Advancements in Municipal Solid Waste Landfill Cover System: A Review

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ABSTRACT

Municipal solid waste (MSW) landfill cover systems have evolved from being merely a soil cap to a multicomponent, nearly impermeable systems providing better control over infiltration and landfill gas (LFG) emissions. Recently, there has been a widespread development of alternative cover systems which addresses the shortcomings of conventional cover systems such as high construction and maintenance costs, susceptibility to damage due to desiccation cracking and freezing, and ineffective control of LFG emissions. Landfills are regarded as the third largest source of anthropogenic methane (CH_4) emissions in the United States. Apart from CH_4, landfills are a significant source of various other gases such as carbon dioxide (CO_2), hydrogen sulfide (H_2S) and several other odorous and non-methanogenic organic compounds (NMOCs). The modern engineered landfills typically install gas collection systems in addition to the conventional soil cover to mitigate LFG emissions. However, these systems are not always 100% efficient in capturing all the emissions. Moreover, at the older landfills where installing gas collection systems is not economical and practically feasible, the fugitive LFG emissions is a persistent problem. In this regard, alternative cover systems with wide range of cover materials have been explored to address the fugitive LFG emissions. This paper summarizes the advancements in the MSW landfill cover systems over the years, along with the core mechanisms underlying their function. Then, advancements in the alternative cover systems, including their advantages, are discussed. Finally, the research challenges/opportunities in the field of exploring alternate landfill cover systems are presented.

Keywords: Municipal solid waste; Landfill gas; Landfill odors, Alternative cover systems; Biocover; Biogeochemical cover

1 Introduction

Thousands of tons of municipal solid waste (MSW) are generated annually across the globe, and some of the major contributors are the high-income countries in North America, Europe, and Central Asia (e.g., United States, Russia, Denmark, Switzerland, etc.) contributing about 34% of the total waste generated in the world [1]. In the United States (US) alone, approximately 267.8 million tons of MSW was generated in the year 2017 of which nearly 52% was landfilled [2], making landfills an important part of the waste management system in the country. Landfills have evolved from being mere open dumps to highly engineered and well-regulated waste containment facilities. Resource Conservation and Recovery Act (RCRA) was passed in the US to address the soaring volumes of municipal and industrial waste [3]. Since then, landfill regulations have only been made stricter to limit the environmental pollution from landfill leachate and landfill gas (LFG) emissions.

Modern engineered landfills are provided with nearly impermeable bottom liner and cover systems, gas collection systems, and groundwater monitoring systems to minimize the seepage of leachate and migration of gases into the atmosphere. Placement of waste in the landfill is performed in various stages, and subsequently different types of covers are applied (e.g., daily cover, intermediate cover, and final cover) to prevent exposure of waste to the surrounding environment at different stages of landfill operation. At the end of the day, a layer of soil (~150 to 300 mm thick) is placed over the daily placed and compacted waste as daily cover [4]. Various alternative materials other than soil such as shredded tires, wood chips, removable textile cover or single use plastics are also used as daily cover materials as there are no regulations regarding hydraulic conductivity to such covers [5]. Intermediate covers are applied at those sections of the landfills where another lift of waste will not be placed within 60-90 days of the waste placement. Like daily covers, there are no regulatory requirements governing hydraulic conductivity of the intermediate covers [5, 6]. The final cover is placed when the landfill reaches the designed waste capacity [7]. The primary function of the final cover system is to prevent breeding of rodents and flies, ingress of precipitation into the waste, and migration of harmful gases from the landfill into the atmosphere. The minimum regulations require the landfill cover to have an infiltration layer and an erosion layer, however, landfill cover can have several layers depending on the site conditions, waste composition, and climatic conditions. The conventional final cover systems typically have one or more barrier layers to restrict the infiltration and gas migration [6].

Over the years, various alternative cover systems such as evapotranspirative (ET) cover, capillary barriers, anisotropic cover, and engineered turf cover have been developed as an alternative to the conventional cover systems used in landfills. One of the major advantages of the alternative cover systems is the reduction in construction and maintenance costs associated with the conventional cover systems [6] and mitigation of damage due to physical and biological processes which can further lead to increased infiltration [8]. Apart from infiltration issues, LFG emission is another major issue of landfills. The increasing concerns regarding fugitive CH_4 gas emissions from landfills has led to extensive research on the alternative cover materials which can mitigate the CH_4 emissions. In this regard, the CH_4 oxidation potential of the landfill cover soils was explored extensively by various researchers and the studies related to alternative cover systems have continually evolved to address other gaseous emissions in addition to CH_4.

The main objective of this review is to outline the progressive development of the landfill cover systems over the years. The paper presents a comprehensive summary of the studies exploring alternative cover systems, their benefits, and challenges associated with them. The study also reviews the type of studies (laboratory and field studies) performed to evaluate the performance and efficiency of the different alternative cover systems. In addition, this paper analyzes the underlying mechanisms that govern the functioning of different cover systems and the parameters affecting their performance which can help to delineate the challenges for the current and future research in the field of alternative cover systems for landfills.

2 Cover Design Criteria

As per the United States Environmental Protection Agency (USEPA), the specific functions of landfill cover systems are to minimize vector breeding, control water movement to minimize infiltration and erosion, control harmful gas movement, and minimize fire hazard potentials [9]. The landfill cover regulations mainly focus on minimizing the infiltration into the waste until the confined waste ceases to cause impermissible threat to human health and environment [10]. A post-closure care period of 30 years is mandated for monitoring the integrity of the landfill performance including the final cover system [11]. However, the design life of landfill cover may be longer than the regulatory 30 years post-closure care period which depends on several factors including service life of the materials used in cover construction [10]. Other than using durable materials for cover construction, an adequate cover design involves ensuring the stability of the veneer slope, sufficient internal drainage, surface-water runoff controls, surface erosion protection, freeze-thaw protection, and ability to sustain sufficient vegetation [10]. Some of the important aspects of cover design are explained in the following sections.

Infiltration

One of the primary functions of landfill cover system is to restrict the percolation of water into the waste and minimize the amount of leachate generated in the landfill. Increased infiltration leads to increase in leachate head at the landfill bottom liners thereby increasing the potential for seepage which can possibly cause landfill slope failures and subsurface contamination. When the precipitation exceeds runoff, evapotranspiration (ET) and any storage in the cover materials, the water infiltrates into the waste. There are several water-balance models developed for wide range of hydrologic problems. One of the water balance programs specifically developed for water balance analysis of landfills, cover systems, and solid waste disposal and containment facilities is Hydrologic Evaluation of Landfill Performance (HELP) model [12]. USEPA requires hazardous and nonhazardous waste facilities to use HELP model to assess closure designs [13]. The model is applicable for open, partially closed, and fully closed waste containment facilities. The model takes into account various components of the landfill such as vegetation, cover soils, waste cells, drainage layers, barrier layer, and geomembrane (GM) liners, and provides estimates for runoff, evapotranspiration, drainage, leachate collection, and liner leakage [13]. Unsaturated soil water and heat flow model (UNSAT-H[14]), HYDRUS [15], and Finite Element subsurface FLOW simulation system (FEFLOW[16]) are some of the computer programs used for simulating water balance for landfill cover systems.

The RCRA regulations require landfills to provide ~45 cm (18 inches) thick barrier layer to minimize infiltration in an MSW landfill. However, in practice, a drainage layer made of granular soil or geosynthetic material (e.g., geotextile) is provided above the barrier layer or infiltration layer to intercept the infiltrating water and minimize percolation into the barrier layer and underlying waste. The drainage layer should have adequate flow capacity to minimize the buildup of hydraulic head on the barrier layer [10].

Gas Emissions Control

The waste undergoes decomposition in different phases in the landfill and generates huge amount of leachate and gases (mainly CH_4, CO_2 and trace amounts of NMOCs. The gas generation in the landfill depends upon waste composition, age of waste, presence of oxygen, moisture content and temperature [17]. Various models have been developed to predict the gas generation, gas composition, and spatial variability of gas generation in landfills, and are mostly based on the zero, first or second order decay kinetics [7]. One of the most popular and simplified mathematical tool for estimating LFG emissions from MSW landfills is Landfill Gas Emissions Model (LandGEM) developed by USEPA. It is based on the first-order decay equation (**Eq. 1**) and is used for quantifying annual LFG emissions over a period in an MSW landfill [18].

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_0 \left(\frac{M_i}{10}\right) e^{-kt_{ij}} \qquad (1)$$

where,

Q_{CH_4} = annual CH_4 generation in the year of calculation (m^3/year)

i = 1 year time increment

n = (year of the calculation) – (initial year of waste acceptance)

j = 0.1 year time increment

k = CH_4 generation rate ($year^{-1}$)

L_o = potential CH_4 generation capacity (m^3/Mg)

M_i = mass of the waste accepted in i^{th} year (Mg)

t_{ij} = age of the j^{th} section of waste mass M_i disposed in the i^{th} year (decimal years, e.g., 2.2 years)

The LandGEM model provides an estimate of the gas generation during the waste placement years, the corresponding emission rates, and an estimate for the waste stabilization period as well. **Fig. 1** shows the annual LFG emission rates for an MSW landfill with waste capacity of 60,702 megagrams (Mg) and annual waste input of 2,500 Mg/year. As shown in **Fig. 1**, LFG generation persists for a longer duration even after the closure of the landfill.

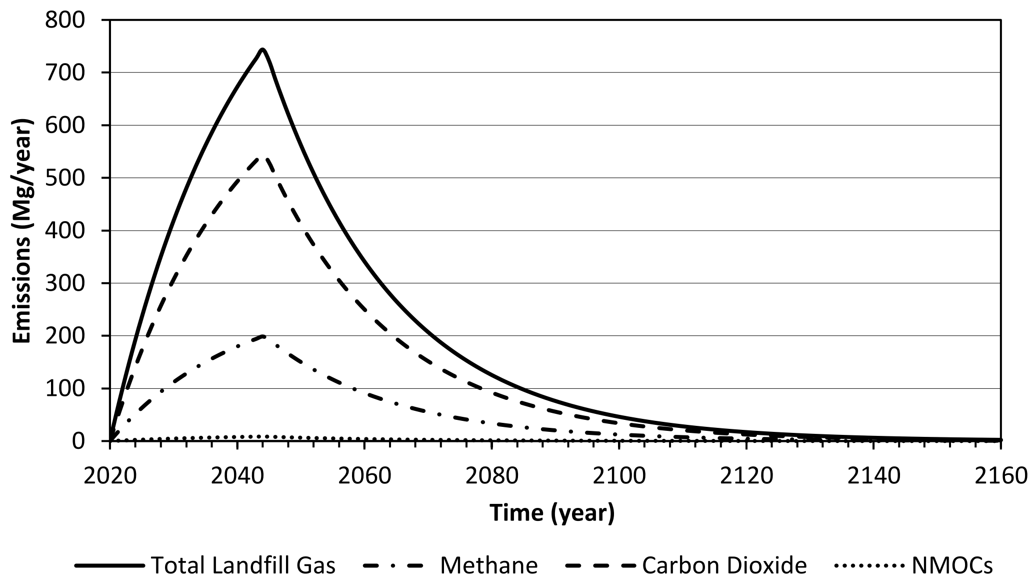


Figure 1. Landfill gas generation estimated by LandGEM model.

The LFG migrates laterally and upwards through the landfill side walls and cover surface. Generally, landfill covers are placed to restrict the upward migration of the gases however, upward restriction leads to horizontal migration along the waste layers, ultimately making their way to the areas outside of the landfill [17]. Some of the major factors affecting the migration of gases in the landfills are diffusion, pressure gradient, permeability, and temperature [17, 19]. Diffusion is the movement of gases from areas of high concentration (within landfill) to the regions with relatively lower concentration of the gases (e.g., atmosphere). The LFG is generated in significant amounts and the gas movement is generally restricted by the compacted waste and soil cover which leads to increase in gas pressure. This causes the advection of gases under the pressure gradients. Specifically, the LFG tends to migrate through the path of least resistance. Hence, they tend to migrate easily through coarse grained soils while the fine-grained soils like clay offers more resistance to the flow. Temperature or heat generation during waste decomposition also affects the migration of the gases [19]. Hence, the landfill cover should be designed to control migration of LFG and prevent hazards associated with LFG. The federal regulations (40 CFR part 60) require MSW landfills to install gas collection and control system within 30 months after LFG emissions exceed a NMOC emissions rate of 34 Mg/year [20]. Active and passive gas control systems are provided in modern landfills to control LFG emissions. The passive systems divert the gas to a collection point or vent by natural pressure gradient (advection mechanism), and active systems apply vacuum to channel the gas to the collection point [6].

Slope Stability

Landfill covers are constructed with slight inclination to facilitate surface runoff and minimize ponding. Generally, the cover is designed to have a minimum slope of 2 to 5% at top deck as the slopes flatter than 2% may lead to ponding of water in the event of localized settlement [10]. However, steeper slopes are also not recommended as the potential for erosion and slope failure increases with increase in inclination [10]. The side slopes are made steeper with a typical slope of 2H:1V in case of soil cover, and 3H:1V or flatter in case of cover with geosynthetics [6]. Veneer slope failure is one of the commonly observed slope failures in landfills. Hence, landfill cover should be designed to have sufficient stability during and after construction. Rigorous analysis of slope stability should be performed by considering the shear strength of each component, expected loading, and seepage pressures [21]. Similarly, the cover system incorporating geosynthetics should be analyzed for interface slope stability as the stability is often impacted by the interface shear strengths of the materials [6]. If the landfill is located in a seismic zone, the landfill cover slope should be designed for seismic slope stability along with the static slope stability. Similarly, the MSW landfills generate gases in huge amount which may exert pressure on the landfill cover thereby challenging their stability. Hence, the slopes should be stable against the gas pressures that may develop in the cases when gas wells are not functioning properly or are damaged or clogged due to perched leachate.

Runoff Control and Erosion Protection

Drainage and runoff control is a key aspect of landfill cover design. It is utmost important to minimize run-on into the active portion of the landfill as it may generate excess leachate. The typical runoff management strategies include construction of diversion berms, downslope flumes or channels, perimeter ditches, culverts, sedimentation, or detention basin. Diversion berms shorten the slopes, reduce erosions, and divert the runoff water. The downslope flumes carry runoff water from diversion berms to the perimeter diches through the side slopes. They should be designed carefully to accommodate the runoff velocities. The downslope channels are susceptible to erosion from runoff and hence should be lined with riprap or reinforcement. Each element of storm water management system should be designed carefully as it may affect the overall stability of the landfill. The erosion potential varies according to climatic conditions. Covers in arid and semi-arid areas, and in steep slopes are more prone to erosion as these sites offer poor support for vegetation [10]. The cover should have sufficient vegetation as it substantially reduces the potential for surface erosion, reduces surface runoff velocity, and binds the soil strongly with root action. In the locations on the landfill (e.g., steep slopes) and for the landfills located in climatic conditions with higher erosion potential (e.g. arid and semi-arid regions), erosion control measures in the form of gravel, rip rap, or geosynthetic controls such as geogrids may be provided [10].

Durability

The current landfill regulations in the U.S. mandate a 30 year post-closure after care period, however, the stabilization period for landfill waste may extend for over a hundred years which calls for a requirement of longer design life of landfill components including landfill cover. A properly functioning landfill cover is warranted for eliminating long-term post-closure leachate and gas generation potential of MSW [21]. Landfill cover is subjected to wide range of climatic conditions, and excessive settlements and subsidence. The post-closure total settlement may range from 10 to 20% of the landfill height in an MSW landfill [21]. Hence, it is imperative to consider long-term durability and integrity, and effectiveness in the design of landfill cover system. Similarly, if geosynthetics like GM are part of the cover system, the geosynthetic material should be so chosen which can withstand excessive settlements, corrosive gases, heat, and pressure, and require minimum post-closure maintenance. In addition, while designing alternative cover systems, the material chosen should be stable for the long-term performance of desired function. For example, alternative cover systems such as biocovers are prone to self-degradation if the organic amendment contains unstable carbon thus hindering the CH_4 oxidation potential of the biocover. Therefore, the integrity of the cover components is of utmost importance in the selection and design of the cover system.

Sustainability

Most of the cover systems are designed to limit infiltration and migration of gases, and little regard is paid towards the sustainability of the cover materials and cover system as a whole. Sustainability is often considered equivalent to environmental sustainability and any material which does not engender harmful environmental impacts is considered environmentally sustainable. However, sustainability is not just about environmental impacts. It is an amalgamation of environmental, economic, and social aspects. A sustainable landfill cover system is the one which is technically sound in executing the intended function while causing minimum amount of net environmental, economic, and social impacts. For example, the use of geosynthetics such as GM and geotextile (GTX) are gaining prominence in landfill cover design, but it is not known how sustainable they are in terms of the environmental, economic and social impacts considering their entire life cycle stages (from material acquisition to their disposal). Similarly, in alternative cover designs, the sustainability of the alternative cover components is of prime importance. For example, waste materials such as sewage sludge are commonly used in biocovers for CH_4 mitigation. The waste materials may seem a sustainable choice for landfill cover from economic point of view but its environmental (e.g., leaching toxic chemicals) and social impacts (e.g., odors) need to be assessed before using it in the landfill cover. Therefore, sustainability assessment shall be incorporated in the design and development of the landfill cover systems and the decision-making process.

End Use of Landfill

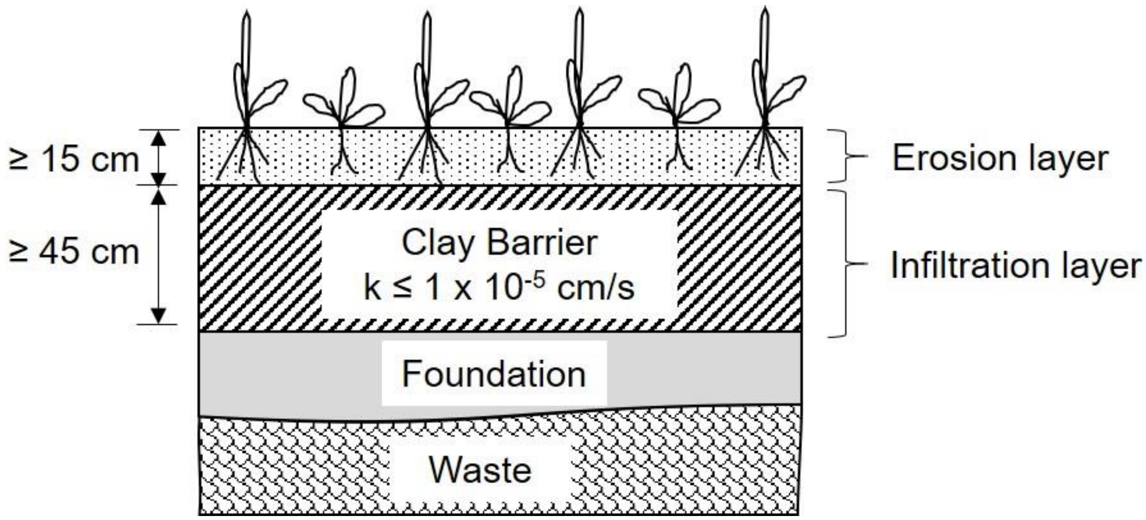
Landfills are normally spread over many acres of land and the area often remains unused after the closure of the landfill due to various health and environmental concerns. However, with the stricter landfill regulations, and better leachate and gas management techniques, the end uses of landfills are being explored extensively. There has been an increasing trend of real estate development over the former landfill sites [22]. Similarly, the closed landfills can be used for recreational parks and other land uses such as golf courses, playgrounds, ball fields, botanical gardens, and residential development [23]. Landfill cover systems should be designed considering the end uses of the landfill. For example, if the end use of the landfill is development of a recreational park, then the cover should be designed to sustain vegetation and elevate the aesthetics. Similarly, if the end use of the landfill is developing solar farm, then the landfill cover can be designed as an exposed GM cover without a vegetative layer. There exist many challenges in using landfill surface after closure some of which are subsidence, fugitive gas emissions, and odor [23]. Hence, landfill cover should be designed to accommodate possible end uses.

Resiliency

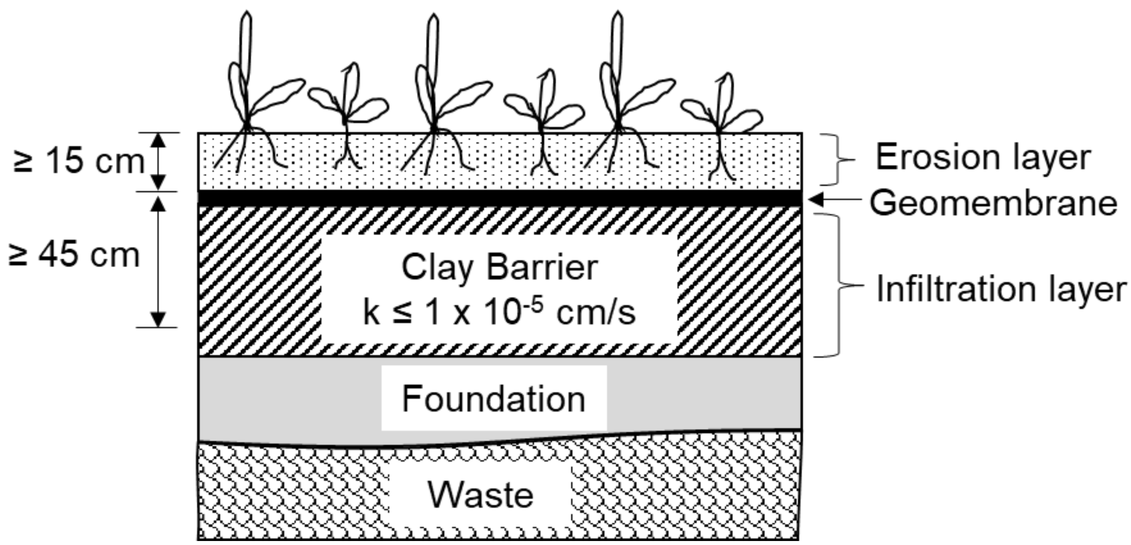
With the global climate change, the extreme climatic events are becoming a recurring event, and the impacts are being felt at every part of the world. For example, extreme precipitation, extreme drought, hurricane and storm surges, sea level rise, and saltwater intrusion are some of the commonly experienced extreme climatic events. Since landfills are essentially considered to be a storehouse for all the toxic pollutants, any kind of breach in the containment system may cause severe damage to the human health and environment. In this regard, the design of landfill cover systems for resiliency is gaining wide prominence. Resiliency is the ability of a system to cope up with the unforeseen changes in the environmental conditions without substantial damage and quickly adapt to the changing conditions [24]. Given the magnitude of consequences associated with failure of a landfill, it is imperative for the landfill to be resilient and be able to perform its intended function in changing climatic conditions. Since the landfill cover is directly exposed to the environmental conditions, it is important that the cover materials and the entire cover system itself are resilient to the changing environmental conditions. For example, the extreme flooding events can jeopardize the functional performance of the landfill cover by increased infiltration in conventional cover, water logging, and obstruction of gas transport in biocovers leading to reduced CH_4 oxidation efficiency. These factors should be considered in the design of the cover so that the performance of the cover system is not compromised by such extreme climatic events.

3 Regulatory Requirements

In the U.S., MSW landfills are managed under RCRA Subtitle D [11]. Federal regulations prescribed under 40 CFR Part 258, Subpart F, require that landfill owner/operators to place a final cover system to reduce the infiltration of liquids and erosion of soil [11]. The permeability of the final cover system should be less than the bottom liner system (if present) or the existing natural subsoils and in no case, should it exceed 1.0×10^{-5} cm/s [6, 11]. As per the regulations, the final cover should consist of an infiltration layer or barrier layer of a minimum of 45 cm (18 inches) of earthen material overlain by an erosion layer of a minimum of 15 cm (6 inches) of earthen material capable of sustaining vegetation [3]. **Fig. 2** shows the schematic of the Subtitle D cover system for MSW landfills with and without GM liners at the bottom.



(a)



(b)

Figure 2. Subtitle D landfill cover system for a) unlined MSW landfill and b) MSW landfill with geomembrane liner at the bottom

The regulations require barrier layer in the cover to have permeability less than or equal to that of the bottom liner, however, the use of GM in the cover is not obligated. If a GM is used in the bottom liner, then it becomes a necessity to use one in the cover to comply with the permeability requirements. The landfill cover (the final cover) can have various components depending upon the site conditions and anticipated gas generation. **Fig. 3** shows a typical cross section of a landfill cover with various components [25]. The top layer also called the vegetative or erosion layer provides protection against erosion and supports vegetation if the climate supports vegetation growth [4]. Sometimes, nutrients are added to the topsoil or the vegetative layer to enhance vegetative growth [26]. An additional cover soil layer below erosion layer may be provided as a protection layer in areas susceptible to frost degradation [25]. The protection layer may serve to store excess infiltrated water which is removed later by ET [4]. Similarly, the areas which receive substantial rainfall are provided with drainage layer to minimize seepage through the barrier layer, reduce water head on the liner due to percolation, and reduce instability induced by water pressure [4]. For the landfills where high CH_4 generation is anticipated, gas collection layer is provided to install gas vents. Federal regulations allow the use of alternative cover designs which can provide equivalent protection against infiltration and erosion; however, the designs must be approved by authorized personnel [3].

Different countries have different regulatory requirements. For example, in India, the final cover is required to have a 60 cm thick barrier layer of clay or amended soil with permeability less than 1×10^{-7} cm/s and an overlying 15 cm thick drainage layer. A 45 cm thick vegetative layer shall be placed on top of the drainage layer to support natural vegetation and protect from erosion [27]. Similarly, in Germany, the MSW landfills are grouped as Class I which receive virtually inert waste with total organic carbon (TOC) ≤ 20 mg/L and Class II which receive higher organic or degradable waste with TOC ≤ 100 mg/L [28]. The Class I landfills are also referred to as mineral solid waste landfills as they receive inert wastes which are not expected to undergo chemical or biological reactions [29]. The Class II MSW landfills are required to have a surface protection layer with thickness adequate for long-term protection. A drainage layer of thickness 30 cm is provided below surface layer made up of granular soil with minimum hydraulic conductivity of 0.1 cm/s. The drainage layer is underlain by hydraulic barrier layer of 50 cm thickness made up of compacted clay with hydraulic conductivity $\leq 5 \times 10^{-7}$ cm/s [29]. A high-density polyethylene (HDPE) GM of thickness ≥ 2.5 mm is placed over the compacted clay barrier. A gas venting layer of thickness adequate to accommodate gas collection pipes with minimum diameter of 100 mm is provided below barrier layer and finally a foundation layer is placed above the waste to provide required gradation to the overlying cover layers [29].

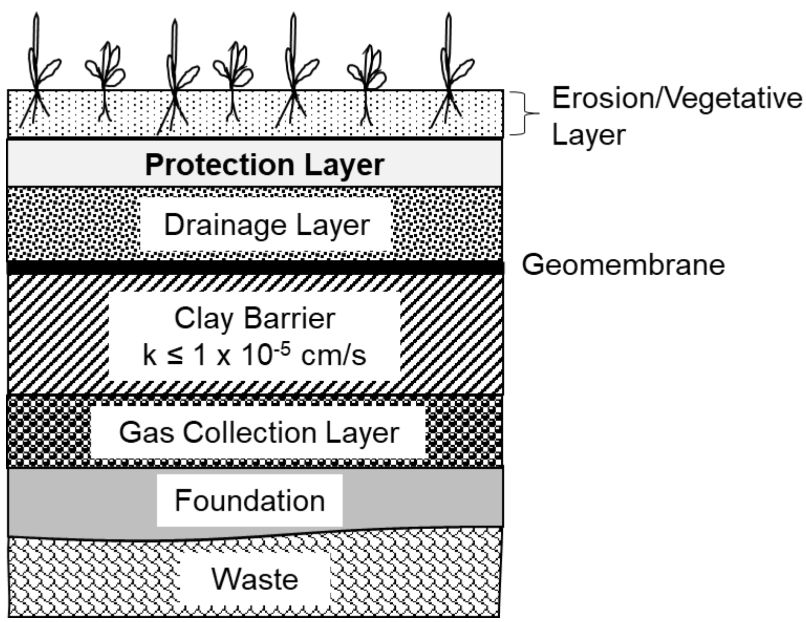


Figure 3. Cross section for a typical final cover system for MSW landfills with various layers

4 Alternative Cover Systems

As per the federal regulations, alternative cover systems which perform equivalent to a conventional cover system can be used as MSW landfill cover. Alternative cover systems for MSW landfills have been explored by various researchers from the past two decades. Cost is one of the important considerations for exploring alternative landfill cover systems as the construction and maintenance cost can be reduced significantly by using alternative covers at the landfills [6, 30]. In addition to the cost considerations, the conventional cover system may not always provide long-term protection against infiltration due to the formation of desiccation cracks, limited water holding capacity of the topsoil, and increase in permeability of the barrier soil due to freezing/thawing and root activity [8, 31]. In an assessment conducted in California, out of 544 landfills in California which are located in wide variety of climatic conditions, 72-86% were found to have failing compacted clay barrier and it was also found that the landfills, irrespective of the climatic or geologic conditions, had failing clay barriers [31]. Hence, the need to explore alternatives for conventional clay barrier was realized. Some of the alternative cover systems are discussed in the sections below.

4.1 Infiltration Cover Systems

4.1.1 Capillary Barrier

A capillary barrier consists of a fine-grained soil layer underlain by a coarse-grained soil layer and the combination acts as a barrier for infiltrating water by capillary action [31-33]. A typical cross section of a capillary barrier cover system is shown in **Fig 4**. The cover system relies on the differences in the pore sizes of the fine-grained and coarse-grained soil layers for limiting infiltration through the cover [10]. When the water held in the fine pores of unsaturated soil meets the contrastingly larger pore sizes of coarse-grained soil layer, the capacity of the fine pores to hold water at the existing matric suction reduces significantly. The water can advance only when the matric suction is low enough to fill the pores with water i.e., at saturation [9]. In other words, the integrated coarse-grained soil under a fine-grained soil layer system works on the principle of contrasting hydraulic conductivities of the two soils at similar matric suctions [33]. Such type of capillary barrier works effectively until the fine soil is fully saturated. Moisture accumulated in the fine-grained soil layer needs to be removed to increase the efficiency of the cover which can be done by evapotranspiration through the vegetative cover, or by lateral transport in an inclined cover [33]. Morris and Stormont [33] compared the infiltration performance of basic capillary barriers (0.6 m vegetative layer underlain by a coarse layer made up of gravel) and minimal Subtitle D cover for five sites in the US using HELP and TRACER3D models. The results of their study showed that an efficiently designed capillary barrier cover can perform equivalent or superior to a minimal Subtitle D cover at many sites. They also evaluated the performance of the capillary barrier with a transport layer at the interface of fine-grained and coarse-grained soil layer and found a significant reduction in percolation.

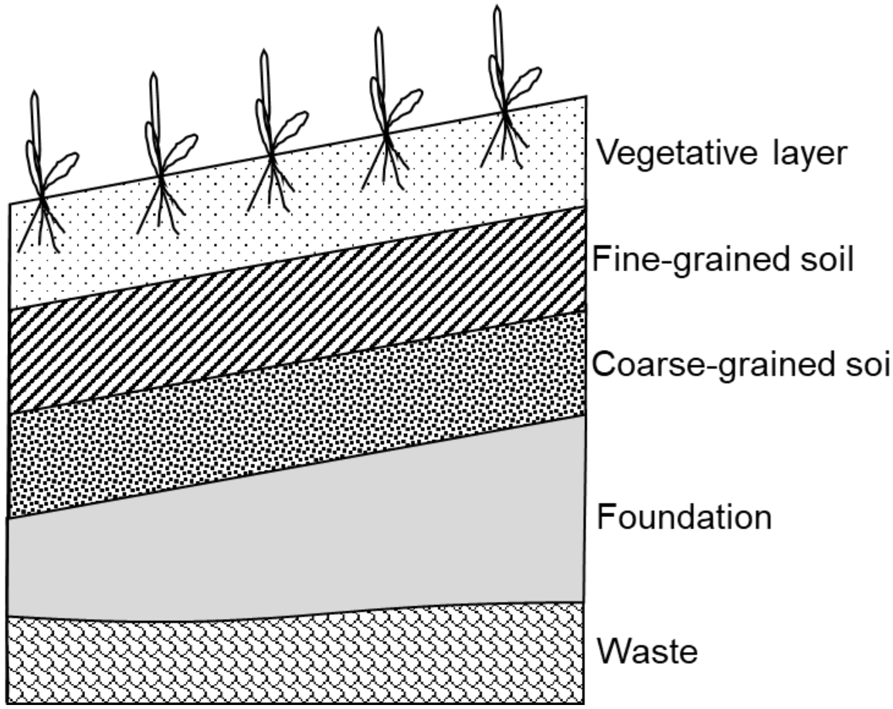


Figure 4. Cross section of a typical capillary barrier cover system

Over the years, many researchers have attempted to modify capillary barriers to serve for purposes other than infiltration protection. One such example is the study by Berger et al. [34], who investigated CH_4 oxidation potential of capillary barrier comprised of compost-amended sand overlying a layer of loamy sand. They reported CH_4 oxidation ranging from 57 to 98% in the capillary barrier cover. In the recent years, studies have been conducted to modify capillary barriers to enhance the performance as well as the sustainability. For example, Rahardo et al. [35] investigated the performance of dual capillary barrier using recycled asphalt pavement (RAP) waste materials as the fine- and coarse-grained soil as an alternative to natural soil. The dual capillary barrier comprised of two composite layers of each fine-grained RAP material overlying a coarse-grained RAP material layer. Seepage analysis was performed using Seep/W software after establishing saturated and unsaturated properties through laboratory testing. The dual capillary barrier using RAP waste material showed efficacy in preventing rainwater infiltration and hence was found to be a sustainable alternative to natural soil or aggregates. Similarly, Ng et al. [36] investigated a modified capillary barrier by adding a fine-grained soil (clay) layer beneath the two-layered capillary barrier layer (silt layer overlying gravel layer). They carried out column tests simulating one-dimensional (1D) water infiltration and performed transient seepage simulations to simulate the performance of three-layered modified capillary barrier cover. The results from their study indicated that the addition of clay layer at the bottom of two-layer barrier system enhances the percolation protection significantly making it effective for a rainfall return period of more than 1,000 years. However, the performance of such cover systems needs to be verified through extensive field studies. Capillary barriers can serve as an effective landfill cover barrier component mainly in the arid and semi-arid climates [33, 37]. Nevertheless, the performance of the capillary barrier cover system may be limited in the regions which receive heavy rainfall annually. One important aspect that needs attention in using capillary barriers is the propensity of occlusion of pores in fine grained soil upon saturation leading to obstruction of gas transport which may lead to accumulation of landfill gas underneath the barrier layer if there are no provisions for gas management such as gas wells or gas collection headers in the cover.

4.1.2 Evapotranspirative Cover System

Evapotranspirative (ET) cover is an alternative cover system which utilizes natural processes to protect infiltration of water into the waste [8]. Two major phenomena are used in ET covers to minimize infiltration: 1) water retention by soil making it available for plants and 2) evapotranspiration from soil and plants removing water from the soil [8, 38-41]. The ET cover works on the principle of water balance and functions based on the soil properties such as soil texture and water holding capacity to store water [40, 42]. ET covers are also referred to as water balance covers and are mostly preferred over conventional cover in semiarid and arid climates [38-40, 42]. The ET covers are designed as monolithic cover with a single fine-grained soil layer to absorb water and bear vegetation (**Fig. 5**) or modified by adding a coarse-grained soil underneath to form a capillary barrier explained heretofore (**Fig. 4)**.

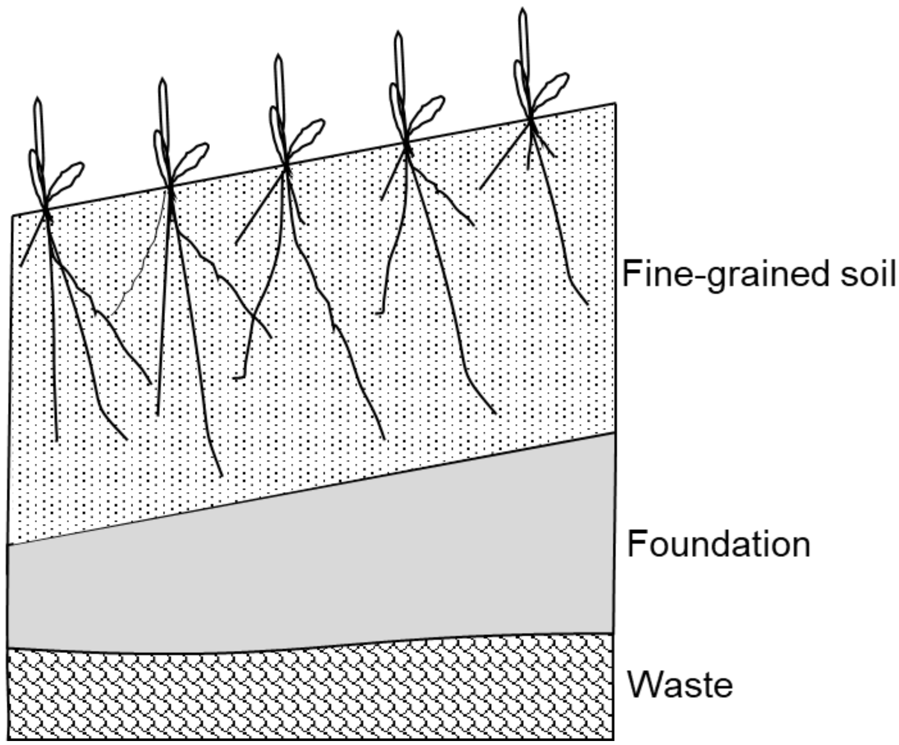


Figure 5. Cross section of a typical Evapotranspirative cover system

The major advantages of ET covers are: 1) they are less prone to failure through desiccation, cracking and freeze/thaw cycles, and 2) require lower cost for construction and maintenance than conventional covers. The ET covers do not have compacted barrier layer which saves a fair amount of cost in labor and equipment. Locally available soils are typically used for ET covers averting the purchase or supply of clay soil. The operation and maintenance cost for ET covers are also lower than the conventional covers [8, 42]. ET cover designs are affected by local soil type and resources, evapotranspiration potential, native plants, and the interactions of plants with soil and the resulting water balance [8]. The thickness of the ET covers is designed to store the water for the most critical climatic events. Soil layers of 0.60 m to 3.0 m thickness have been used in monolithic ET covers [42].

In 1998, USEPA initiated a program called Alternative Cover Assessment Program (ACAP) to obtain field-scale performance data for alternative covers [43,44]. Test facilities were established at twelve sites across the US with broad sampling of the environmental factors which affect the performance of landfill cover system [43]. Abichou et al. [44] assessed the performance of ET cover in relation to a conventional cover system at one of the ACAP test sites by monitoring percolation rates through the covers. The ET cover comprised of a 0.7 m thick compacted soil overlain by a 0.6 m thick 3:1 mixture of soil and peanut hull compost. The ET cover was vegetated with hybrid poplar trees and underwood of bermudagrass. The results showed that the use of ET cover reduced percolation by 43% in comparison to conventional cover. Similarly, Barnswell and Dwyer [45] assessed the long-term performance of ET covers for MSW landfills in Northwestern Ohio. The ET cover was designed to generate percolation rates less than 32 cm/year which is accepted by Ohio Environmental Protection Agency (OEPA) using dredged sediment amended with sewage and lime sludge. The ET covers were constructed in drainage lysimeter and simulated 100-year rainfall events. The percolation rates through ET in a one-year monitoring period were much lower than the OEPA standards. The mature plants were found to have better water balance than immature plants.

Although ET covers have been a popular alternative to conventional covers due to the lower cost, self-renewing and aesthetic qualities, they have certain limitations which include typical applicability in arid and semiarid climates, effectiveness is affected by local climatic conditions such as precipitation, snowpack, etc. Similarly, the ET performance is significantly affected by the vegetation type and the time duration when the vegetation is not mature. Vegetation plays a major role in ET process; hence the design of the ET covers should consider growth period of vegetation and potential saturation of the ET layer in the event of any heavy precipitation before full development of vegetative layer which may hamper the proposed function of the cover system.

4.1.3 Anisotropic Barrier

Anisotropic barrier is a type of capillary barrier which is constructed by layering of capillary barriers. They are designed to restrict the downward flow of water and simultaneously stimulate the lateral flow of water [46-48]. The cover comprises of layers with variation in soil properties and compaction techniques to enhance the capillary forces and render anisotropic properties to the cover system [48].

The US Department of Energy (USDOE) with an initiative of improvement of environmental restoration and management technologies started the Alternative Landfill Cover Demonstration (ALCD) program. It involved a large-scale field demonstration of performance of different conventional and alternative covers at Sandia National Laboratories in Albuquerque, New Mexico [46]. Two conventional cover designs (RCRA Subtitle D and Subtitle C covers) and four alternative covers (ET, capillary barrier, geosynthetic clay liner (GCL) cover, and anisotropic barrier) were constructed side by side. The cover performance was evaluated based on the flux rates (percolation, mm/yr) and efficiency (percolation/precipitation*100). The anisotropic cover had four layers (from bottom to top): 15 cm thick gravel drainage layer, 15 cm thick fine-grained sand interface layer, 60 cm thick non compacted native soil layer and a 15 cm thick top vegetation layer comprised of local topsoil and pea gravel [48] (**Fig. 6**). The anisotropic barrier, ET cover and Subtitle C cover performed significantly well whereas the Subtitle D cover did not perform well during the five-year testing period [49]. Anisotropic barrier and ET covers are much cheaper to install than the subtitle C cover [46]. Anisotropic barrier covers perform better in arid and semiarid climates; however they also suffer from similar limitations as ET covers.

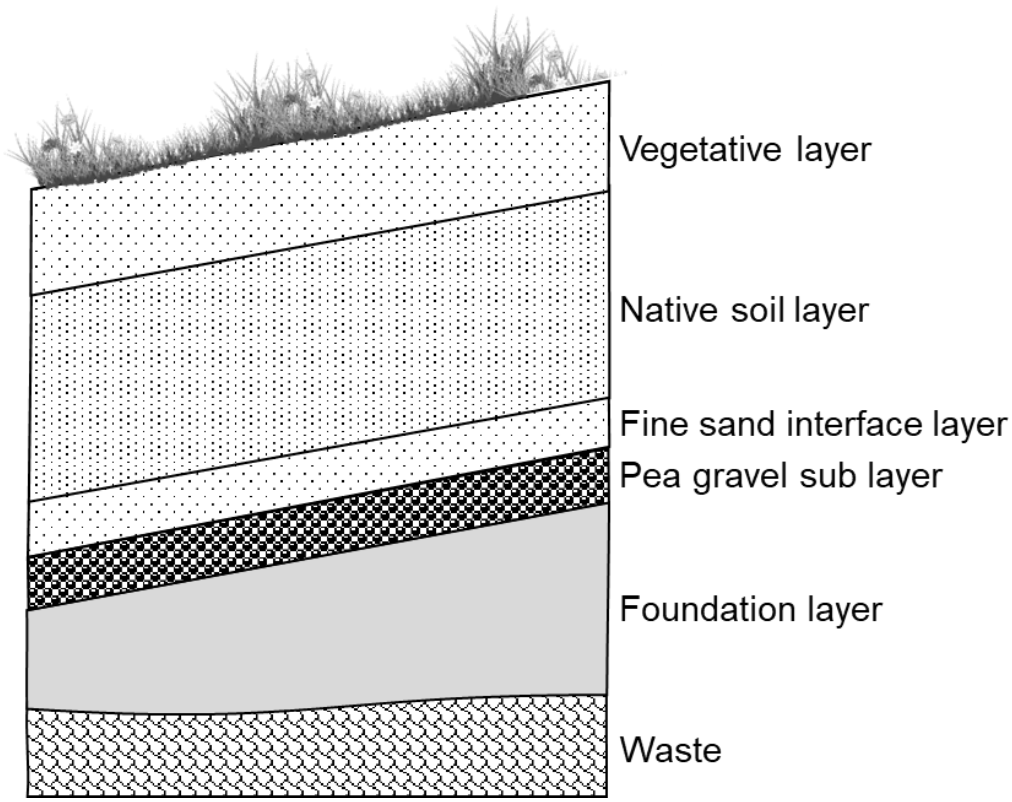


Figure 6. Cross section of an anisotropic cover system (from USDOE [48])

4.1.4 Geosynthetic Clay Liner Cover

Geosynthetic clay liners (GCLs) were developed as a synthetic replacement to the conventional compacted clay liners. GCLs are the hydraulic barriers which consist of clay (mainly bentonite) either sandwiched between GTX or bonded to GMs in some cases [50-52]. GCLs prove more cost-effective in regions where low permeability clay is not locally available, and the thinner structure of GCL reduces the space requirement while increasing the landfill waste capacity [53]. GCLs gained prominence in barrier applications in landfills due to their low hydraulic conductivity (~10^{-9} cm/s), ease of installation, lower thickness, lower cost, and resiliency to adverse environmental conditions such as freeze-thaw and wet-dry cycles [50, 52, 54]. The lower hydraulic conductivity of GCLs is attributed to the physicochemical properties of bentonite which is a naturally occurring clay with characteristic high swelling potential, ion exchange capacity, and low hydraulic conductivity [55]. Most of the commercial GCLs use sodium (Na) bentonite due to their low hydraulic conductivity ranging from 6×10^{-10} to 2×10^{-9} cm/s [50, 52, 56,57]. Na bentonite is composed primarily of the mineral Na montmorillonite which has high surface area, high cation exchange capacity, and ability for interlayer swelling which contributes to the high swelling potential and thus low hydraulic conductivity [54]. The water, when comes in contact with the Na bentonite, is bound to the clay mineral surface, also called swelling, thereby sealing off the macroscopic flow paths and increasing the tortuosity of the flow paths [54, 56]. The volume of interlayer bound water is associated with the degree of swelling and hydraulic conductivity of the bentonite in the GCL [56]. Swelling properties of bentonite renders unique self-healing abilities to the holes and cracks formed during the operation of the GCL as a barrier [53]. It has been reported that a hole as large as 75 mm in diameter can self-repair maintaining the original properties which makes GCL a perfect candidate for barriers in landfill applications [53]. GCL, especially with needle punched or stitch bonded GTX, can provide appreciable shear strength with high internal shear resistance. Koerner et al. [58] assessed the internal shear strength of the GCLs in landfill cover in fourteen full scale test plots. The test plots involved two cover designs: one with GCL alone with 0.3 m sand drain layer and 0.6 m cover soil layer overlying the GCL, and the second cover design had a GCL/GM composite (GCL beneath GM) as a barrier layer. A geocomposite drainage layer made of geotextile/geonet/geotextile combination was overlain on a GCL/GM combination and a cover soil layer of 0.9 m was placed above the geocomposite drainage layer. In the 24 months of operation, only two slides and one internal slide were reported. The interface slide was between GM and GTX interface which was attributed to the extrusion of the bentonite through the GTX and lubricating the interface. The internal slide was attributed to the installation inconsistencies rather than GCL functioning. Overall, the GCLs showed appreciable internal shear resistance, low differential deformations, and better slope stability.

Since the introduction of GCLs in 1986 [53], extensive research has been conducted to assess the performance of GCLs as a barrier material. Studies have shown that several factors such as ion exchange, desiccation, penetration of roots from vegetation, humidity, confining pressure, and age of installation can alter the hydraulic conductivity of GCL barriers significantly [50-52, 59]. An increase in hydraulic conductivities of GCLs by an order over 5 was observed by Meer and Benson [52] while analyzing the GCLs exhumed from four landfills after 4.1 to 11.1 years of installation. A complete exchange of Na with calcium (Ca) and magnesium (Mg) was observed with swell index similar to Ca or Mg bentonite. It was concluded that the cation exchange is inevitable unless the underlying or overlying soil is rich in Na. In addition, desiccation combined with cation exchange can lead to irreversible increases in hydraulic conductivity of the GCLs. Melchoir et al. [60] presented the results of the long-term (18 years) performance of different landfill cover systems, which included cover system with GCL barrier, equipped with in situ large scale lysimeters at a landfill in Germany. The GCL which was covered by 0.15 m of gravel layer and 0.30 m of cover soil showed significant crack formations and seepage after within three years of operation. Exchange of Na ions with Ca and Mg ions were observed. Mackey and Olsta [51] who analyzed the performance of GCLs used in landfill covers in two landfills in Florida also had similar observations. They suggested that providing a thicker soil cover above GCL or a GM can protect the GCL from desiccation and root penetration which may help to minimize increase in hydraulic conductivities despite ion exchange. The observations from various studies suggest that GCLs should be used with precaution in landfill cover applications.

4.1.5 Exposed Geomembrane Cover

Exposed geomembrane cover (EGC) has been used in many landfills in place of conventional cover systems. The EGCs do not incorporate overlying drainage layer and topsoil or erosion layer provided in a typical landfill cover system [61]. In a typical conventional cover with GM, it is covered with soil layer to support vegetation as well as reduce direct damage to the GM. However, such cover systems are susceptible to slope failure due to slippage at interface [62, 63]. The EGCs are preferably provided for the interim or temporary cover applications [62-64]. The major benefits of providing EGC in intermediate cover are significant reduction in the amount of percolation of precipitation and containment of LFG [63]. Reduced percolation results in reduced leachate generation and thus significant cost reduction in leachate management. Providing EGC in interim cover also helps to protect steep slopes with no potential erosion which is otherwise a bigger concern for soil covers. Apart from interim cover, EGC can also be placed as a final cover in the landfills, however it will require stricter considerations for long-term stability and thus may call for the use of high-interface friction GMs and management of surface water drainage [64].

EGC have been used in many landfill projects across the US. Although EGC application was approved for interim cover since 1992, the use as final cover was approved much later [65]. For example, Sabine Parish Landfill, Louisiana was permitted to use EGC as final cover in 1999 and the performance was encouraging [66, 67]. Similarly, Yolo County landfill near Davis, CA chose to use EGC for the bioreactor landfill [68, 69]. The anchor trenches, provided to hold GM in place, were backfilled with soil and temporary ballast consisting of 20 kg sandbags were installed to counteract the uplift forces caused by the wind and protect the exposed GM [68]. Hickory Ridge landfill, Altanta, GA is another landfill to use EGC as final cover and was the first fully permitted EGC final cover closure system [70]. The 48-acre landfill used 1.5 mm thick Thermoplastic Polyolefin (TPO) reinforced GM for EGC. The EGC covered landfill was combined with solar cap technology by installing solar panels over the EGC cap and was transformed into the biggest solar energy generating facility in Georgia as well as became the world's largest solar energy cap.

Although, EGC provides cost saving in terms of construction and maintenance, it is subjected to degradation through various mechanisms other than accidental damages. The lifetime of the GMs reduces significantly in the exposed condition due to the major degradation mechanisms; ultraviolet radiation, elevated temperatures, and atmospheric oxidation [71]. Where a nonexposed HDPE GM can have a lifetime of 166 to 446 years between temperatures of 30 to 20 °C, for an exposed HDPE GM the lifetime can be as much as 36 years [72]. In addition, EGCs are exposed to high uplift pressures from wind which requires installation of numerous anchor trenches as well as access to the EGCs during post closure care can be difficult [73].

4.1.6 *Engineered Turf Cover*

In the recent years, attempts have been made to overcome the shortcomings of the EGC by introducing engineered synthetic turf cover. One of the patented turf covers comprise of synthetic grass and GM [74]. The synthetic grass comprises of GTX clumped with synthetic strands manifesting the appearance of grass. The GM used is usually textured GM liner, however it can be designed as a drainage liner comprising of GM with geonet drainage media, or a drain liner with studs integrated with HDPE sheet [74]. Such type of cover system not only reduces construction cost by eliminating the need for cover soil and reduces operation and maintenance requirement annually, but also enhances the aesthetic appearance of the landfill.

Several configurations of turf covers have been explored to enhance their performance in the dynamic environmental conditions. West et al. [73] presented an engineered turf cover for final landfill cover which comprised of synthetic turf and impermeable GM layer (**Fig. 7**). The synthetic turf comprises of UV resistant polyethylene turf with sand infill which provides additional protection and increases longevity of the underlying GM. The GM used by West et al. [73] was textured, structured GM with drainage studs and downward spikes which provide high friction angles, resistance against sliding failure, and facilitates drainage under various gradient conditions. The impermeable GM layer can sustain high vacuum pressures applied by active gas collection systems at landfills. Sanchez and Zhu [75] performed a comparative analysis of stormwater pond design between conventional cover system and engineered turf cover system also known as ClosureTurf cover which had similar configuration as West et al. [73]. Their analysis results showed that the engineered turf cover system generates higher surface runoff than a conventional cover system which engenders the need for a slightly deeper perimeter drainage channel and larger stormwater pond. Simultaneously, it reduces the infiltration by increasing the runoff.

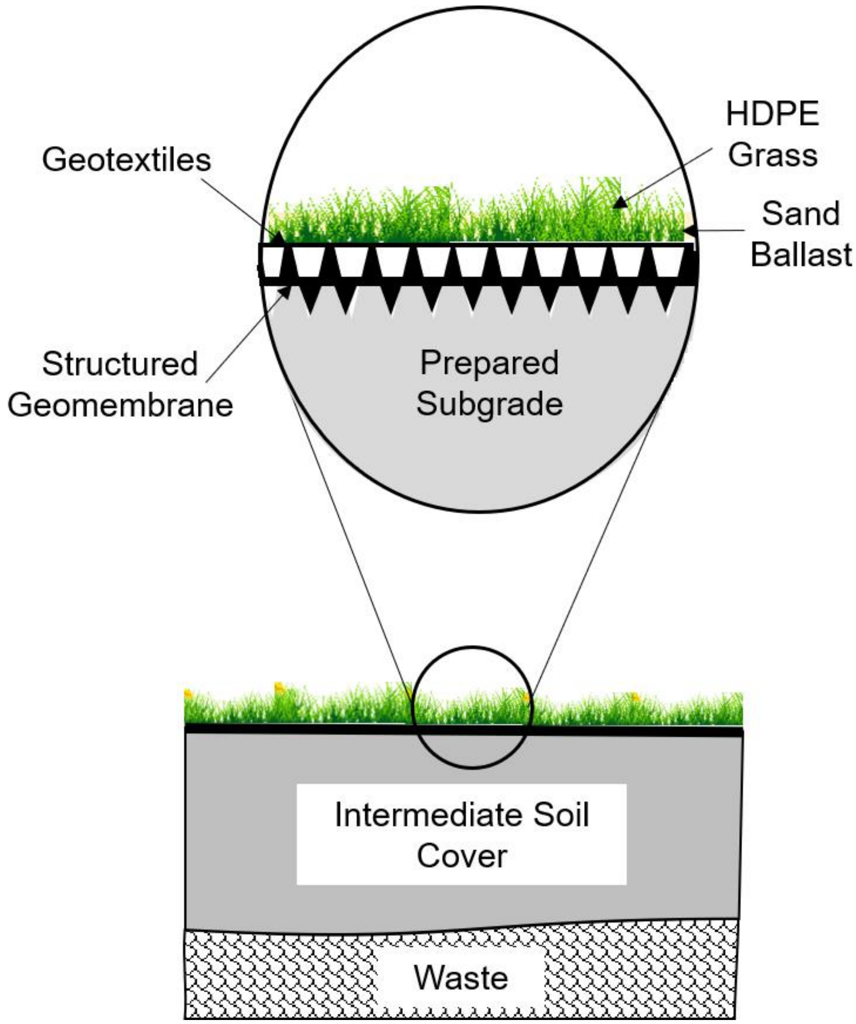


Figure 7. Schematic of turf cover system (modified from West et al. [73])

Engineered turf covers are increasingly being adopted by the landfill operators due to the ease of installation, applicability in steep slopes, and reduced construction cost, and reduced operation and maintenance requirements. Some of the completed projects include Bi County landfill, Tennessee, Berkeley County landfill, South Carolina, and Hartford landfill, Connecticut. Engineered turf covers have been successfully implemented in many states across the US and have been considered a remarkable innovation to enhance the aesthetics of the landfills. However, the long-term performance of such type of cover systems needs to be validated with extensive field studies. In addition, the availability of such cover systems in developing countries or low-income countries could be a concern.

4.2 Gas Mitigating Covers

Initially, the regulatory landfill cover designs were solely based on the infiltration consideration with the focus on reducing leachate generation and preventing CH_4 generation to prohibit the incidences of landfill fires or explosions [76]. LFG is typically composed of nearly 50% (*v/v*) CH_4, 50% (*v/v*) CO_2 and trace NMOCs [11]. CH_4 and CO_2 constitute 16% and 65%, respectively of the global anthropogenic (GHG) emissions [77]. CH_4 is a more potent GHG than CO_2 with global warming potential (GWP) of 28-36 over 100 years [78]. CH_4 is a short-lived gas with atmospheric lifetime of 12 years however, its radiative energy is much higher than CO_2 [7, 79]. Atmospheric CH_4 concentration has increased tremendously over the years and surpassed the pre-industrial period by 150% [80]. MSW landfills are the third largest source of anthropogenic CH_4 emissions globally as well as in the US and accounted for 17.4 percent of total CH_4 emissions in the US in 2018 [78, 81]. Because CH_4 has more potential to trap heat than CO_2 and landfill serves as a major source of anthropogenic CH_4 emissions, continuous efforts have been made towards controlling landfill CH_4 emissions.

The emission guidelines for MSW landfills (40 CFR 60) require landfills to install gas collection and control system for open landfills if NMOC emissions exceed 34 Mg/year or the surface CH_4 emissions exceed 500 parts per million (ppm), and for closed landfills if NMOC emissions exceed 50 Mg/year [20]. Thus, gas collection systems are installed at landfills for LFG emissions control as well as beneficial use of CH_4. However, gas collection is efficient only after the placement of impermeable final cover which often takes several years from the start of waste disposal point [82]. Typically, intermediate covers are installed before placement of final cover however, they are not impermeable to gas migration. Besides, the installed gas collection systems may not be 100 percent efficient in capturing all the gases generated in the waste. LFG collection efficiency varying from 50% to 100% (average 75%) depending on the cover type and coverage of the collection system has been reported [83, 84]. Hence, a fraction of LFG is often emitted into the atmosphere despite having gas collection system in place. Moreover, at the older and abandoned landfills where providing gas collection system is not economical or practically feasible, the problems of fugitive emissions is preeminent. As a result, in the recent years, focus has been shifted to developing alternative cover systems which can mitigate fugitive CH_4 emissions from landfills.

Bogner et al. [85] monitored landfill emissions at two landfills located at two different climatic regions: Illinois (Mallard Lake) and California (Brea-Olinda) using a closed chamber technique. During the monitoring period of 1988-1994, landfill cover soil was found to act as a sink for CH_4 in well-aerated regions and the consumption of CH_4 was attributed to CH_4 oxidation. CH_4 oxidation by microbes was identified in early 1900s and the first CH_4 oxidizing bacterium was isolated by Söhnhen in 1906 [86]. Earlier, the CH_4 consumption in aerated temperate forest soils had been reported [87, 88]. Apart from forest soils, CH_4 oxidation potential has also been reported for wide range of natural environments such as agricultural soils, wetlands, rice paddy fields, and peatlands [76, 89]. Whalen et al. [90] investigated the CH_4 oxidation potential of topsoil from a park constructed over a landfill in California. They observed high CH_4 oxidation rates (45 g m^{-2} d^{-1}), which was the highest reported value for any environment to that date. Likewise, Kightley et al. [91] performed laboratory incubations of different soils with CH_4 for six months and evaluated their CH_4 oxidation potential. In their study, porous coarse sand showed highest CH_4 oxidation potential (166.5 g m^{-2} d^{-1}) among all the soils tested. Similarly, Bogner et al. [92] evaluated CH_4 oxidation rates in landfill cover soil at Northeastern Illinois landfill using static flux chamber technique under real field conditions. They observed a swift change in CH_4 oxidation rates (up to 4 orders of magnitude) with change in CH_4 concentrations. Negative fluxes of CH_4 were observed at locations near and far from the gas collection wells, even into full winter with freezing conditions, showing high CH_4 oxidation potential in soil and a maximum oxidation rate of 48 g CH_4 m^{-2} d^{-1} was observed. In another study, Scheutz et al. [89] investigated the attenuation of CH_4 in landfill cover soil sampled from a location emitting CH_4 by performing soil microcosms incubation and observed a high rate of CH_4 oxidation ranging from 24 to 112 µg CH_4 g^{-1} h^{-1}. Likewise, Scheutz and Kjeldsen [93] performed batch incubation experiments on landfill cover soil obtained from a depth of 15 to 20 cm below ground surface (bgs) at room temperature (22 °C) and attained a maximum oxidation rate of 104 µg CH_4 g^{-1} h^{-1}. In a similar laboratory incubation experiment by Reddy et al. [94], a maximum CH_4 oxidation rate of 195 µg CH_4 g^{-1} h^{-1} was attained at 30 °C in landfill cover soil sampled from a depth of 30-60 cm bgs.

CH_4 oxidation occurs in landfill cover soils with the help of methanotrophic bacteria. The continuous influx of CH_4 from the underlying waste results in the enrichment of cover soil with CH_4 oxidizing bacteria called methanotrophs. CH_4 serves as the sole source of carbon and energy for the methanotrophs. Methanotrophs oxidize CH_4 to CO_2 in the presence of oxygen as shown in **Eq. 2** [7, 95].

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (2)$$

The complete methanotrophic CH_4 oxidation process involves oxidation of CH_4 to methanol, methanol to formaldehyde, formaldehyde to formate and finally to CO_2 [86, 96-97]. The methanotrophic CH_4 oxidation is catalyzed by various enzyme and enzyme methane monooxygenase (MMO) is a key enzyme to catalyze oxidation of CH_4 to methanol [86, 93, 95-96]. Aerobic methanotrophs have been classified into two phyla: the *Proteobacteria* which are further classified into classes *Alphaproteobacteria, Gammaproteobacteria,* and *Verrucomicrobia* [98, 99]. The methanotrophs in the group *Gamma- and Alphaproteobacteria* are also known as Type I and Type II methanotrophs, respectively [97]. Type I methanotrophs can initiate CH_4 oxidation even in lower concentration ranges (<12 ppm), hence called high-affinity methanotrophs and are more commonly present in the environment. On the other hand, the Type II methanotrophs can only perform CH_4 oxidation at higher concentrations of CH_4 (> 40 ppm) and hence called low-affinity methanotrophs [76, 99]. Both Type I and Type II methanotrophs have been found in landfill cover soils. Some commonly found Type I methanotrophic genera in landfill cover soils are *Methylomonas*, *Methylobacter*, *Methylomicrobium, and Methylocaldum, and* Type II methanotrophic genera are *Methylosinus* and *Methylocystis* [94, 100].

Although, CH_4 oxidation in landfill cover soil is found to be a probable sink for the landfill CH_4 emissions, several physical and environmental factors affect the methanotrophic activity and reduce the efficiency of the microbial CH_4 oxidation in landfill cover soils. Temperature, moisture, pH, CH_4 availability, and aeration are some of the factors affecting CH_4 oxidation in landfill cover soil. The optimum temperature for CH_4 oxidation has been found to be nearly 30 °C, however, it is found to occur even at lower temperatures (~2-6°C) showing that methanotrophs can adapt to extreme temperatures [7, 93, 94]. Different studies have reported different optimum temperatures for CH_4 oxidation however: the optimum range varies from 25-

35 °C [101-102]. Similarly, soil moisture also affects microbial activity in the landfill cover soil as it controls the diffusive ingress of gases into the soil. Scheutz and Kjeldsen [93] obtained maximum CH_4 oxidation at moisture content range of 18–24% (*w/w*). At lower moisture content, CH_4 oxidation reduces due to microbial water stress and at higher moisture contents (≥ 35% *w/w*), waterlogging may occur hampering the gas diffusion thereby lowering the microbial activity [93]. In terms of pH, the methanotrophs perform well at the near neutral pH conditions (pH ~7) in landfill cover soil [93, 100]. Bogner et al. [92] observed that initial CH_4 concentrations and oxygen availability have a major effect on the oxidation rates in a landfill cover soil rather than temperature and moisture. Since efficiency of CH_4 oxidation is affected by various physical and bio-chemical factors, a need for engineering the cover systems using suitable sustainable materials was soon realized, which led to extensive studies exploring alternative cover materials that can enhance the CH_4 oxidation in landfill cover by providing favorable environmental conditions for the microbial communities.

4.2.1 Cover Systems for Mitigating Methane

An international working group of scientists and researchers from Europe, USA, Canada and Australia was formed in 2002 called Consortium for Landfill Emissions Abatement Research (CLEAR) to address topics related to LFG generation and emissions, control and mitigation strategies, prediction and modeling, microbial methane oxidation and biodegradation of other NMOCs in landfill cover soils [103]. One of the focus areas of CLEAR was bio-based mitigation of landfill CH_4 emissions. After microbial CH_4 oxidation in landfill cover soil was realized as a potential CH_4 sink, suitable cover systems capable of CH_4 oxidation were explored as a low-cost alternative to conventional covers in old landfills [104]. In the wake of enhancing microbial CH_4

oxidation potential of landfill cover soil, the engineered bio-based systems emerged as the promising and cost-effective option for low-level CH_4 emissions control in landfills [76]. Initially, bio-based cover systems comprising of organic rich materials such as compost, sewage sludge, and peat were explored to create conducive environment for the methanotrophs and enhance the CH_4 oxidizing potential of landfill cover soil [7]. The bio-based cover systems have been explored in various forms in terms of application and operations which include biocover, biofilter and biowindow [76].

Biofilters

Biofilters function similar to engineered filters used for contaminants except that the landfill biofilters are designed to absorb CH_4 by enhancing microbial CH_4 oxidation [76, 105]. Biofilters are constructed over a certain portion of the landfill cover and require continuous feeding of LFG through active or passive gas collection system [76, 106]. The biofilters are designed as fixed bed reactors packed with organic media which can sustain and induce proliferation of methanotrophs. Providing bio-based cover system over entire landfill may raise some issues related to infiltration. Biofilters appear to be suitable option in such cases as it can be integrated with the conventional cover system thereby maintaining the regulatory infiltration requirement of the cover system [107]. Various biofilter media have been tested to optimize the CH_4 oxidation efficiency of the biofilters. Gebert et al. [108] designed a biofilter integrated with landfill cover system. The designed biofilter was an upflow system consisting of five layers (base to top): drainage gravel, expanded clay pallets, gravel, sand and topsoil (loamy sand) for vegetation packed in a 15 m^3 polyethylene container divided into two compartments of 6 and 9 m^3 size. The biofilter was connected with the passive gas vent of the landfill. CH_4 oxidation rates of biofilter media were assessed through laboratory batch experiments and CH_4 removal rates ranged from 35 to 109 g CH_4 h^{-1} m^{-3}. Oxygen intrusion appeared to be an important driver for CH_4 oxidation as it occurred at oxygen concentrations above 1.7-2.6 % (*v/v*). The long-term monitoring of the biofilter showed the CH_4 oxidation is significantly affected by the CH_4 influx rates with higher CH_4 removal rates obtained for lower CH_4 influx [109]. Two types of biofilters: water-spreading biofilter comprising of coarse sand overlain by fill sand, and vertical compost biofilter comprising of a mixture of compost and polystyrene pellets were designed and evaluated for CH_4 oxidation potential by Powelson et al. [110]. Both the biofilter designs resulted in similar CH_4 removal efficiency (63-69%). Similarly, Abichou et al. [111] designed two types of biofilters: vertical and radial, based on the direction of gas flow in the filter. The filters were housed in glass barrels for protection. The filters had a drainage layer/gas distribution layer of gravel or recycled glass which had the LFG inflow at the bottom. A mixture of compost and peanut foam was placed over the gravel layer. The radial filter had greater surface area (459% more) than the vertical filter which was designed to allow greater access to atmospheric oxygen and thus increase CH_4 oxidation. The radial biofilter resulted in higher CH_4 oxidation rates than the vertical filter. The average percent oxidation achieved was 20% with a maximum of 100%. Dever et al. [107, 112] designed a central biofiltration system with four different filters each with different biofilter media and gas distribution layer. The biofilter media comprised of 1) composted garden organics with 10% shredded wood, 2) composted MSW with 10% shredded wood, 3) composted garden mix, and 4) composted MSW with 20% shredded wood. A field scale trial was set up and monitored for four years to investigate the effectiveness of the biofilters. The passively aerated biofilters were able to oxidize CH_4 resulting in maximum and average oxidation efficiency of 90% and 50%, respectively. CH_4 loading rate was found to be a controlling parameter for CH_4 oxidation which in turn governed the diffusive ingress of oxygen into the biofilter.

Some of the notable advantages of biofilters are easier implementation and requirement of less maintenance during operation. Some of the challenges associated with biofilters are higher CH_4 loading which impedes the diffusive ingress of oxygen into the filter and thus reduces the microbial CH_4 oxidation potential. In the event of extreme precipitation, waterlogging may be experienced in the biofilters thereby reducing gas transport through the filter. In addition, formation of exopolymeric substances (EPS) due to microbial activity may lead to clogging of the biofilter media affecting the gas transport [76]. Similarly, while designing biofilters, the choice of biofilter media plays an important role. For example, filter media like compost can cause formation of anaerobic zones or cavities and may lead to production of CH_4 if moisture is not regulated [109]. Therefore, materials with low organic contents make a better candidate for a biofilter.

Biowindows

Biowindows are bio-based cover systems which are placed over a smaller portion of landfill instead of the whole landfill. Biowindows are more suited at the older landfills where gas production is low, and bio-coverage is not needed over the whole expanse of the landfill [113]. Unlike biofilters, biowindows do not require separate arrangement for supply of LFG as they receive enough LFG directly from the waste due to the higher gas permeability and greater surface area [76]. Biowindows generally have two layers: a gas distribution layer overlain by a biological layer suitable for methanotrophic growth. About ten biowindows with active biologic layer consisting of yard waste derived compost were installed at Faske landfill, Denmark and their performance was monitored for over a year period [113]. The CH_4 oxidation efficiency was measured before and after installation of biowindows using a mass balance approach based on flux measurements as well as stable carbon isotopes method [113]. An increase in CH_4 oxidation efficiency from 16% to 40% was observed after installation of biowindow. Similar biowindow approach was followed in an older section of landfill in Austria for degasification after elimination of the gas collection wells [114]. Two biowindows (8 m × 8 m each) were installed at the location of previous two gas collection wells in the older section of the landfill. The biowindow comprised of a lower gas distribution layer of gravel and upper biological layer composed of compost mixed with wooden chips. The performance of the biowindows was monitored for over 2.5 years through flux measurements and gas concentration profiling. A sharp decrease in CH_4 emission rates were observed with the biowindow installation.

Although biowindow is a good alternative measure for mitigating CH_4 emissions from landfills, there are some challenges associated with its functional performance one of which is the lack of homogenous distribution and supply of CH_4 to the biowindow [113, 114]. In addition, challenges similar to biofilters such as formation of EPS and clogging of pores in the biologic layer may occur with increase in microbial activity.

Biocovers

Biocovers are similar to biowindows except that they are installed over the entire waste area or essentially over the entire landfill. Extensive studies have been conducted exploring various bio-based materials for biocovers. Organic rich materials such as compost derived from various sources such as MSW, sewage, garden waste, as well as compost mixed with other materials such as wood chip have been explored as biocover substrates. Typically, configuration of biocovers are close to biowindows with gas distribution layer overlain by a biologic layer and a vegetative layer at the top [115]. The first biocover was tested by Huber-Humer and Lechner [104] in laboratory column studies where they tested MSW compost, sewage sludge compost and mixture of compost and sand. The MSW and sewage sludge compost proved to be a suitable carrier for methanotrophs, however, there are certain requirements which must be met for using compost in biocover, which include use of matured compost with solid organic matter and minimum ammonium and salt concentrations. Ever since the testing of first biocover prototype, there has been extensive number of studies exploring various organic-rich substrates for biocovers. Earlier studies mainly focused on compost as the biologic layer in biocovers. Barlaz et al. [82] compared the performance of biocover made of yard waste compost with soil cover in landfill cells for over a period of 14 months. The static chamber technique was employed to measure the fluxes at the cover site and stable carbon isotope analysis was used to evaluate the in-situ CH_4 oxidation rate. CH_4 oxidation efficiencies of biocover was nearly 2.6 times more than that of the soil cover. Stern et al. [116] evaluated the CH_4 oxidation potential of biocover consisting of garden waste or pre-composted yard waste overlying a gas distribution layer of crushed glass, placed over an existing 40-100 cm thick soil cover at a hotspot location with high CH_4 emissions. They reported a 10-fold reduction in CH_4 emissions as well as two times more CH_4 oxidation than a control area without biocover. Biocover helped to enhance the gas retention time as well as moisture retention in the underlying existing cover soil thereby reducing desiccation cracking and preferential flow [116]. Bogner et al. [115] analyzed the performance of a biocover placed over a 15 cm thick intermediate clay cover at a landfill in Florida. Two types of biocovers (deep and shallow) consisting of a 15 cm thick gas distribution layer made up of crushed recycled glass overlain by ground garden waste (30 cm for shallow and 60 cm for deep) were installed at the test areas. The CH_4 emission fluxes were monitored using static flux chamber technique for over a year period. The deep biocover generally showed higher CH_4 oxidation (ranging from 20-70%) than the shallow biocover and the soil cover. In addition, deep and shallow biocovers showed higher percentage of negative fluxes showing uptake of atmospheric CH_4 due to high CH_4 oxidation potential of the biocover. In the recent biocover study by Lee et al. [117], an onsite pilot biocover was set up at a sanitary landfill in South Korea which consisted of a mixture of soil, perlite, earthworm cast and compost (6:2:1:1 *v/v*) and was monitored for 240 days. The study showed the seasonal variation in temperature strongly affects CH_4 removal efficiency with 35-43% removal efficiency in winter to 86-96% in summer.

Various factors affect the performance of compost as a biocover substrate. Huber-Humer et al. [118] assessed the CH_4 oxidation potential of 30 different compost materials and their mixtures and reported that bulk density, nutrient content, type of organic matter (maturity) are the major factors affecting CH_4 oxidation rate. Similarly, Scheutz et al. [119] chose kitchen waste derived compost over garden waste in their study due to its lower oxygen demand for their biocover study. A biocover comprising of kitchen waste derived compost was placed over an old unlined landfill without gas collection system in Denmark [119]. CH_4 oxidation efficiency of 80% was reported over the monitoring period of nearly two years. Discrepancies in the gas distribution in the landfill cover substantially affects the performance of the biocover leading to formation of hotspots with high CH_4 fluxes at some portion of biocover surface [120]. In order to address this issue of uneven gas distribution, Scheutz et al. [120] designed a semi-passive biocover system at a landfill in Denmark, in which the compost biocover was fed by LFG collected from three leachate collection wells. The biocover resulted in a CH_4 oxidation efficiency of 81-100%. In addition, the authors evaluated the respiration potential of the compost and highlighted that the surface flux may constitute CO_2 from respiration in addition to CH_4 oxidation. It suggests that microbes may compete for oxygen for respiration and oxidation. One of the major challenges posed by using compost in biocover is its propensity for self-degradation leading to production of CH_4 and ultimately increasing the surface CH_4 flux [7]. Compost maturity was identified as a major factor for the design of compost biocover [73, 104, 106] as it may lead to increased oxygen demand and reduction in CH_4 oxidation if the compost used is not mature initially. Similarly, excessive formation of EPS in the zones of maximum oxidation was observed by Wilshusen et al. [121, 122] leading to pore clogging and ultimately hindering oxygen intrusion in the compost-based biocover. In addition, composts are rich in nutrients which may not always be favorable for the methanotrophs leading to growth of other heterotrophs. In addition, compost production is self-controlled as a result, it is hard to regulate their properties to suit the methanotrophic growth.

Addressing the drawbacks of compost as a biocover substrate, an inert and recalcitrant substrate called biochar was explored for landfill CH_4 mitigation. Biochar is a solid product produced by pyrolysis of waste biomass in the oxygen deficient condition at temperatures ranging from 300-1000 °C [123, 124]. The properties of biochar vary depending on the conditions of pyrolysis and types of feedstock [125, 126]. A wide variety of feedstocks can be used for biochar production such as wood chips, manure, and MSW. Biochar is characterized with high surface area and porosity, and adsorption potential for various chemical compounds including organic pollutants and gases [95, 127]. Owing to its unique physicochemical properties, use of biochar has gained prominence in various environmental applications [123]. The use of biochar in soil drew attention for carbon sequestration and mitigating climate change by replacing the organic biomass with less degradable form of carbon [126, 128]. Biochar had long been used in agriculture to improve the physical properties of the soil, fertility, and crop yield [128, 129].

Biochar as a biologic amendment to landfill cover soil to mitigate fugitive CH_4 emissions was first explored by Yaghoubi et al. [127] and Reddy et al. [95]. Laboratory column experiments were performed to simulate biocover with biochar-amended soil. The simulated biocover comprised of gas distribution layer (gravel) overlain by pinewood-based biochar-amended soil (20/80 weight%) and exposed to synthetic LFG for 4 months with variable flux rates [95]. High CH_4 oxidation rates were attained in biochar-amended soil layers with higher abundance of methanotrophic communities. The maximum CH_4 oxidation was observed at the upper 0-30 cm of the biochar-amended soil cover. Since, these studies established that biochar can enhance the CH_4 oxidation potential of the landfill cover soil by increasing oxygen availability and providing habitable environment for the methanotrophs, further investigations were carried out to establish the optimum biochar amendment ratios to economize the biocover application at landfills. In this regard, Yargicoglu and Reddy [130, 131] performed a series of large-scale column experiments with variable biochar amendment ratios and different cover configurations and assessed the long-term performance of the biochar-amended soil under dynamic gas flow conditions. Yargicoglu and Reddy [131] tested 2% and 10% biochar amendment to landfill cover soil and varied the biochar amendment depth. In two of the columns, biochar amendment (2% and 10%) were applied at 20-40 cm depth from ground surface of 60 cm thick biocover. One column had 10% biochar-amended soil over entire 60 cm of biocover thickness and another column had 60 cm of soil (control). Batch incubations were performed on the samples exhumed from various depths of each of the two columns to evaluate the CH_4 oxidation potential of the biochar-amended soil samples. The 10% biochar-amended soil showed the highest CH_4 removal potential for wide range of CH_4 loads (50- 200 g CH_4 m^{-2} d^{-1}) during the incubation period of 478 days. Biochar-amended soil showed characteristically higher moisture retention capacity reducing desiccation cracking which was otherwise very prominent in soil control column. Maximum CH_4 oxidation rate of 270 μg CH_4 $g^{-1}d^{-1}$ was observed in 10% biochar-amended soil cover at 30 cm depth. Yargicoglu and Reddy [130] also evaluated the effect of providing biochar alone as a thin layer within the soil cover. They observed that biochar helps to increase the moisture retention and provides favorable conditions for methanotrophs to proliferate, but biochar, being an inert material, does not increase CH_4 oxidation if used alone in the cover. Therefore, for an enhanced CH_4 oxidation, biochar needs to be mixed with landfill cover soil. In addition to laboratory column tests, field-scale pilot tests were performed to evaluate the performance of biochar-based biocover [99, 132] under real landfill conditions. Eight test plots including four replicate plots with 60 cm thick biocover and 30 cm thick gravel gas distribution layer placed over the existing 30 cm thick intermediate cover soil layer were tested over a span of 8 months (September to May) at a landfill in Illinois. Biocover profiles with 2% and 10% (*w/w*) biochar-amended soil were tested in the pilot-scale field tests. Surface emissions were analyzed with static flux chamber and the gas concentration along the depth of the cover through gas probes clusters. The field tests were highly impacted by the heterogeneity of the waste which led to very low CH_4 loads at the biochar-based biocover test plots and high CH_4 loads at the soil control test plots. Due to the high differences in the CH_4 loading from the waste, soil core samples showed high CH_4 oxidation rates in batch incubation than the biochar-amended soil samples [99]. This observation was further supported by the high relative abundance of the methanotrophic genera in the samples from soil control test plot. Type I methanotrophs were more abundant than Type II methanotrophs in the field samples as well as the laboratory column samples [99]. The effect of irregular gas distribution on biocover performance had previously been identified in several studies such as Scheutz et al. [120] who designed a semi-passive biocover system to deal with the uneven gas distribution from the waste. High variability in CH_4 oxidation rates and diversity in methanotrophic communities due to heterogeneity of waste at landfills had been reported in prior field studies [133, 134].

In a recent study by Huang et al. [135], biochar derived from cottonwood shavings were used for amending landfill cover soil for CH_4 oxidation. Column experiments (along with soil control) were performed by amending cover soil with 15% (*v/v*) biochar at 10-30 cm depth and performance was monitored for over a period of 101 days. Methanotrophic culture was poured at every 5 cm depth of soil to enrich the soil with MOB prior to exposure to synthetic LFG. In addition, one of the biocover test columns was supplied with additional aeration from a point below the biochar- amended soil layer besides air supply from the top of the column to increase the oxygen supply. Biochar-amended soil columns showed higher CH_4 oxidation rates (90.6% - 85.2%) than the soil control (78.6%). The authors observed a reduction in the CH_4 oxidation rates at the later stage of the experiment which was attributed to the depletion of the nitrogen nutrient in the soil. The relative abundance of Type II methanotrophs was more than that of Type I which contrasts with the observations of Reddy et al. [99] where Type I methanotrophs were reported to be more abundant, and the reason could be likelihood of a shift in microbial community due to the formation of microaerophilic environment from EPS formation which favors the growth of Type II methanotrophs [122]. Another recent study explored hydrophobic biochar-amended soil through laboratory column tests and compared its CH_4 oxidation potential with hydrophilic biochar amended soil and soil control [136]. The rice straw-based biochar was pretreated to render hydrophobic properties to tackle the high hydraulic conductivity of hydrophilic biochar. The authors observed high CH_4 oxidation rates in biochar-amended soil than the soil control with hydrophobic biochar attaining similar oxidation rates as hydrophilic biochar.

Most of the biochar-based biocover studies are based on the laboratory column studies which represent more idealized conditions whereas in the field the gas flow conditions as well as meteorological conditions vary severely which ultimately affect the performance of the biocover system. There have not been many field-scale studies performed till date with biochar-amended soil cover which have limited its full-scale application for a landfill closure. Although, biochar-amended soil cover appears to be effective for enhancing landfill CH_4 oxidation and mitigating CH_4 emissions, there is a need for extensive field studies to establish the performance of biochar-amended soil under various climatic conditions.

One of the issues that could impact the performance of the biocovers and biowindows could be the contrasting difference in the permeabilities of CH_4 oxidizing layer and gas distribution layer giving rise to capillary effect. Many studies[137, 138] have reported formation of capillary barrier and accumulation of water at the interface of CH_4 oxidizing layer and gas distribution layer resulting in uneven gas distribution and formation of CH_4 hotspots. Although capillary effect may be inexorable due to the functional requirements of biocover, it can be minimized by proper selection of the materials and designing the biocovers to minimize clogging due to water at the interfaces. For example, Cassini et al.[138] designed the gas distribution layer in zig-zag shape to allow water to collect at low points and break the capillary barrier due to pressure build up.

4.2.2 Cover Systems for Mitigating Non-Methane LFG Components

Apart from CH_4, LFG comprise of other trace organic compounds such as alkanes, alkenes, aromatic hydrocarbons, halogenated aliphatic compounds, and organic sulfur compounds [82, 139] which pose serious threats to environment as well as human health. The volatile organic compounds (VOCs) generated in the landfill are the outcome of the anaerobic decomposition of the organic waste in the limited oxygen environment [140]. The CH_4 oxidation potential of landfill cover soil suggested that some organic compounds may also be oxidized under similar conditions which prompted many researchers to explore biocovers for mitigation of other NMOCs in LFG. **Table 1** summarizes some of the studies which investigated the attenuation of NMOCs present in the LFG through biologic degradation. Some of the aromatic hydrocarbons such as benzene and toluene are rapidly oxidized in aerobic conditions and they show maximum removal in the oxic regions of the soil cover [143]. Methanotrophs can co-metabolize various hydrocarbons including halogenated aliphatic hydrocarbons [139]. Scheutz and Kjeldsen [142] investigated the degradation potential of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) along with CH_4 in laboratory column experiments and soil microcosms in landfill cover soil. High degradation potential of both HCFCs and CFCs was observed in column experiments with HCFCs degraded in aerobic conditions and CFCs in anaerobic conditions. In another study by Scheutz et al. [139], an inverse relation between chlorine/carbon ratio and degradation rates was observed. The lower chlorinated carbons such as vinyl chloride (VC) had highest degradation rates and trichloroethylene (TCE) had the lowest with no degradation of polychlorinated ethylene (PCE). Although fully substituted aliphatic compounds such as PCE and CFC-11 show limited oxidation in aerobic conditions, they form intermediate compounds like VC under anaerobic condition which are more prone to aerobic degradation [89]. Since methanotrophic conditions are suitable for degradation of several NMOCs, the use of biocovers (such as compost) have shown to favor the reduction of NMOC emissions in landfills over the soil covers [82]. Wang et al. [144] also observed a positive correlation between CH_4 oxidation and NMOCs attenuation. Although, laboratory-scale studies have shown potential for degradation of various NMOCs in landfill cover soils and biocovers, the same needs to be verified with extensive field demonstrations.

In addition to GHG emissions and NMOCs, odor is another challenging concern of the landfills. Odor problems impose environmental as well as societal impacts such as degradation of quality of life, depreciation of the property value, health risks to workers as well as people living near the landfills [146]. The odorous components of LFG comprise of phenols, nitrogen compounds, sulfur compounds, VOCs, and organic acids [117, 147]. Of the many odorous compounds, H_2S, methyl mercaptan, dimethyl sulfide and dimethyl disulfide are considered the major odor causing compounds [148, 149]. Among the sulfur compounds, H_2S has the highest abundance (~80%) and thus, a major contributor of the odor around landfills [146, 149]. In addition, H_2S is also considered the most perceptible odorous compound with the unique stench of rotten egg [150].

Table 1. Summary of studies exploring alternative covers for mitigating non methane compounds from landfill gas

Non methane LFG components	Type of cover material	Type of study	Observations	Reference
Selected NMOCs and speciated organic compounds (halogenated aliphatics, aromatics, halocarbons)	Soil cover (clay) and biocover (yard waste compost)	Field investigations	Most of the highest emissions of NMOCs and speciated organic compounds measured were from soil cover. The suitable conditions induced by biocover promotes aerobic degradation of organic compounds other than methane.	Barlaz et al. [82]
Selected VOCs (chlorinated alkanes, alkenes, halocarbons, aromatics)	Soil cover (loamy sand)	Laboratory batch incubations	Lower chlorinated compounds are more prone to aerobic degradation. Oxidation rates of • Halogenated aliphatics ranged from 0.03-1.7 $\mu g\ g_{soil}^{-1}\ h^{-1}$ • Aromatics ranged from 0.17-1.4 $\mu g\ g_{soil}^{-1}\ h^{-1}$)	Scheutz et al. [89]
Selected VOCs (CFC-11, HCFC-21, HCFC-31, and fluoromethane (HFC-41))	Compost derived cover (compost/wood chips (1:1), compost/sand (1:1), compost/sand (1:5), and supermuld)	Laboratory batch incubation and dynamic column experiments	The compost derived simulated covers showed significant attenuation capacity for the VOCs (56- 94 % removal efficiency in compost/woodchip).	Scheutz et al. [106]
Selected NMOCs (halogenated aliphatics, aromatics)	Soil cover (Coarse sand + silty to sandy loam)	Laboratory batch incubation tests and Field	Oxidation rates for • halogenated aliphatic compounds ranged from 0.06 to 8.56 $\mu g\ g_{soil}^{-1}\ d^{-1}$ • benzene and toluene were 28 and	Scheutz et al. [139, 141]

		investigations	39 μg g_{soil}^{-1} d^{-1}, respectively	
Halocarbons (CFC-11, CFC-12, HCFC-21, and HCFC-22)	Soil cover (Loamy sand to sandy loam)	Laboratory column experiments and batch incubation tests	• Anaerobic degradation of CFCs (90% and 30% removal of CFC-11 and CFC-12, respectively) with no degradation under aerobic conditions • Aerobic degradation of HCFCs (61% and 41% removal of HCFC-21 and HCFC-22, respectively)	Scheutz and Kjeldsen [142]
Selected VOCs (TeCM, TCM, DCM, TCE, VC, benzene, toluene)	Soil cover (loamy sand, sandy loam)	Laboratory batch incubations and column experiments	Degradation of all chlorinated compounds with removal efficiency > 57%, high degradation rates of benzene and toluene (0.18 and 0.12 g m^{-2} d^{-1}, respectively)	Scheutz and Kjeldsen [143]
Selected NMOCs (sulfur compounds, halogenated hydrocarbons, aromatics, aliphatic hydrocarbons, terpene, oxygenated compounds)	Intermediate cover soil	Field investigations	Significant reduction in concentrations of NMOCs (halogenated compounds and aromatics) observed in the soil cover. A synergistic effect of methane oxidation on NMOCs degradation was observed	Wang et al. [144]
Selected NMVOCs (toluene)	Waste biocover soil and landfill cover soil (sandy loam)	Laboratory column experiments	Waste biocover soil (99.7-99.9%) showed relatively higher toluene removal potential than landfill cover soil (97.8-99.6%). Toluene removal was higher in the absence of methane due to lesser competition for available oxygen.	Su et al. [145]

Significantly higher H_2S concentrations are prevalent in the construction and demolition (C&D) landfills due to the biological degradation of gypsum ($CaSO_4 . 2H_2O$), a prime component of C&D waste, by the sulfate-reducing bacteria (SRB) [151]. Since C&D waste landfills do not have strict gas collection regulations as MSW landfills, the odorous gases are more likely to escape to the atmosphere [152]. H_2S is also generated in notable amounts in MSW landfills from sulfur containing organic waste such as paper and food, and sludge from wastewater treatment plants [153]. Although H_2S is produced in trace amounts in MSW landfills, H_2S can be perceived at very low concentrations (odor threshold of 0.01-1.5 ppmv) and can be harmful at low concentrations of 30-40 ppmv [154]. The concentrations can reach 450 ppmv and more in landfill cells [152].

Although alternative landfill cover systems with wide variety of substrates were developed, most of them focused on biological CH_4 oxidation. As the odor nuisance from landfills started to emerge as a pressing challenge, alternative cover systems were explored to mitigate odor and reduce releases of odorous compounds. Plaza et al. [152] performed laboratory-scale column experiments to simulate the H_2S production from C&D waste and tested five different cover materials: 1) sandy soil, 2) lime amended sandy soil, 3) clayey soil, 4) fine concrete (particle size < 2.5 mm), and 5) coarse concrete (particle size > 2.5 cm) by placing the cover materials over the waste in the experimental columns. H_2S production from the waste ranged from 5% to 15% (*v/v*). Lime amended sandy soil and fine concrete showed highest H_2S removal efficiencies (> 99%) followed by clayey (65%) and sandy soils (30%) with coarse concrete showing lowest H_2S removal efficiency. The reduction in H_2S emission through clayey and sandy soil cover was attributed to the formation of physical containment by the cover system limiting the diffusive migration of H_2S. H_2S removal in lime amended soil and fine concrete was attributed to the reaction between hydrated lime and H_2S forming sulfide minerals (**Eqs. 3** and **4**) under alkaline conditions induced by the lime and concrete [152]. Although mineralogical identification was not done to assert the formation of sulfides, the change in color of the cover substrates to black towards the end of the experiment was taken as an indication of formation of the metal sulfides.

$$Ca(OH)_2 + H_2S \rightarrow CaS + 2H_2O \quad (3)$$

$$H_2S + CaO \rightarrow CaS + H_2O \quad (4)$$

Similarly, Xu et al. [151] performed field tests as well as laboratory microcosm tests to evaluate the attenuation of H_2S by six different alternative cover materials: 1) sandy soil, 2) fine concrete, 3) compost, 4) sandy soil amended with 10% agricultural lime ($CaCO_3$), 5) sandy soil amended with 1% hydrated lime [$Ca(OH)_2$] and 6) sandy soil amended with 3% hydrated lime. All the covers were able to remove H_2S (99%) during the field-testing period of ten months, however, sandy soil cover showed the lowest removal rates among the six cover systems. In the laboratory batch experiments, fine concrete showed a rapid H_2S removal rate (90% within 5 mins of exposure). Similarly, the hydrated lime (3% and 1%) amended soil took 10 mins for 90% removal of H_2S. Sandy soil showed the lowest H_2S removal capacity, 60% in 60 mins. The removal of H_2S by concrete and lime-amended soils was attributed to the adsorption on the particle surface and conversion to metal sulfides as reported by Plaza et al. [152]. Compost showed substantial H_2S removal both in field and laboratory tests. Although it did not have high alkalinity as that of lime, the H_2S removal was attributed to the biotransformation by sulfur oxidizing bacteria (SOB) which was supported by reduction in pH from 7.4 to 6.3 [151].

Table 2 summarizes some of the studies which studied potential of various alternative cover materials for mitigating odorous compounds including H_2S in LFG. A wide range of biological materials such as waste biocover soil, compost, mixtures of soil and earthworm casts have shown appreciable adsorption capacity for malodorous compounds such as H_2S, trimethylamine, aldehydes, etc. (**Table 2**). The prime mechanism for H_2S removal in biocovers and landfill cover soils has been attributed to adsorption and biotransformation [149, 151, 155]. Xia et al. [149] observed high diversity of SOB such as *Halothiobacillus*, *Thiobacillus*, *Thiovirga* and *Bradyrhizobium* and SRB such as *Desulfobacca*, *Desulforhabdus* and *Syntrophobacter* in the landfill cover soils. SOB oxidizes H_2S to elemental sulfur (S^0) and sulfate (SO_4^{2-}) under aerobic conditions [158]. SRBs are mostly anaerobes but they may be present in oxic environments as some of the species show oxygen tolerance [159]. Xia et al. [158] studied the sulfur metabolizing bacteria in the waste biocover soil and landfill cover soil and observed 4.3 to 5.4 times increase in sulfur oxidation rate in waste biocover soil in comparison to landfill cover soil. pH affects the abundance of SOB and SRR in the soil and a neutral or slightly alkaline pH has been found to be favorable for oxidation of sulfur in landfill cover soils [149]. Many studies have shown the potential in biocovers and landfill cover soils for mitigation of odorous compounds emanating from landfills, however there is a need for exploring an integrated system which can mitigate all the major LFG components such CH_4, CO_2 and H_2S at once as it is not feasible and economical to place separate cover systems in a landfill to mitigate each LFG component.

Table 2. Summary of studies exploring alternative covers for mitigation of malodorous compounds from landfill gas

Target Compound	Cover Material	Key Observations	Reference
Ammonia, hydrogen sulfide, methyl mercaptane, acetic aldehyde, toluene, xylene and other 16 odorous compounds	Biocover made of mixture of soil, perlite, earthworm castings, compost, 6:2:1:1, v/v)	• The removal efficiency of odorous compounds was higher in biocover and achieved nearly 85% in all seasons. • Among the 22 odorous compounds tested, biocover showed highest removal efficiency for H_2S across alls the seasons. • Mechanism for H_2S removal attributed to adsorption and biodegradation. • Sulfur oxidizing bacteria (SOB) such as *Arthrobacter* were identified in the biocover which can oxidize sulfur compounds like H_2S, dimethylsulfide and dimethyldisulfide to sulfate.	Lee et al. [117]
Total reduced sulfur (TRS) compounds	Four cover types tested: 1) mixture of sand-compost and gravel; 2) Mixture of sand-compost; 3) sand overlain by topsoil; and 4) mixture of topsoil and compost underlain by topsoil and sand layers	• The odor and TRS removal efficiency were > 95% in all four cover systems. • The major parameters affecting the removal efficiencies were degree of saturation and gas loading rate. The odor concentrations following significant precipitation events (48- hour accumulated precipitation) were lower. • Higher biogas loading resulted in increased emissions of odor as well as TRS compounds.	Capanema et al. [146]
Hydrogen sulfide	Waste biocover soil, landfill cover soil, mulberry soil and sandy soil	• Highest adsorption capacity shown by waste biocover soil in comparison to landfill cover soil, mulberry soil, and sandy soil. • Maximum adsorption by waste biocover under optimum temperature, moisture and pH condition was	He et al. [154]

		60 ± 1 mg/kg.	
Hydrogen sulfide	Waste biocover soil and landfill cover soil	• H_2S removal efficiency of greater than 90% achieved in both waste biocover soil and landfill cover soil, however waste biocover soil showed better removal efficiency among the two cover systems. • The major H_2S removal mechanism was adsorption of H_2S gas on particle surface, dissolution into pore water and biotransformation. • Sulfide was observed as the major H_2S removal. • The growth of sulfur oxidizing bacteria and sulphate reducing bacteria were observed with the exposure of the covers to H_2S.	He et al. [155]
Trimethylamine (TMA), and dimethyl sulfide (DMS)	Biocover made of mixture of tobermolite, landfill cover soil, and earthworm castings (2:1:1, w/w)	• The malodorous components were completely removed by the cover system with the removal efficiencies of 100%. • The major mechanism was oxidation and the removal of the components started from the bottom of the cover system (40-50 cm below top surface).	Lee et al. [156]
Hydrogen sulfide	Four different cover materials tested: 1) Charcoal sludge compost (CSC); 2) final landfill cover soil (FCS); 3) Aged refuse (AR); and 4) Clay soil (CS)	• CSC showed highest H_2S removal in both laboratory (~88%) and field studies (~82%) followed by FCS (81-68%) and AR (77-59%) with CS showing lowest removal efficiency (72-50%). • The H_2S removal was attributed to adsorption, chemical reactions, and biological oxidation. • Significant increase in sulfate and total sulfur concentrations observed in CSC confirming biotransformation of H2S by Sulfur oxidizing bacteria.	Ding et al. [157]

4.2.3 Biogeochemical cover system

Most of the alternative cover systems have been studied with respect to mitigation of CH_4 or NMOCs or odor. Although, CO_2 constitutes 50% of the volume of LFG and is a highly potent GHG, very little focus is given to landfill CO_2 mitigation. In addition, mitigating CH_4 alone or odor alone does not solve the problems of fugitive landfill emissions. In this regard, an alternative cover system called biogeochemical cover is being developed which comprise of biochar-amended soil and basic oxygen furnace (BOF) steel slag [160-162]. The biogeochemical cover system leverages on the CH_4 oxidation potential of biochar-amended soil [131] and the CO_2 and H_2S sequestration potential of BOF slag [162, 163-166] to mitigate CH_4, CO_2 and H_2S simultaneously thus rendering MSW landfills nearly emissions free. A schematic of the biogeochemical cover system is shown in **Fig. 8**. CH_4 is oxidized into CO_2 in the biochar-amended soil layer of the biogeochemical cover. Biochar amendment assists in enhancing the CH_4 oxidation potential of the soil as discussed in the biocover section earlier. The CO_2 produced during oxidation of CH_4 in the biochar-amended soil layer and CO_2 and H_2S generated in the waste passes through the overlying BOF slag layer where it gets sequestered by the geochemical reaction mechanisms. BOF slag is a type of steel making slag which is generated as the byproduct during steel making process. The similarity of steel slag's chemical composition to natural minerals capable of binding CO_2 naturally led to intensive studies exploring CO_2 sequestration potential of steel slag [167]. The peculiar properties of BOF slag such as high alkalinity ($pH > 11$), presence of Ca, Mg and iron (Fe) containing minerals, and high shear strength properties make it suitable for use in landfill cover applications. The Ca containing minerals such as lime (CaO), portlandite [$Ca(OH)_2$] and larnite (Ca_2SiO_4) present in the BOF

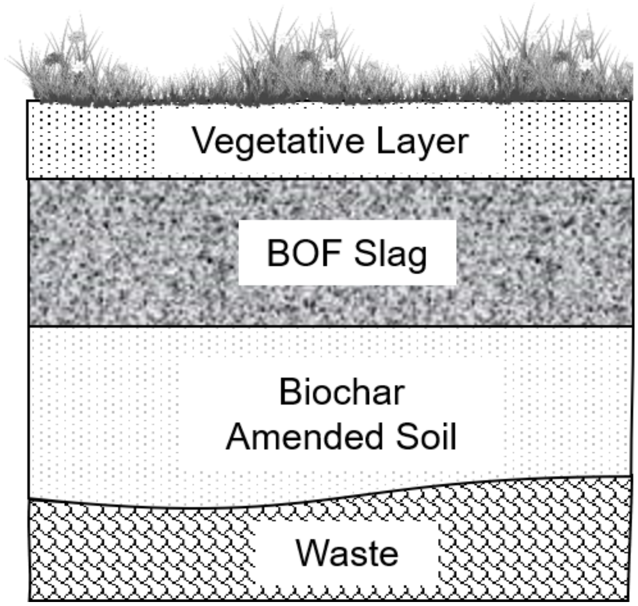


Figure 8. Schematic of biogeochemical cover system

slag can readily bind CO_2 and convert it into stable form of carbonates ($CaCO_3$) as shown in the **Eqs. 5–7.**

$$CaO + CO_2 \rightarrow CaCO_3 \quad (5)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 \quad (6)$$

$$Ca_2SiO_4 + 2CO_2 \rightarrow 2CaCO_3 + SiO_2 \quad (7)$$

Reddy et al. [163-165] investigated CO_2 sequestration potential of the BOF slag under various conditions such as moisture, temperature, LFG loading rates, LFG conditions (dry and humid), BOF slag types, and slag particle sizes (fine to coarse). BOF slag showed significant potential for CO_2 sequestration under simulated LFG conditions. Moisture appeared to be an important parameter for initiation of the carbonation reactions in the slag however, the moisture content as low as 10% (*w/w*) resulted in significant carbonation (68 g CO_2/kg BOF slag) in the laboratory batch experiments [162]. A prolonged carbonation was observed upon exposure to continuous flow of humid LFG (mixture of 50% CH_4 and 50% CO_2, *v/v*) resulting in CO_2 sequestration of 350 g CO_2/kg BOF slag [163]. Apart from moisture, particle size and BOF slag type have pronounced effect on the CO_2 sequestration capacity of the BOF slag. In the study by Reddy et al. [165], fine slag (mean particle size = 0.094 mm) showed highest CO_2 sequestration (255 g CO_2/kg BOF slag) followed by the slag with original gradation as obtained from the steel plant (mean particle size = 0.47 mm) which was 155 g CO_2/kg BOF slag. Coarse slag (mean particle size = 3.05 mm) showed the lowest CO_2 sequestration potential (66 g CO_2/kg BOF slag). The properties of BOF slag vary depending on the production batch and the proportions of the fluxing agents charged during the steel making process [164, 168]. In the study by Reddy et al. [164], the BOF slags obtained from different plants showed different CO_2 sequestration potential which was mainly attributed to the heterogeneity in the mineralogical composition and the average particle sizes of the BOF slag. Overall, BOF slag appeared to be a promising alternative for CO_2 sequestration from LFG.

Several studies have explored H_2S removal potential of steel slag [166, 169-173]. All the studies showed a promising potential for H_2S removal in steel slag. Iron appeared to be the leading metal in binding H_2S in the form of iron sulfides (**Eqs. 8–9**).

$$FeO + H_2S \leftrightarrow FeS + H_2O \quad (8)$$

$$Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O \quad (9)$$

Since steel slag has abundant iron content in the form of iron oxides, it makes a suitable alternative for mitigating H_2S at the landfills. Recently, Chetri et al. [166] performed a series of laboratory batch and column experiments with BOF slag under various simulated LFG conditions (48.25% CH_4, 50% CO_2 and 1.75% H_2S *v/v*). The BOF slag was able to sequester both CO_2 and H_2S resulting in maximum CO_2 and H_2S removal potential of 300 g CO_2/ kg BOF slag and 38 g H_2S/kg BOF slag, respectively.

The highly alkaline nature of steel slag may be favorable for CO_2 and H_2S sequestration, but it may also impede the survival of methanotrophic community for CH_4 oxidation in the biogeochemical cover, as the optimum pH for CH_4 oxidation has been reported to be in the range of 6.5–7.5 [93, 100]. Although, the biogeochemical cover proposed by Reddy et al. [160, 161] aims to have biochar-amended soil and steel slag layers in separate layers, there is still concern for effect of infiltrated water percolating through the slag layer on the microbial CH_4 oxidation in underlying biochar-amended soil. Hence, Reddy et al. [174] investigated the effect of slag infiltrated water on CH_4 oxidation and microbial community in the landfill cover soil. The results from the study showed that the slag infiltrated water did not have a significant impact on the CH_4 oxidation potential due to the high buffering capacity of the landfill cover soil. Moreover, the slag infiltrated water did not impact the microbial community composition substantially even at the highest concentration of the slag infiltrated water (100% of the soil's moisture content of 20% *w/w*). Therefore, using BOF steel slag as a CO_2 and H_2S sequestering layer in the biogeochemical cover does not appear to have a negative impact on the microbial CH_4 oxidation of the biochar amended soil layer. However, the effect of BOF slag carbonation on the cover's porosity, hydraulic conductivity, volumetric stability, etc. during long-term operation needs to be evaluated as these may significantly affect the performance of the cover system. Studies have reported reduction in the porosity of the BOF slag due to calcite precipitation [175, 176]. Although reduction in pore size may suggest that the carbonation may result in reduction of hydraulic conductivity of the carbonated slag, the studies confirming the same are scarce. On the other hand, studies[177] have also reported increase in particle size after carbonation due to particle aggregation and volume expansion increasing average pore size and gas diffusion. Hence, there is a paucity of information asserting the behavior of BOF slag under actual landfill condition. Therefore, there is a need to evaluate the engineering behavior of carbonated slag for a sustainable cover design. Similarly, the performance of biogeochemical cover needs to be validated with the help of field investigations under dynamic meteorological field conditions.

5 Research Challenges

Over the years, the landfilling practices have evolved with significant technological advances in landfill cover systems. Modern engineered cover systems with very low permeability and high strength have been developed with the advanced geosynthetic designs and performance. Parallelly, there have been remarkable advancements in the alternative cover systems. However, the literature unveils some key challenges associated with the modern engineered cover systems and the alternative cover systems. Some of the research challenges are described as follows:

- **Resiliency**: With the extreme climatic events becoming recurrent and landfill cover being directly exposed to the environmental conditions, there is a need to develop cover systems which can perform their design functions and meet regulatory requirements even under the extreme climatic events such as flooding, draught, excessive snow, etc.
- **Elevated temperatures:** The issues of elevated temperature landfills where the temperatures of waste within the landfill exceeds well over 65 °C [178, 179] are gaining wide prominence. Hence, the performance of conventional and bio-based cover systems under elevated temperature conditions needs investigation.

- **Emerging pollutants**: As the waste composition is changing continually, more and more emerging contaminants are being recognized. Hence, the future research needs to focus on developing cover systems to mitigate these emerging pollutants from LFG emissions.
- **Economic feasibility**: Landfilling practices vary significantly in low income countries or developing countries where open dumping forms a popular waste disposal alternative with nearly 93% of wastes being openly dumped [1]. Similarly, the type of waste varies geographically and thus the gas composition and gas emission rates. Hence, the landfills designed for one geographic region or income region might not be attainable for another region. It is a challenge for researchers to develop cover systems which can serve in wide range of economic and geographic conditions.
- **Management of abandoned landfills:** The modern engineered landfills are designed to comply with the stringent regulatory requirements however, the abandoned landfills which do not have necessary components such as an impermeable bottom liner system, leachate collection system and impermeable cover system to meet the regulatory requirements are often the cause for concern. Although the majority of LFG, mainly CH_4, is generated during first few years of waste disposal, the gas generation continues for several hundred years after the closure of the landfill [180]. Hence, landfills without proper enclosure systems in place such as abandoned landfills may pose threat to human health and environment for a prolonged period. Therefore, it presents a challenge for current and future researcher to develop cover systems which are not only deemed serviceable for modern engineered landfills but also to the abandoned landfills without imposing significant economic burden on the managers of abandoned landfills.

- **Longevity and durability**: Because landfills emit gases for a prolonged duration of time after closure, it is utmost important that the alternative covers perform their function for the entire service life of the landfill. For example, some bio-based cover materials such as compost are subject to self-degradation in the long-term thereby generating CH_4 rather than mitigating it [7]. Similarly, the physical processes such as capillary action may develop in some covers such as biocovers in the event of precipitation due to the stark differences in the hydraulic conductivities of biogenic layer and gas distribution layer causing occlusion of the pores and limiting gas transport. Hence, it necessitates further research in exploring alternative cover materials which have better long-term performance without significant economic ramifications as well as improve the cover design to incorporate any potential water-logging due to infiltration.
- **Slope stability:** With the increasing scarcity of open lands, the landfills are designed with steeper slopes and greater heights to increase the waste containment capacity. This calls for developing cover systems with enhanced slope stability. It presents a bigger challenge for alternative cover systems whose core function is gas mitigation or infiltration barrier. Hence, it is a challenge to design alternative cover systems to provide slope stability in addition to gas mitigation and minimizing infiltration.

6 Summary

Landfilling has transformed enormously over the years from mere dumping to modern engineered landfills. Landfill covers have evolved from basic soil covers protecting breeding of flies and birds to advanced engineered cover systems with impermeable GMs and gas collection systems. The regulations regarding landfill cover management have become stricter over the decades to reduce leachate generation and prevent emissions of LFGs. The conventional landfill covers are mainly designed to prevent infiltration into the landfill to minimize the leachate generation. The newer regulations require landfills to manage LFG emissions by installing gas collection systems if the CH_4 emissions are high. The older landfills where providing gas collection systems is not economically and practically feasible, managing gas migration becomes a major challenge. Similarly, conventional cover systems are cost intensive and are susceptible to desiccation cracking and erosion, leading to increased infiltration and gas migration. Hence, extensive research has been conducted in the past two decades exploring various alternative cover systems.

The alternative cover systems are required to meet the regulatory requirements in terms of minimizing the infiltration. Various alternative cover systems such as ET covers, anisotropic covers, capillary barriers and engineered turf covers have been developed which utilizes the natural processes to control rainwater infiltration into the waste. These covers are not only economic but also add aesthetic value to the landfills. However, each of these cover systems suffer from some limitation regarding their applicability in dynamic climatic regions.

As MSW landfills emerged as a prime contributor of anthropogenic CH_4 missions globally, CH_4 oxidation potential of landfill cover soil was investigated, and several organic based alternative cover systems such as biocovers have been explored to enhance microbial CH_4 oxidation in landfill cover. Several organic materials have been tested as the biocover substrate such as compost, waste biocover, earthworm cast and sewage sludge. One of the challenges associated with using biobased cover systems is their long-term stability and hence there is a need to explore cover systems which are durable and sustainable at the same time. In this regard, biochar-based cover systems are gaining popularity as they are more recalcitrant under adverse climatic conditions and enhances the physical properties of the cover systems favoring the growth of CH_4 oxidizing microbial population.

Apart from CH_4, other trace gas emissions such as H_2S, methyl mercaptan, aldehydes, BTEX compounds, etc., from landfills pose serious concerns for health and environment. Alternative cover systems have been explored to mitigate these non-methane emissions from landfills. However, there is a need to develop an integrated cover system which addresses all the fugitive LFG emissions together resulting in zero emissions at the landfills. The newly proposed biogeochemical cover system offers promise in mitigating three of the major LFG components (CH_4, CO_2 and H_2S) by utilizing byproducts from the steel making process (steel slag) and waste biomass in the form of biochar. This could be an environment friendly and sustainable alternative to the fugitive LFG emissions however, the cover system is still in its infancy and needs to be validated with extensive field-testing programs to affirm the laboratory findings and conclusions.

Altogether, this review outlines how MSW landfill cover systems have evolved over the past three decades and how these advancements in the cover systems are benefitting the environmental pollution prevention. Furthermore, this study also presents the basic mechanisms underlying the functioning of the various alternative cover systems for mitigating various components of LFG. In the end, the study casted light on the research challenges associated with the development and performance of the alternative cover systems and prospects for the researchers.

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8 Conflict of Interest Statement

The authors have no conflict of interest.

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