already proved the hydraulic conductivity of that material type [59,60]. The mix ratio for the mineral sealing layer was elaborated in Tables 3 and 4. The alternative materials were made as a partial replacement for the conventional layer in different mixes.

Table 3. Mix ratio for milled brick (MB) used in lab testing.

Mixture	Milled Brick (%)	Clay (%)	Fine sand (%)	Bentonite (%)
MB 1	43	54	1.5	1.5
MB 2	54	43	1.5	1.5
MB 3	50	50	-	-
MB 4	75	22	1.5	1.5
MB 5	25	72	1.5	1.5
MB 6	97	0	1.5	1.5

Table 4. Mix ratio for rice husk ash (RHA) used in lab testing.

Mixture	RHA (%)	Milled Brick (%)	Clay (%)
RHA 0 (pure)	100	-	-
RHA 1	20	20	60
RHA 2	40	20	40
RHA 3	40	20	20
RHA 4	20	-	80
RHA 5	40	-	60
RHA 6	60	-	40
RHA 7	80	-	20

2.2. LCA

Life Cycle Assessment (LCA) is the most widely used holistic methodology, a multi-stage process, whose detailed definition is given in the International Standards in the series ISO 14040. According to ISO 14040, LCA is defined as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [61]. The UNEP/SETAC Life Cycle Initiative defines LCA as "a technique that is used to assess the environmental aspects associated with a product over its life cycle" (UNEP/SETAC, 2011). The combination of individual processes (unit processes) that form a product's life cycle is called the 'product system' [62]. LCA aims to evaluate the environmental burdens of a product or a process. Thus, it can be applied for various purposes, including identifying the source of environmental impacts associated with a product, comparing similar products, designing new products, etc. Other major applications of LCA to products include green purchasing, eco-labelling, and eco (green)-design [62]. LCA studies can also be used in support of complex business strategies and decision-making, government policies, or sector-level initiatives. LCA serves to express the potential environmental impacts and damages associated with a product or service system in a way that supports comparisons between alternatives, both at the level of the individual substance emission and at the level of the entire studied system [63]. Figure 3 illustrates the LCA methodology used in this study [64].

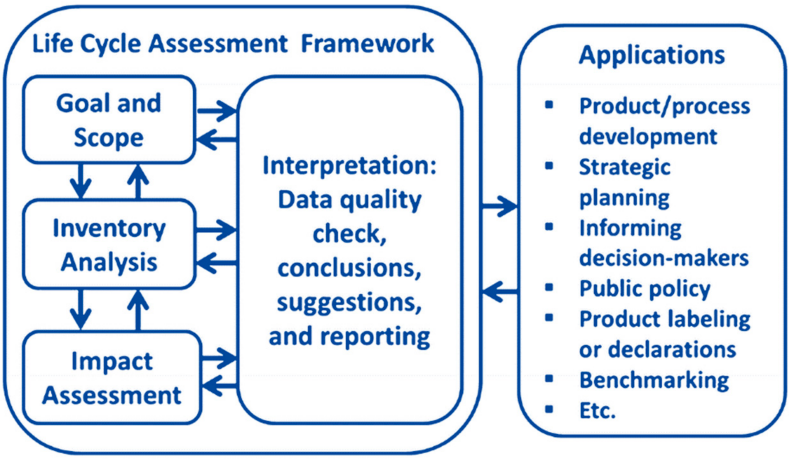


Figure 3. Life Cycle Assessment Framework Structure (Source: [64]).

LCA has a structured four-stage framework:

- goal and scope definition;
- life cycle inventory;
- life cycle impact assessment;
- interpretation.

The LCA is especially effective in comparing products, e.g., building materials that differ in their raw materials composition but have the same functionality [65]. In such cases, LCA can serve as a basis for decision-making to improve sustainability in the construction industry [66].

The life cycle assessment was carried out using the "Ecoinvent 3.6" database and the software "Simapro 9.2". The software provided a user interface, the environmental information from the Ecoinvent database, and the options for the impact assessment method. The choice of assessment method was "ReCiPe 2016 Midpoint (H) V1.04/World (2010) H" because of its wide range of preferences among several LCA studies and guidelines as well [67–69].The midpoint method also has low variation in understanding the impact categories than the endpoint method or even in a single score indicator [70].

2.2.1. Goal and Scope

This study involves the utilisation of the LCA tool to calculate and analyse the environmental impacts of different landfill mineral sealing layers using conventional and secondary raw material materials relevant to Vietnam. The studied alternative materials could be used to partially or completely replace conventional raw materials such as clay and bentonite in landfill capping applications. Using the LCA tool, the environmental footprints of the secondary raw material-based layers were compared with each other and with the corresponding conventional layers. The primary goal of this study was to evaluate the potential environmental benefits of using secondary residual materials and determine which of the alternative mixes was relatively more or less sustainable. This study used transport distances from cradle to gate as 30 km for normal building materials and 65 km for ashes.

2.2.2. Functional Unit

The functional unit for the study was the mineral sealing layer in the landfill capping. The functional unit was a mineral sealing layer of a thickness of 0.6 m (before compaction) for an area of 1 hectare for several variants of a mineral sealing layer to be replaced by alternative materials mix utilising fly ash, brick waste, rice husk ash, construction and demolition waste, and brick waste. The materials considered in the study were in the majority produced outside of the landfill area. In this LCA analysis, only the production stages involved in the supply of raw materials and alternative materials were considered. Therefore, this is called the cradle-to-gate approach (Figure 4). The onsite installation process, geosynthetic layer, drainage layer, recultivation layer, and service life of landfill capping layers in conventional or alternative caps were assumed to be similar, so they were not considered in the analysis. The system boundaries for both conventional and alternative layer mixes included the production of raw materials such as the extraction of natural aggregates, their processing, waste processing, and transport to the site. The volume of materials required to fill 6000 m^3 of a mineral sealing layer of 0.6 m thickness over a 1-hectare area was estimated based on the density values from Table 5.

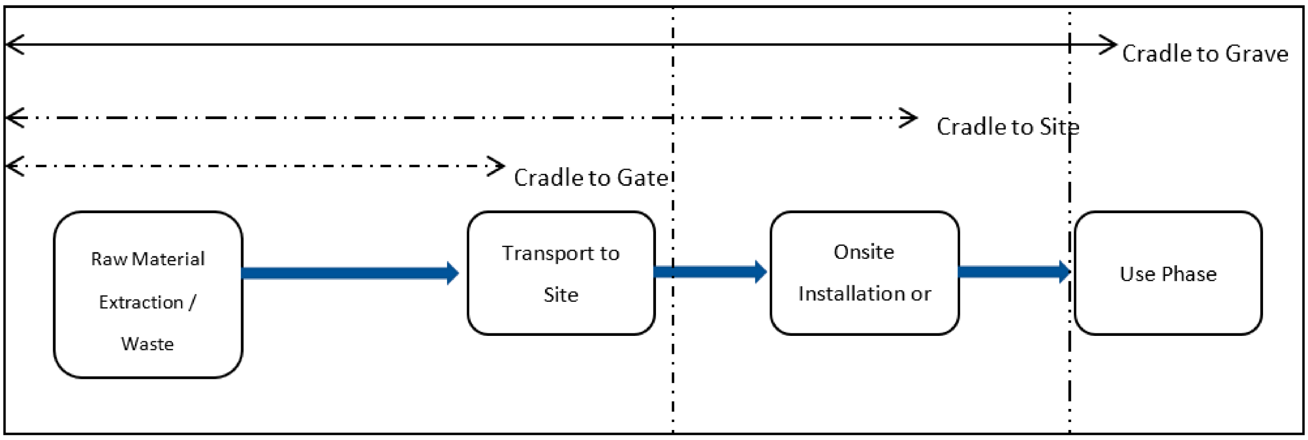


Figure 4. System Boundary Description—Cradle to Gate.

Table 5. Density of materials used in the mineral layer comparative LCA study.

Materials	Density (t/m^3)	Reference
Clay	1.76	[71]
Bentonite	1.50	[72]
Brick Waste	2.00	[73]
Fly Ash (closely packed)	1.20	[74,75]
Rice Husk Ash	2.11	[76]

2.2.3. Life Cycle Inventory

LCA is a very data-intensive methodology because a typical life cycle of a product or service covers thousands of human activities, which must be understood and documented in environmental relevance material and energy flows [77]. The collection of this information is usually a tedious process. Thus, good background data and foreground data are important. Such information is available worldwide in the Ecoinvent database. The life cycle inventory (LCI) information involving material and energy flows considered for the processes in the study were obtained from the "Ecoinvent" database and literature. Most data were used from the Ecoinvent database, well-known for the data quality and consistency on a global production processes level [77]. The database has more relevant information for the building material sector [78], covering material and energy flows for the selected conventional materials' production, transportation to places, fuel production, and treatment or processing of alternative waste materials.

The selected unit processes for the LCI were modified for energy and water consumption, and emissions of geographic relevance to the study. The usual landfill disposal prevention of alternative waste materials was not included in LCA as it avoided the process scenario according to the European standards and other similar studies [15,79]. In construction applications, the transportation of materials causes a substantial contribution to the environmental footprint [15,80,81]. Considering the information from the region, project partners, and discussion with Vietnamese partners, a relatively short distance for material transportation is about 30 km for all materials, except slag and ashes which was assumed to be 65 km in this study. The transport using Euro 4 type trucks with a payload capacity of 16–32 tons was assumed for all materials.

Table 6 shows the primary materials flow unit process involved in the landfill mineral sealing layer construction as a part of capping. The clay extraction, bentonite production, and alternative waste recycling inventory involved the generic global data from Ecoinvent and Agri Footprint. The guidelines [82] proposed an equivalent distribution method for the impact assessment for waste recycling. However, this method was not adopted in this study because it does not consider the relative weight of inputs and outputs for energy and material flows in the product system and the non-availability of geographic relevance data. The waste ashes have been given zero allocation; therefore, the associated impacts are mainly from the transport involved. A transport distance of 30 km for building materials and 65 km for coal ash and rice husk ash were considered.

2.2.4. Life Cycle Impact Assessment

The study adopted the ReCiPe 2016 Midpoint method to assess the various impacts and the cumulative energy demand method for energy use analysis. The method was introduced in 2008 [83] and combined the strengths of other methods such as CML and Eco-Indicator 99 [84]. The primary objective of the ReCiPe method was to transform the long list of life cycle inventory results into a limited number of indicator scores. These indicator scores express the relative severity of an environmental impact category. This method was chosen because of its advantage with a broad set of midpoint categories and utilising an impact mechanism with global scope [85]. Despite the main impact category, global warming potential, land use and mineral resource scarcity, other relevant categories were also included (Table 7). The energy demand scenario analysis was carried out using the method "cumulative energy demand (CED) V1.11" in Ecoinvent, representing the direct and indirect energy use in the MJ unit throughout the life cycle. The method is based on higher heating values (HHV) [86].

Table 6. Unit Processes used for LCA from Ecoinvent.

Unit Process	Changes Made		
Bentonite quarry operation RoW | APOS, U	Water, unspecified natural origin, VN Electricity, medium voltage (VN) | market for electricity, medium voltage | APOS, U Emissions—Water, VN	Water and Electricity input changed to Vietnam region Water emission changed to Vietnam Region	30 km
Claypit operation RoW | APOS, U	-	-	
Sand quarry operation, extraction from river bed IN | APOS, U	Water, unspecified natural origin, VN Electricity, medium voltage (VN) | market for electricity, medium voltage | APOS, UEmissions—Water, VN	Water and Electricity input changed to Vietnam region Water emission changed to Vietnam Region	
Treatment of waste brick, recycling RoW | APOS, U	-	-	
Market for transport, freight, lorry 16–32 metric ton, EURO4 RoW | APOS, U			
(Coal Ash) Electricity production, hard coal TH | APOS, U	Water, unspecified natural origin, VN Emissions—Water, VN	Water input changed to Vietnam region Water emission changed to Vietnam Region Zero allocation for ash as waste	65 km
(Rice Husk Ash) White rice (raw), at processing/CN Mass	Agri FootPrint—5/zero allocation Ecoinvent—Water, unspecified natural origin, VN Ecoinvent—Emissions—Water, VN	Water, unspecified natural origin, VN Rice, at farm/VN Mass Zero allocation for ash as waste	
Market for transport, freight, lorry 16–32 metric ton, EURO4 RoW | APOS, U			

Table 7. Different Impact categories selected from ReCiPe.

Category Group	Impact Category	Category Indicator
Climate Change	Global warming potential	kg CO_2 eq
Depletion of Abiotic Resources	Mineral Resource Scarcity Fossil Resource Scarcity	kg Cu eq kg oil eq
Acidification Eutrophication Particulate Matter	Terrestrial Acidification Freshwater Eutrophication Fine Particulate Matter Formation	kg SO_2 eq kg P eq kg PM2.5 eq
Ozone	Stratospheric Ozone Depletion Ozone Formation Terrestrial Ecosystem	kg CFC11 eq kg NOx eq
Cumulative energy demand	Cumulative energy consumption	KJ

3. Results and Discussions

3.1. Soil Mechanics Result

The lab resultsfor the potential sealing layer material indicated very low permeability values for some mixtures of about 10^{-10} m/s that meet German quality requirements which require $k \leq 5 \times 10^{-9}$ m/s for landfill class I and $k \leq 5 \times 10^{-10}$ m/s for class II [54]. The interim conclusion was that we could add the rice husk ash and milled brick as substitutive materials up to 40 % of the sealing mix to reach the required hydraulic conductivities. The following soil mechanical parameters have been determined:

w (-) water content

ρs (g/cm3) installation density
ρPr (g/cm^3) proctor density
wPr (-) Water content at proctor density
kf (m/s) hydraulic permeability
FC (%) usable field capacity
AC (%) air capacity

The results in Table 8 show that mixes MB 2 and MB 3 were feasible material mixtures to reach the quality requirements for class II landfill mineral sealing systems. The mix MB 1 and MB 5 still reached the quality requirements for class I landfill mineral sealing systems. Meanwhile the mixes MB 4 and MB 6 did not comply with quality requirements and remained unsuitable for sealing applications.

Table 8. Soil mechanical properties of the material mixtures with milled brick.

Mixture	w (-)	ρs (g/cm^3)	ρPr (g/cm^3)	wPr (-)	kf (m/s)	FC (%])	AC (%)	Feasibility
MB 1	0.0072	2.709	1.826	0.1415	1.79×10^{-10}	22.61	4.93	Class II
MB 2	0.0072	2.709	1.791	0.1378	2.66×10^{-9}	28.74	5.64	Class I
MB 3	0.0065	2.718	1.799	0.1393	1.14×10^{-9}	26.30	5.77	Class I
MB 4	0.0058	2.711	1.744	0.1650	1.06×10^{-8}	38.09	5.32	Not Applicable
MB 5	0.0078	2.715	1.791	0.1422	1.71×10^{-10}	34.88	5.42	Class II
MB 6	0.0054	2.700	1.555	0.1891	3.69×10^{-7}	34.95	7.28	Not Applicable

The results in Table 9 show that mixtures RHA 1, RHA 3 and RHA 4 were feasible material mixtures to reach the quality requirements for class II landfill sealing systems. The mix RHA 2 values remained to be eligible for the quality requirements for class I landfill sealing systems. The mixes RHA 5, RHA 6, and RHA 7 did not comply with the quality requirements (Table 9). Further materials have been considered in the LCA study, particularly fly ash, which has already been proven in the past as a feasible substitutive building material for landfill sealing layers [16,18,59,60]. Based on the pre-feasibility verification, the mix in Table 10 was adopted for further LCA assessment.

Table 9. Soil mechanical properties of the material mixtures with rice husk ash.

Mixture	w (-)	ρs (g/cm^3)	ρPr (g/cm^3)	wPr (-)	kf (m/s)	FC (%)	AC (%)	Feasibility
RHA 0	0.1848	1.655	0.184	0	n.m.	7.64	60.50	Not Applicable
RHA 1	0.0081	2.598	1.500	0.2155	5.05×10^{-10}	22.70	9.35	Class II
RHA 2	0.0064	2.407	1.233	0.3125	3.43×10^{-9}	20.87	17.16	Class I
RHA 3	0.0067	2.576	1.530	0.2065	3.56×10^{-10}	25.07	11.22	Class II
RHA 4	0.1043	2.187	1.076	0.3405	4.47×10^{-10}	20.10	3.75	Class II
RHA 5	0.0824	2.179	0.864	0.5148	7.39×10^{-9}	26.97	10.61	Not Applicable
RHA 6	0.0968	2.175	0.998	0.4030	2.04×10^{-8}	29.11	16.67	Not Applicable
RHA 7	0.1756	1.764	n.m	n.m	1.22×10^{-4}	18.88	44.64	Not Applicable

n.m—not measurable.

Table 10. Mix ratio of the different materials for mineral sealing layer used in the comparative study.

	Clay	Bentonite	Milled Brick	Fly Ash	Rice Husk Ash	Sand
Mix 1	97%	3%	-	-	-	-
Mix 2	47%	3%	50%	-	-	-
Mix 3	54%	1.5%	43%	-	-	1.5%
Mix 4	72%	1.5%	25%	-	-	1.5%
Mix 5	50%	-	-	50%	-	-
Mix 6	-	20%	-	80%	-	-
Mix 7	20%	20%	-	-	60%	-
Mix 8	60%	-	-	-	40%	-
Mix 9	60%		20%		20%	

3.2. LCA Analysis

The LCA analysis involved comparing conventional mineral sealing layer mix 1 and alternative material layers (Supplementary Materials S1). The GWP impact results showed that all alternative mixes except mixes 6 and 7 had a lower impact than the conventional mix 1. The higher GWP impacts seen for mix 7, was greatly contributed to by the bentonite material flow, as the mix had 20% bentonite, along with the 65 km transport involved for ash. Mix 5 had the least GWP impact (107,984.38 kg CO_2 eq), with 50% fly ash having zero allocation for its production and the only impact was from the 65 km transport. The impact contribution was 62.7% from the transport process and 37.3% from clay extraction (Figure 5). The LCA analysis for the landfill capping layers highlighted that the greatest environmental footprint contribution resulted from material transportation processes. Thus, sourcing of materials closer to the site is indicated, or using low emission transport alternatives are needed to be considered.

Similarly, mixes 2, 3 and 9 had a lower impact than the other alternatives and conventional mix 1, which could be directly associated with the reduced clay percentage in these mixes (Figure 6). The contribution analysis indicated that the mixes with an ash transport of 65 km had a transportation impact contribution of over 50% to 65%, while the mixes with regular materials with 30 km transport had a 37–46% impact contribution from transportation (Figure 5). This higher contribution from the transportation process remains a concern in similar other studies [87,88]. Mix 2 and mix 3, using brick waste in its composition, had approx. 10% lesser GWP impact than the conventional mineral mix 1. Within mix 2, 30.1% of the GWP impact arose from clay, 8.63% from bentonite processes, and 15.6% from brick waste processes. Meanwhile the composition of mix 3 had 34.80% GWP impact from clay processes, 4.34% from bentonite, 0.89% from sand, and 13.5% from brick waste.

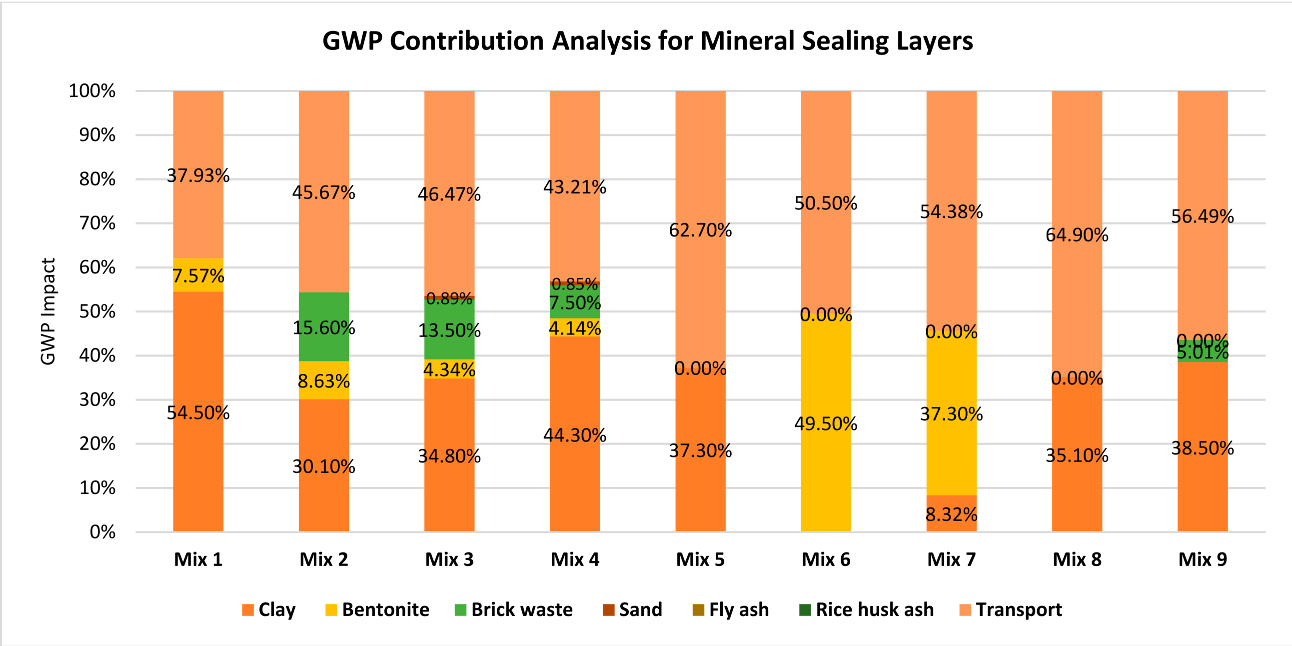


Figure 5. Mineral sealing layer—Contribution analysis for GWP impact category.

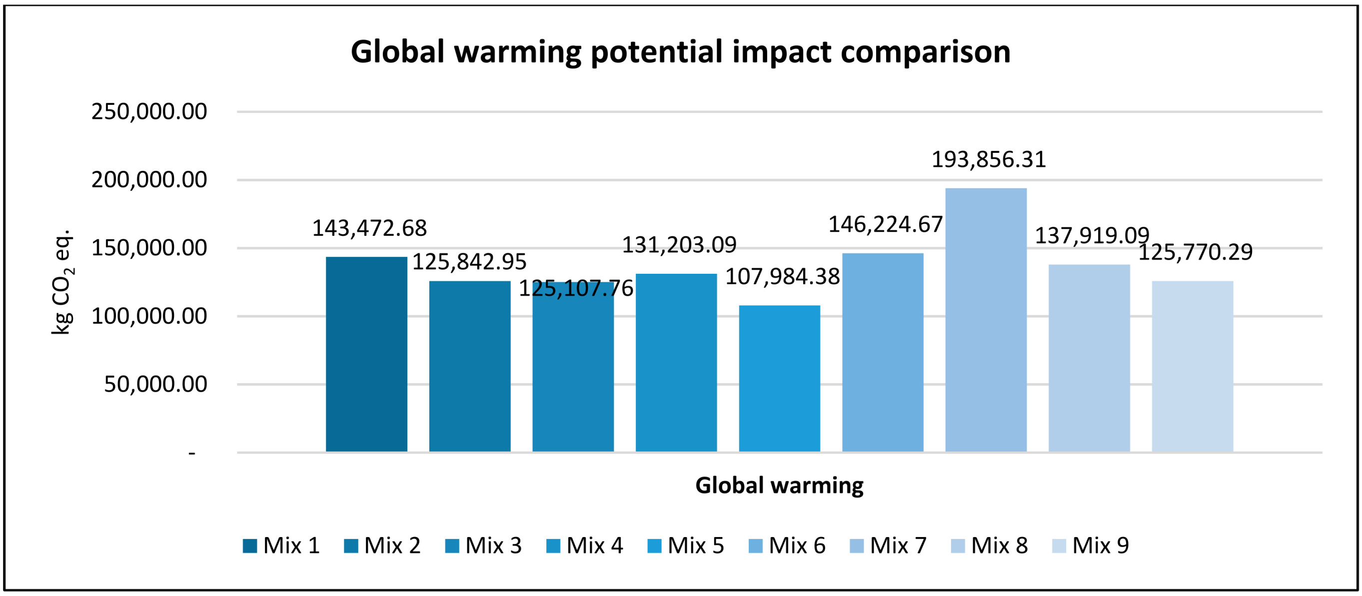


Figure 6. Global warming potential impact comparison between mineral sealing mix combinations.

Overall, mixes 8 and 9, containing rice husk ash at 40% and 20%, respectively, carried an approx. 40% lower GWP impact footprint than the conventional mineral sealing layer (mix 1), while mix 2 has a 50% reduction. In the mineral resource impact category, mix 6 with fly ash 80% had the least footprint, which was about 81.9% lower than mix 1. In general, all the alternative material-based mix layers possessed a lower mineral resource impact footprint than the conventional layer mix (Figure 7). Apart from mix 4 and mix 7 among the proposed alternative mix layers, other mixes on average had 40% lower land use impact than mix 1 (Figure 8). The higher percentage of 72% clay in mix 4 and a higher percentage of 20% bentonite in mix 7 along with ash transport 65 km contributed to this increased impact.

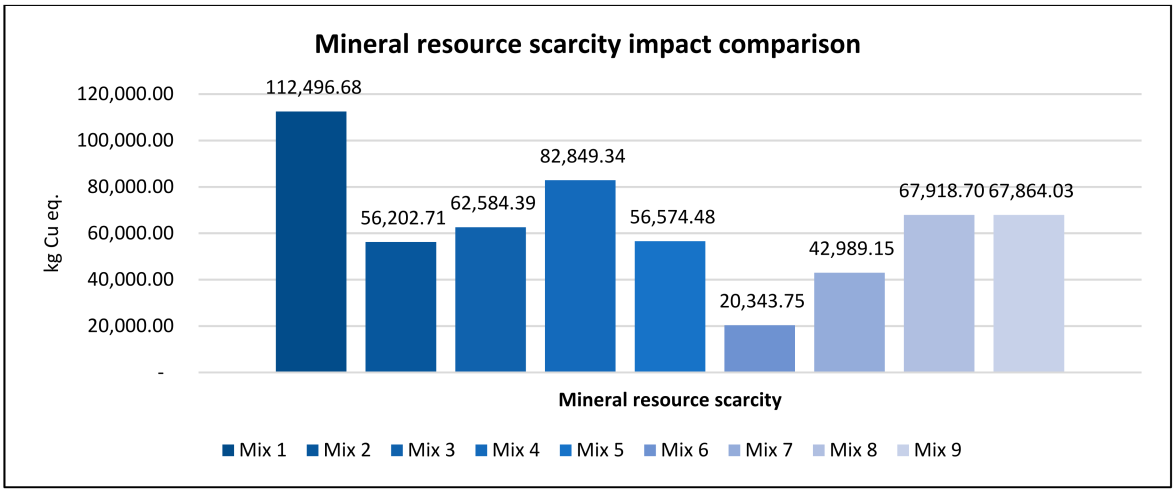


Figure 7. Mineral resource scarcity impact comparison between mineral sealing mix combinations.

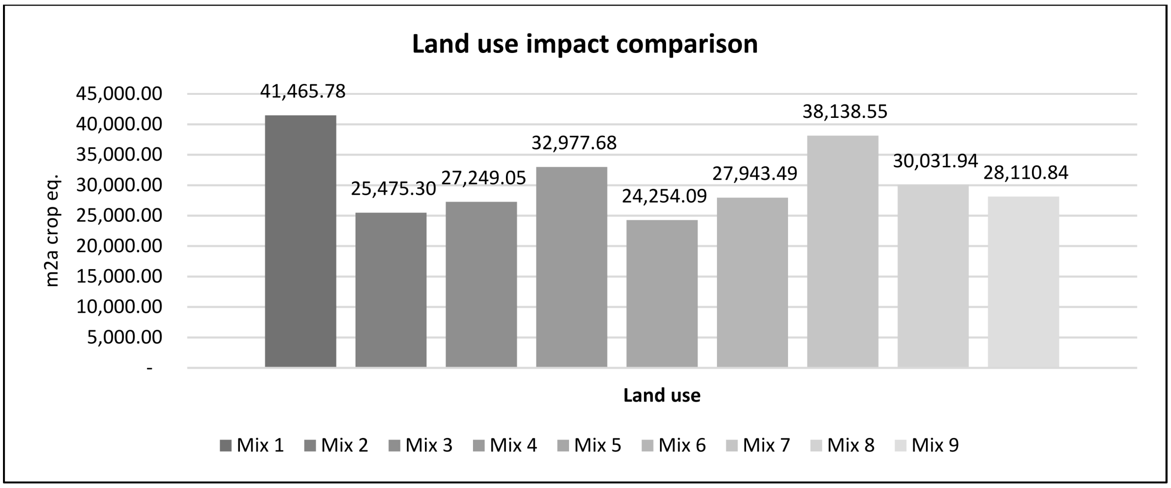
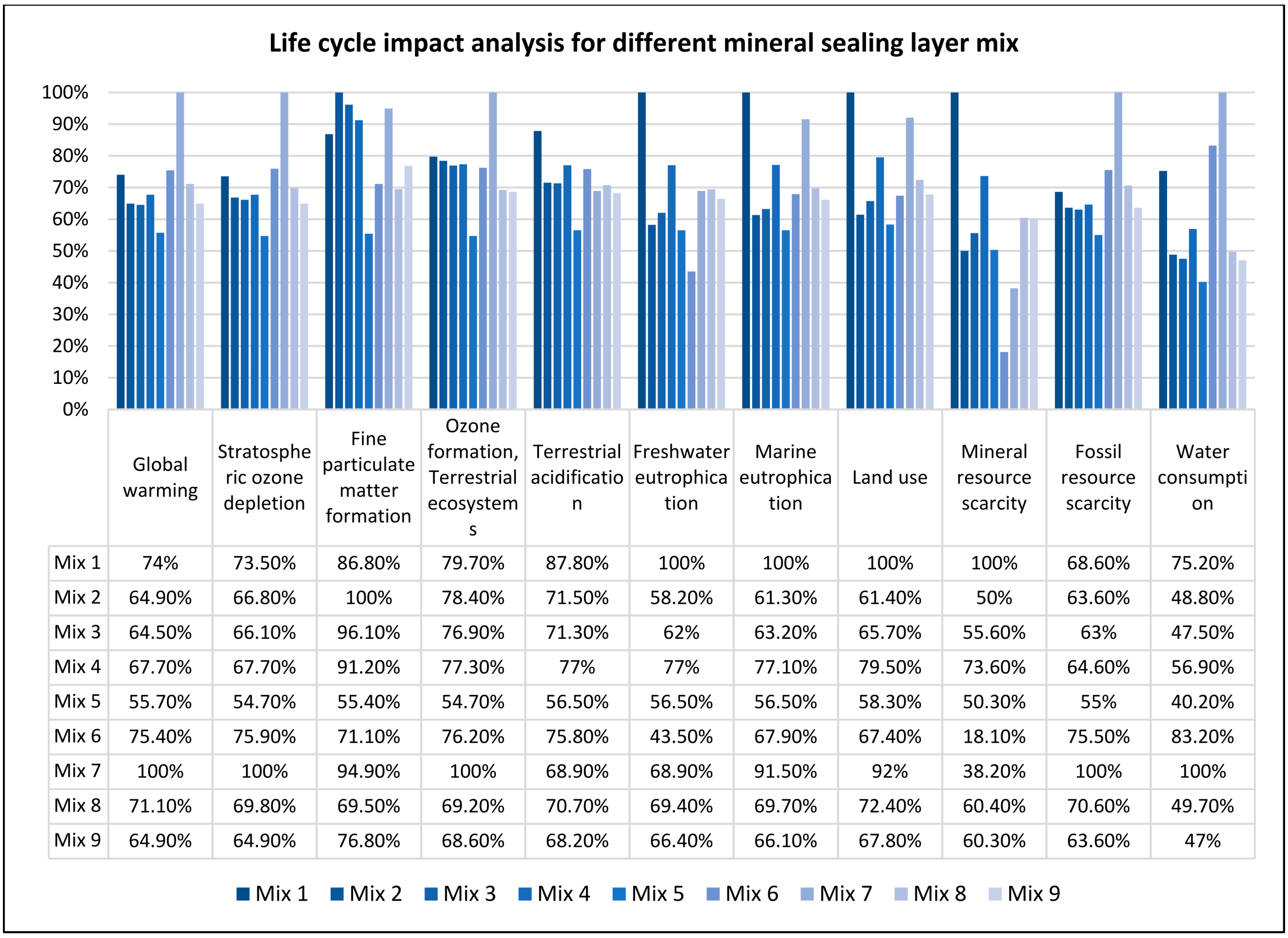


Figure 8. Land use impact comparison between mineral sealing mix combinations.

The impact categories of acidification and eutrophication for the alternative layer mixes remained lower than the conventional mix 1 (Figure 9). Mix 7 posed higher impacts than the other proposed alternatives across categories—global warming potential, stratospheric ozone depletion, fossil resource scarcity, and water consumption. This variation of mixes 6 and 7 was mainly contributed to by 20% bentonite and the 65 km ash transport in the mix recipe. The alternative mixes, except mix 6 and mix 7, contributed 25% less water consumption impact than the conventional mineral sealing mix 1. Overall the utilisation of the alternative materials demonstrated that reusing wastes can lead to a considerable reduction in environmental impacts caused by conventional materials, as commonly discussed in several types of research [89,90].

Mix 5 exhibited a lower energy demand in non-renewable fossil sources (coal), based on the considered unit processes from the Ecoinvent, which was Vietnam's current scenario [91]. Mix 5 had an energy reduction of approx. 45% compared with mix 7 and 15% reduction in comparison with conventional mix layer 1. The alternative mix 6 and mix 7 have higher energy consumption among the mixes in non-renewable fossil sources which were about 2,088,089 MJ and 2,764,583 MJ, respectively (Figure 10). All alternative mixes consume lesser energy in the renewable-based sources than conventional mix 1 (Annex), which showed that the benefits could be higher on moving towards complete renewable energy sources. The cumulative energy demand analysis highlights the need to shift from fossil-based to renewable energy sources, benefiting the environment.



	Global warming	Stratospheric ozone depletion	Fine particulate matter formation	Ozone formation, Terrestrial ecosystems	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Land use	Mineral resource scarcity	Fossil resource scarcity	Water consumption
Mix 1	74%	73.50%	86.80%	79.70%	87.80%	100%	100%	100%	100%	68.60%	75.20%
Mix 2	64.90%	66.80%	100%	78.40%	71.50%	58.20%	61.30%	61.40%	50%	63.60%	48.80%
Mix 3	64.50%	66.10%	96.10%	76.90%	71.30%	62%	63.20%	65.70%	55.60%	63%	47.50%
Mix 4	67.70%	67.70%	91.20%	77.30%	77%	77%	77.10%	79.50%	73.60%	64.60%	56.90%
Mix 5	55.70%	54.70%	55.40%	54.70%	56.50%	56.50%	56.50%	58.30%	50.30%	55%	40.20%
Mix 6	75.40%	75.90%	71.10%	76.20%	75.80%	43.50%	67.90%	67.40%	18.10%	75.50%	83.20%
Mix 7	100%	100%	94.90%	100%	68.90%	68.90%	91.50%	92%	38.20%	100%	100%
Mix 8	71.10%	69.80%	69.50%	69.20%	70.70%	69.40%	69.70%	72.40%	60.40%	70.60%	49.70%
Mix 9	64.90%	64.90%	76.80%	68.60%	68.20%	66.40%	66.10%	67.80%	60.30%	63.60%	47%

Figure 9. Life cycle impact analysis for different mineral sealing layer mix.

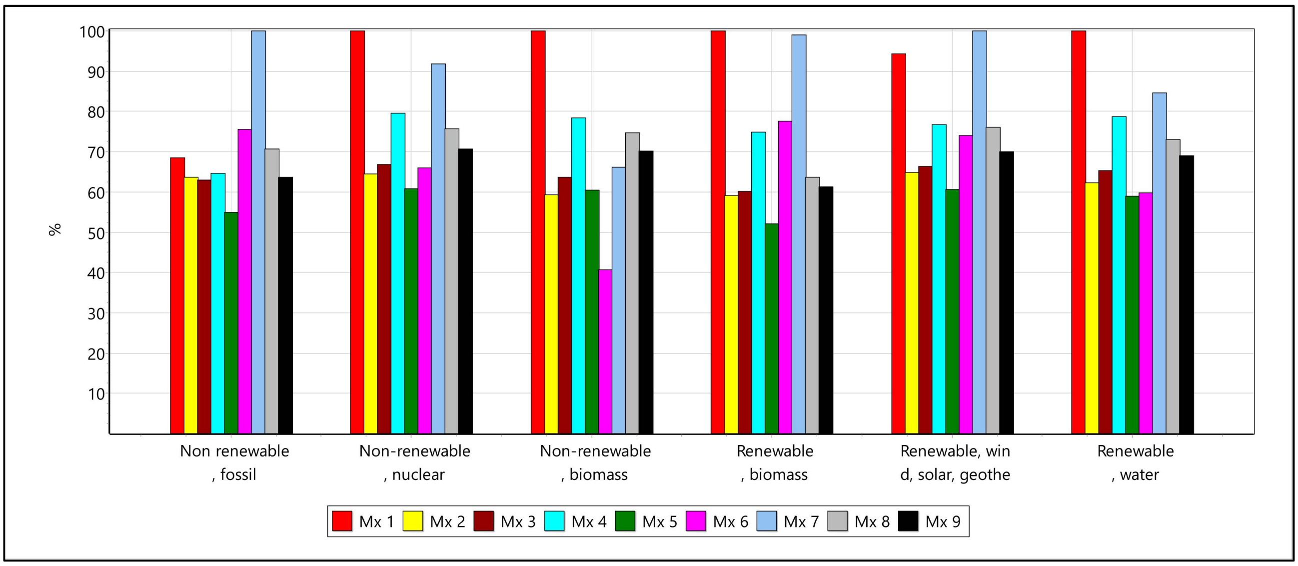


Figure 10. Energy Demand Analysis for different mineral sealing layer materials.

3.3. Future Outlook of Implementation of Waste Materials

After water, sand and clay are important resources in modern societies, as these materials form the main infrastructure building material resource. Having in view the global building material scarcity that is caused by the rapid consumption of primary natural mineral resources, there is a need to fill this gap. One way is the use of secondary building materials made from waste (Figure 11). All over the world, like in Vietnam, the number of landfills is growing. This has caused a growing need for building materials both in the Global North and South, in the landfill sector. Landfill operators increasingly address the material scarcity topic through a request for alternatives. In the present paper, the proposed alternatives focused on ashes and milled brick, material flows that are available not only in Vietnam but also in the rest of Asia. This approach has several environmental and social benefits: material cycles will be closed through recycling activities, environmental awareness will be created at the level of all stakeholders, and new working fields can be established. Moreover, the approach supports economically viable alternatives for building materials that are available close to the landfill site. In particular, rice husk ash offers a variety of beneficial applications in the building sector, including landfill construction.

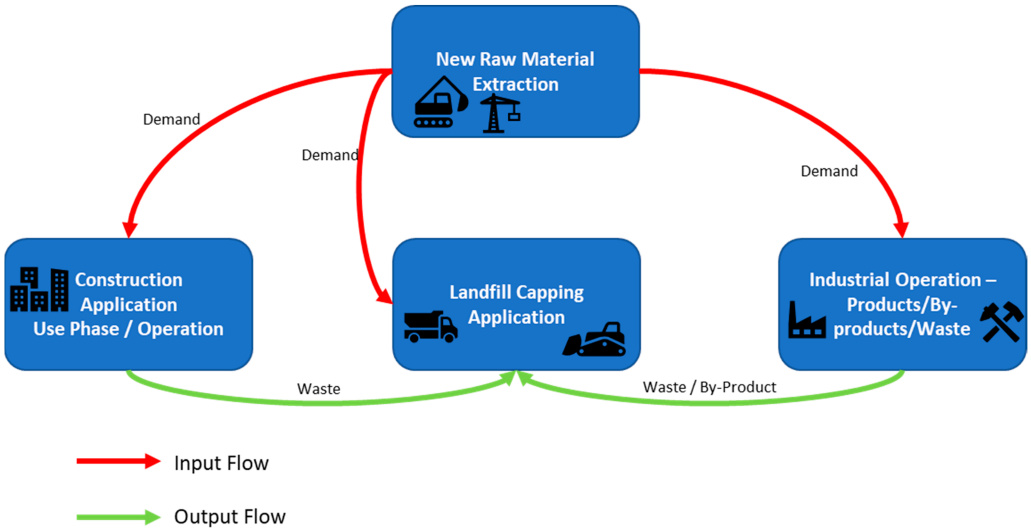


Figure 11. Schematic material demand for landfill sealing applications in Vietnam.

3.4. Limitation

This study remains one of a kind in terms of its relevance to materials' composition used for mineral sealing layer and geographic relevance. A limitation in the study was the LCI data required for the modelling of the LCA. To a great extent, this limitation affected the representativeness of the LCA model to the region. Currently, there is a lack of data relevant for this type of LCA study in Vietnam. The lack of quality data and COVID-19 have placed a constraint on the LCI development, and therefore, the study relies heavily upon the global database from Ecoinvent. Despite new developments in Vietnam in the topic of life cycle assessment, the construction sector authorities and stakeholders should foster life cycle relevant database development for various construction materials on national and regional levels, which could then support the construction sector to adopt a sustainable pathway in the future. The database resource development must focus on the relevance of materials, including basic building materials such as cement, sand, crushed stone, steel, etc., and building materials products such as concrete, mortar, glass, fired clay brick, aerated concrete, etc., the relevance to the region, the data quality and transparency in the availability of the data. The obtained results remain a general overview of the advantages in impact reduction of using secondary raw materials as alternative substitutes in the landfill capping process.

4. Conclusions

This study assessed the potential of secondary raw materials to be used in landfill capping solutions from a resource efficiency aspect. The soil mechanics' results indicated that the secondary raw materials possessed the required permeability capacities for their application as landfill mineral sealing layers at a replacement ratio of up to 50% for milled brick and rice husk ash.

The environmental impacts of utilizing different alternative materials in landfill mineral sealing were analyzed. The study results highlighted the better environmental footprints, especially in the global warming and the mineral resource scarcity impact categories of alternative materials and their specified ratio in substitution. Among the alternatives, the alternative sealing mix containing 20% bentonite carried a higher environmental footprint. The use of secondary raw materials as alternative construction materials provides a significant environmental advantage. It reduced the quantity of virgin raw materials required and promotes the reduction in the quantity of waste materials disposed at landfills. Also, economically, the landfill disposal costs or transport costs of virgin materials from long-distance were reduced by utilizing alternative materials.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app12063063/s1, The following supporting information is presented in S1: Functional Unit for different landfill capping layers used in the study, and Comparing product stages; Method: ReCiPe 2016 Midpoint (H) V1.04/World (2010) H/Characterization.

Author Contributions: Conceptualization, P.S. and N.A.S.; methodology, N.A.S. and P.S.; validation, P.S. and N.A.S.; formal analysis, N.A.S.; investigation, ZAFT e.V HTW Dresden.; resources, N.A.S.; data curation, N.A.S.; writing—original draft preparation, N.A.S. and P.S.; writing, N.A.S. and P.S.; editing, N.A.S.; review, L.H.A., N.T.T. and P.T.M.; visualization, N.A.S. and P.S.; supervision, P.S.; project administration, P.S.; funding acquisition, P.S. All authors have read and agreed to the published version of the manuscript.

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