A true green cover for industrial waste landfills

RUTUPARNA JOSHI

ABSTRACT: Greenhouse gas (GHG) emissions in the United States totaled 5,981 million metric tons of carbon dioxide equivalent (MMT CO_2eq) in 2020. Of that, GHG emissions by the pulp and paper sector amounted to 35 MMT CO_2eq direct emissions and those by industrial waste landfills summed to 7.4 MMT CO_2eq direct emissions. Loss of GHG sinks due to change in land use further contributes to the net GHG emissions. Industrial waste landfills are typically required to comply with certain federal and state regulations, including meeting requirements for final cover systems. Conventional final cover systems have included use of soil covers and/or soil-geosynthetic composite covers. An engineered turf cover provides for an excellent "green" alternative final cover system for industrial waste landfills.

This paper discusses various sustainability aspects pertaining to use of an engineered turf final cover, including: (i) significantly low carbon footprint associated with the construction of an engineered turf alternative final cover when compared to closure using a traditional or prescriptive cover system; (ii) saving valuable soil and land resources; (iii) saving water resources by reduction in its use during and after construction; (iv) reducing impacts associated with borrow areas; and (v) reducing overall carbon footprint. Further, when using an engineered turf cover, opportunities exist for beneficial reuse of land, including development of solar energy. A brief discussion on the potential for development of solar energy is included.

Application: Readers are introduced to various sustainability aspects in selecting solutions for industrial waste landfills, including detailed emissions quantification for closures. Using similar assessments and methodologies, organizations can use data to measure progress towards their sustainability and environmental, social, and governance (ESG) goals.

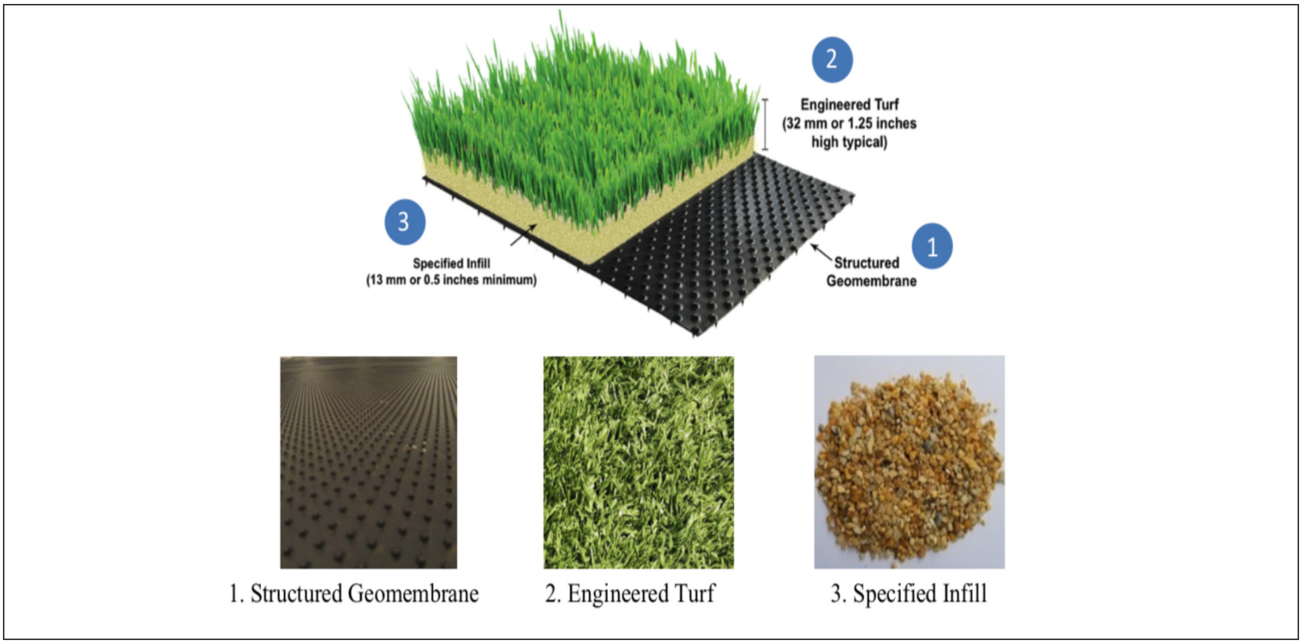
Greenhouse gases (GHG) absorb infrared radiation, thereby trapping heat in the atmosphere and making the planet warmer. Global warming and resulting global climate change are unequivocal. The dominant cause of global warming since the mid-20th century is human activity. It is of paramount importance to drastically reduce anthropogenic GHG emissions (also referred to as carbon emissions or emissions, hereafter). In 2020, total gross GHG emissions in the United States were 5,981 million metric tons of carbon dioxide equivalent (MMT CO_2eq) [1]. Of that, emissions by the Pulp and Paper sector amounted to 35 MMT CO_2eq and those by the Waste Sector, which includes the industrial waste landfills and industrial wastewater treatment systems, summed to 105.5 MMT CO_2eq (non-biogenic). The majority of these emissions, 86.8 MMT CO_2eq, were municipal solid waste (MSW) landfill methane (CH_4) emissions, representing the third largest source of methane emissions in the United States. Emissions from industrial waste landfills accounted for 7.4 MMT CO_2eq [1]. According to the Waste Business Journal (WBJ) database [2], there were approximately 1,200 landfills in the United States accepting industrial and/or construction and demolition debris in 2016. Of those, 169 industrial waste landfills met the threshold of the U.S. Environmental Protection Agency (EPA) Greenhouse Gas Reporting Program (GHGRP) in 2020 and reported their emissions.

Various activities (e.g., construction, regular operations, and maintenance) are conducted at landfill sites that generate carbon emissions. Many of these GHG generating activities may not be required to be recorded or reported to the EPA or other regulatory agencies. Nevertheless, they lead to carbon emissions. Numerous public and private organizations track their annual emissions and have set goals of net-zero carbon emissions. For industrial waste landfills, opportunities exist to use alternative solutions to reduce emissions. One such solution is the use of an alternative final cover system comprised of an engineered turf cover.

The subsequent sections of this paper discuss the following: (i) industrial waste landfills and closure regulations in the U.S.; (ii) engineered turf final cover system; (iii) environmental benefits associated with engineered turf final cover; (iv) comparison of emissions from a traditional final cover to emissions from the alternative final cover; and (v) potential for beneficial use of landfill cover for solar energy generation.

INDUSTRIAL WASTE LANDFILLS AND CLOSURE REGULATIONS

In the United States, non-hazardous solid waste is regulated under Subtitle D of the Resource Conservation and Recovery Act (RCRA). Subtitle D sets forth minimum federal regulations for MSW and industrial waste landfills.



1. Engineered turf cover system components.

Landfill closure requirements typically require a final cover system that is designed to minimize infiltration and erosion. The Office of the Federal Register (OFR) Subpart F of 40 CFR §258.60 [3] indicates that the final cover system must be designed and constructed to: (i) have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} cm/s, whichever is less; (ii) minimize infiltration through the closed landfill by the use of an infiltration layer that contains a minimum 18 in. (450 mm) of earthen material; and (iii) minimize erosion of the final cover by the use of an erosion layer that contains a minimum 6 in. (150 mm) of earthen material that is capable of sustaining native plant growth. States may approve of alternative final cover designs that demonstrate inclusion of an infiltration layer that achieves an equivalent reduction in infiltration and an erosion layer that provides equivalent protection from wind and water erosion.

The final cover system prescribed in the federal regulations relies on an infiltration layer, which is typically, a compacted clay layer (CCL). Often, a soil-geosynthetic or geosynthetic composite cover such as a geomembrane, a geomembrane underlain by a CCL, or a geomembrane underlain by a geosynthetic clay liner (GCL) is used as the infiltration layer. A number of concerns have been identified regarding the performance of a prescriptive final cover system, particularly when it is installed within one year after final waste placement. One of the major concerns in this regard, primarily for MSW landfills, is the impact of landfill settlement during the post-closure care (PCC) period on the integrity of the final cover system. Other concerns include loss of landfill airspace due to cover soil and infiltration soil requirements, veneer slope stability, soil erosion, and the continual need to mow and maintain the cover vegetation [4]. Alternative final cover systems have been developed and implemented to address these concerns. The EPA and multiple state agencies have approved alternative final cover systems.

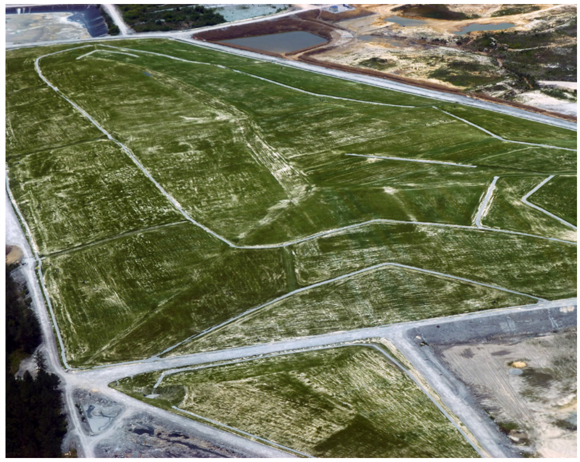
ENGINEERED TURF FINAL COVER SYSTEM

A typical engineered turf cover such as a ClosureTurf system (Watershed Geosynthetics; Alpharetta, GA, USA) consists of, from bottom to top, a structured geomembrane, an engineered turf, and a specified infill, as shown in **Fig. 1**. The structured geomembrane serves as a hydraulic barrier to isolate waste from the environment and minimize infiltration of precipitation into the waste. The engineered turf is manufactured of polyethylene (PE) synthetic turf fibers (synthetic grass blades) tufted into a double layer geotextile backing, which covers the underlying geomembrane and protects it from ultraviolet (UV) radiation exposure and wind uplift. The specified infill, which is a minimum 13-mm-thick sand layer buried in the synthetic grass blades, provides additional wind ballast and UV protection and improves trafficability on the cover surface.

The structured geomembrane provides equivalent performance to that of an infiltration layer, and the engineered turf and sand infill provide performance equivalent to protective and vegetative soil layers. Various concerns (noted previously) when using prescriptive (or traditional) soil covers are eliminated and/or minimized when using an engineered turf cover system.

The engineered turf cover meets the RCRA Subtitle D final cover system requirements and state solid waste management regulations. It has been approved by the regulatory agencies as an alternative to the prescriptive soil cover

Baldwin County Landfill, Georgia



Paper Mill Sludge Pond, Southeast USA

2. Photographs of engineered turf cover installations at Baldwin County Landfill in Georgia and a papermill sludge pond in the southeastern United States.

system for the final closure of landfills. Since the first installation in 2009, more than 1,200 hectares (ha) of engineered turf covers have been installed at sites located in a wide range of weather conditions and geographic areas of the United States. Aerial photographs of two engineered turf cover installations, one at an MSW landfill site and another at an industrial sludge pond, are shown in **Fig. 2**. A detailed account of the final closure of the industrial sludge pond/impoundment is included in a separate publication [5].

ENVIRONMENTAL BENEFITS

Use of engineered turf cover offers numerous environmental benefits over traditional soil covers. These include:

- Significant reduction in final cover system construction emissions.
- Avoiding land use change.
- Avoiding land disturbance and associated impacts.
- Reduction in construction materials.
- Water conservation.
- Improved water quality.

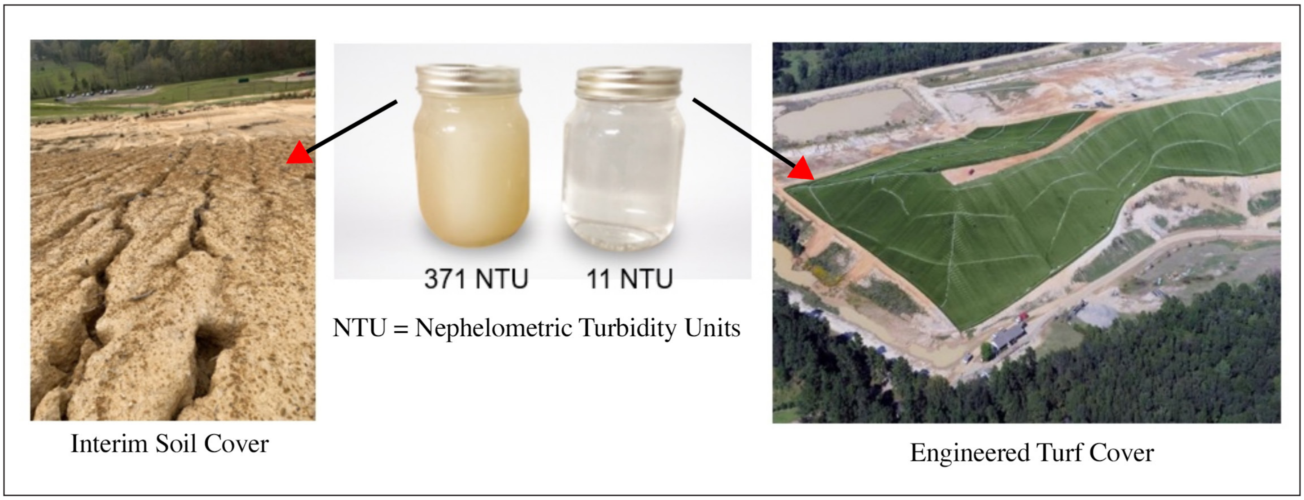
An engineered turf cover offers significant reduction in the final cover system construction emissions as compared to a traditional soil final cover. A detailed evaluation of the carbon emissions from a traditional soil cover and an engineered turf cover is discussed in subsequent sections.

An engineered turf final cover system eliminates the use of soil layers, typically 0.6-m thick, thereby drastically reducing the amount of soil and earthwork necessary for construction as compared to a traditional soil cover. Soil for traditional covers is obtained from borrow areas. Frequently, there are multiple environmental impacts associated with borrow areas, such as deforestation and land use change. When using an engineered turf cover, only an exceedingly small amount of sand (2% of typical 0.6-m thick) is required, and hence, potential deforestation and/or land use change is significantly avoided. This enables preservation of soil and land resources and corresponding preservation of sequestered carbon.

Further, in obtaining soil from borrow areas, the topsoil is destroyed or highly disturbed. In using an engineered turf cover system, loss of topsoil is avoided, thereby preserving the microorganisms necessary for healthy soil and soil organic matter. Land disturbing activities further exacerbate impacts to the environment. Exposed soil areas are subject to erosion due to wind and water. Erosion further leads to deposition and sedimentation in downstream water bodies and infrastructure. These impacts of land disturbance are avoided when using engineered turf, since land disturbance to obtain soil resources is avoided.

Water is a valuable resource and any savings in transportation and use of water provides a positive environmental impact. Conservation of water can be realized during and after construction when using an engineered turf cover. For instance, a traditional soil cover is required to incoporate a CCL. Compaction of a clay layer necessitates moisture conditioning of the clay (typically, addition of a certain amount of water) to achieve certain hydraulic conductivity requirements. Water trucks need to be used for moisture conditioning. Further, earthwork at project sites necessitate use of dust suppression measures, which are primarily performed using multiple full-time water trucks. With an engineered turf cover installation, use of dust suppression water trucks can be dramatically reduced. Further, post-construction use of water for irrigation or other operations and maintenance of engineered turf is not needed.

The construction for traditional soil covers is earthwork intensive. On-road and off-road trucks and various construction equipment are typically necessary. Heavy earth-



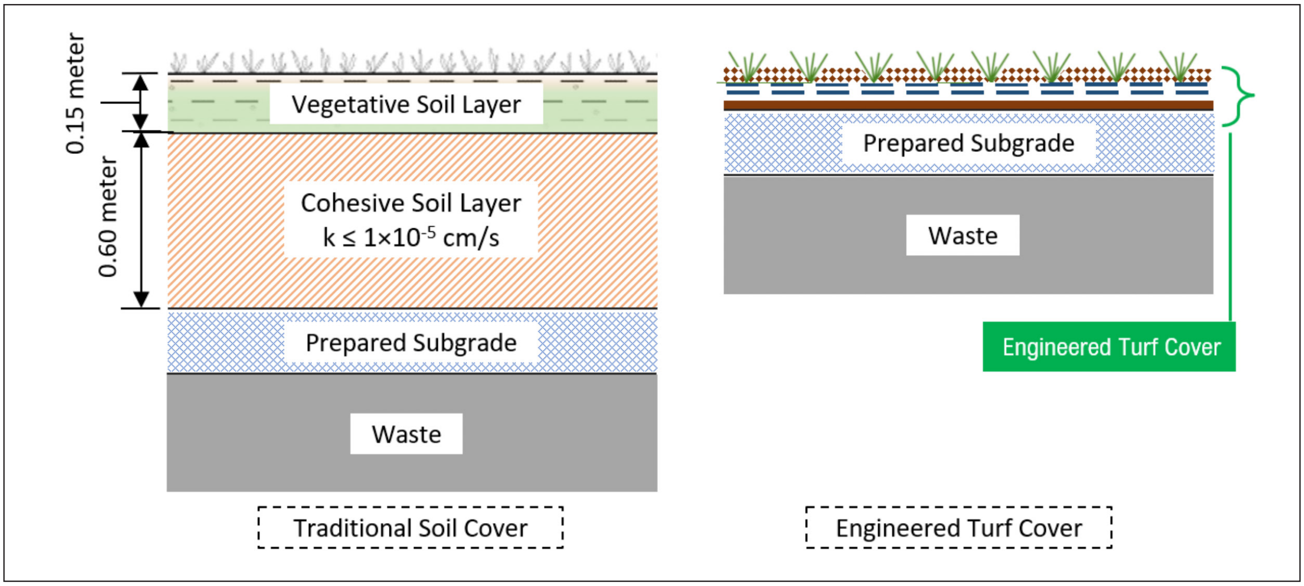
3. Stormwater runoff quality for a soil cover area and an engineered turf cover area.

work construction sites tend to be detrimental to the runoff quality of stormwater and necessitate extensive use of erosion and sediment control measures. Water quality concerns are reduced when construction primarily uses geosynthetics (as is the case with an engineered turf cover). Further, the quality of stormwater runoff from an engineered turf cover area is observed to be much less turbid than from a soil cover area. **Figure 3** shows an example comparison of the quality of stormwater runoff from a soil cover and an engineered turf cover.

The engineered turf cover can be easily integrated with an existing active or passive landfill gas management system. The engineered turf cover consists of a geomembrane that provides multiple orders of magnitude lower hydraulic conductivity than a traditional clay cap over the long term. Therefore, an adequately constructed and maintained final cover with a geomembrane component provides the ability to reduce landfill gas emissions as compared to a clay cap over the long term.

CARBON EMISSIONS COMPARISON

A comparison of the carbon emissions for two alternatives of final cover systems on industrial landfills was performed. Alternative 1, referred to as traditional soil cover, consists of (from bottom to top): prepared subgrade, 0.6-m-thick CCL with a minimum hydraulic conductivity of 1×10^{-5} cm/s, and a 0.15-m-thick vegetative soil layer. Alternative 1 was conservatively selected soil-only cover system not consisting of any geosynthetic components. In addition to a compacted soil component, site permits may require or necessitate use of additional geosynthetics; however, those are conservatively not considered for this comparison. Alternative 2, referred to as engineered turf cover, consists of (from bottom to top): prepared subgrade, 1-mm-thick high-density



4. Traditional soil cover and engineered turf cover alternatives considered for carbon emissions comparison.

polyethylene (HDPE) geomembrane; engineered turf; and sand infill. Alternatives 1 and 2 are shown in **Fig. 4**. These final cover system alternatives are assumed to provide equivalent performance.

Scope and boundaries

The carbon emissions comparison was made only for the final cover system components and does not include emissions associated with other infrastructure (e.g., access roads, storm water features) that may be constructed during a closure project. The size of industrial landfill closure projects is site dependent and may vary; hence, the comparison is made on a per-hectare basis.

In performing comparative life cycle analyses/assessment (LCA) studies, consistency in system boundaries is important to make sure that like-for-like comparisons are made. Typical LCA boundaries relative to use of geosynthetics that may be employed are cradle to gate, cradle to site, cradle to end-of-construction, and cradle to grave [6]. The LCA boundaries employed in this study were cradle to end-of-construction. The corresponding emissions can primarily be classified into three categories: (i) production emissions; (ii) transportation emissions; and (iii) construction emissions. Emissions in these three categories for each component of the two final cover alternatives were calculated.

The carbon emissions in this study are reported in CO_2eq. Gases are converted to CO_2eq by multiplying by their global warming potential (GWP). Per EPA's emission factors for GHG inventories, the 100-year GWP for CH_4 is 25 and that for nitrous oxide (N_2O) is 298 [7].

After construction of a final cover system consisting of a hydraulic barrier (e.g., geomembrane, CCL), a drastic reduction in emissions is typically observed due to the barrier formed on the surface and increased gas collection efficiency. A reduction in emissions is expected to be observed for both final cover alternatives evaluated in this study. As such, emissions avoided in post-construction due to installation of a landfill final cover system are not considered in this study.

Production emissions and embodied carbon

Production emissions can be calculated using embodied carbon (EC). The EC accounts for all the carbon emissions produced from raw material extraction, sourcing, and production of the materials up until the material is ready to leave the factory/manufacturing site. The EC values are reported as kilograms CO_2eq (emitted) per kilogram of material (produced) or kg CO_2eq/kg. The Inventory of Carbon & Energy (ICE) [8] provides a vast database for EC and embodied energy (embodied carbon equivalent value in terms of energy [EE]) values for various materials. The ICE database is one of the most comprehensive sources of EC data for construction materials. The ICE database was developed by extracting data from peer-reviewed literature and resources and provides EC and EE values for hundreds of construction materials. The EC values for certain materials are used from the ICE database. Raja et al. [9] present a study in which EC for certain geosynthetic materials was calculated using first-hand manufacturing process data. The EC values for certain materials within the current study are used based on Raja et al. [9]. For soil materials such as clay, production emissions were specifically computed for this study taking into account emissions generated at borrow areas. **Table I** includes a list of construction materials, their EC values, and sources [8-10] used in this study.

Transportation emissions

Transportation emissions primarily refer to emissions from combustion of fuels used for transportation. All vehicles used in this study use diesel fuel. Based on the EPA's emission factors for GHG inventories [7], emissions from combustion of diesel fuel were computed to be 2.71 kg CO_2eq/L of diesel fuel. For various vehicles used in transporting construction materials, the fuel consumption rate was estimated based on manufacturer, vendor, or other available data sources [11-17], as shown in Table II. The transportation distances used are found in the following sections.

Material	EC, (kg CO_2eq/kg)	Source	Notes
High density polyethylene (HDPE) liner	1.93	[8]	HDPE resin is used as a proxy material.
Polypropylene (PP) (geotextile)	2.35	[9]	Average value of the calculated EC for PP non-woven geotextile used.
Sand	0.00438	[8]	–
Lime	0.78	[8]	–
Nitrogen	8.30	[10]	–
Phosphorus	0.79	[10]	–
Potassium	0.55	[10]	–

I. Embodied carbon (EC) values in kilograms of carbon dioxide equivalent per kilogram (kg CO_2eq/kg) used in the study.

Construction emissions

Construction emissions included emissions from construction equipment in installing final cover system components for the two alternatives. All construction equipment utilized in this study use diesel fuel. As stated previously, the emission factor of 2.71 kg CO_2eq/L of diesel fuel was used. For various construction equipment, the fuel consumption rate was estimated based on manufacturer, vendor, or other available data sources. **Table II** lists construction equipment and vehicles, the corresponding fuel consumption rates, and sources used in this study.

Total emissions from Alternative 1: Traditional soil cover

Production, transportation, and construction emissions for all components of Alternative 1 were calculated. **Table III** shows the aggregate emissions for construction of one hectare of Alternative 1. It was assumed that soils on site can be used to perform contouring and grading on top of waste to achieve a prepared subgrade. Clay for traditional soil cover is often required to be obtained from off-site borrow sources/areas. As such, it was assumed that clay meeting the project specifications was required to be obtained from an off-site borrow area. Borrow areas use standard construction equipment for excavating and harvesting soils, access roadway management, dewatering, and dust control. Emissions from equipment operating at the borrow area were estimated. The distance of the clay borrow area from the application site is project specific. For this study, a distance of 16 km was assumed. Transportation emissions from borrow area to project site were estimated. When using off-site borrow areas, soil needs to be hauled in using on-road dump trucks. The on-road dump trucks typically cannot be used to place soils at the application area, necessitating double handling of soil. Off-road trucks typically need to be used to haul soils from stockpile area to application area. Emissions associated with these activities were considered. Construction of CCL is performed in lifts (typically, about 0.2-m-thick loose lift compacted to 0.15-m-thick compacted lift), and each lift is subject to compaction. Compaction is generally performed using sheepsfoot compactors to break up clods, knead the soil, and perform remolding to obtain a homogeneous mass of soil. Each lift is subject to an adequate number of passes of compactors to meet the compaction requirements in the project specifications. This process also involves moisture conditioning

Vehicle Type[1]	Manufacturer	Model	Consumption Rate[2], L/h	Source and Notes
Excavator	Caterpillar	330	22.3	[11]
Excavator	Caterpillar	329	25.5	[11]
Off-road articulated truck	Caterpillar	740B Articulated Dump Truck	34.3	[11]
Telehandler	Caterpillar	TH255C	14.0	[11]
Motor grader	Caterpillar	140 AWD	22.3	[11]
Dozer	Caterpillar	D6	26.9	[11]
Tractor with box blade	John Deere	5R Series	22.3	[12], average value reported
Sheepsfoot compactor	Caterpillar	815K	42.0	[11]
Smooth drum compactor	Caterpillar	815K	42.0	[11]
On road dump truck	Kenworth	Varies, tri-axle	2.0[3]	[13,14]
Tractor trailer	Varies	Varies	2.5[3]	[15], average value reported
Water truck	Caterpillar	MAC5 CAT725 5,000-gal tank	23.5	[11]
HydroSeeder	Finn	T330 mounted on truck	22.7	[11,16], estimated for Finn HydroSeeder T330 engine + Caterpillar truck
Air Pump	Air Pump USA	Air pump mounted on truck	22.7	[17], estimated based on Air Pump USA truck specifications

1. All vehicles utilize diesel fuel.
2. Fuel consumption rates are based on medium work application and medium engine load factor.
3. Number indicates mileage in km/L.

II. Transportation vehicles, construction equipment, and fuel consumption rates.

Description	CO_2eq Emissions, kg CO_2eq/ha	Estimations and Assumptions
1. Subgrade Preparation		
A. Dozer	2,038	• One Caterpillar D6 dozer operating 28 h/ha.
B. Motor grader	1,690	• One Caterpillar 140 AWD motor grader operating 28 h/ha.
2. Clay: Borrow Area Equipment/Production		
A. Excavator	3,011	• One Caterpillar 330 excavator operating for 50 h excavates and loads approximately 7,500 loose cubic meters of soil necessary for one hectare (i.e., 50 h/ha). • Assume bulking factor for clay is 1.25.
B. Dozer	2,912	• One Caterpillar D6 dozer working the borrow area to perform borrow operations; 40 h/ha.
C. Tractor	1,686	• One John Deere 5M tractor with box blade for access roadway management; operating about 70% of the time (i.e., 28 h/ha).
D. Water truck	1,781	• One water truck, 5,000 gal, operating 70% of the time (i.e., 28 h/ha).
3. Clay: Haul Clay to Site		
A. On-road dump trucks	28,231	• Distance to off-site borrow area is 16 km (one-way). • Estimated payload of 11.5 cubic meters/load; 652 trucks or truck trips are required to haul 7,500 loose cubic meters of soil.
4. Clay: On-site Clay Construction		
A. Excavator	1,927	• One Caterpillar 330 excavator operating for 32 h loads, 7,500 loose cubic meters of soil brought from off-site (i.e., 32 h/ha).
B. Off-road articulated truck	14,852	• Estimated payload of 19 cubic meters/load; about 400 loads are required to haul 7,500 loose cubic meters of soil.
C. Dozer	11,648	• Two Caterpillar D6 dozers working the soils for four (4) lifts; operating 80 h/ha.
D. Tractor	1,325	• One John Deere 5M tractor with box blade for access roadway management; operating 70% of the transportation time (i.e., 22 h/ha).
E. Sheepsfoot compactor	4,546	• One Caterpillar 815 Sheepsfoot compactor operating 40 h/ha.
F. Smooth drum compactor	4,546	• One Caterpillar 815 smooth drum compactor operating 40 h/ha.
G. Water truck	4,789	• One water truck, 5,000 gal, operating 70% of the construction time (i.e., 28 h/ha). • Ten water trucks, 5,000 gal, needed for 3% moisture conditioning of the soil, operating 40 h/ha.
5. Vegetative Soil		
A. Excavator	723	• One Caterpillar 330 excavator operating for 12 h excavates and loads approximately 1,725 loose cubic meters of on-site soil (i.e., 12 h/ha). • Assume bulking factor for vegetative soil is 1.15.
B. Off-road articulated truck	3,342	• Estimated payload of 19 cubic meters/load, 91 loads are required to haul 1,725 loose cubic meters of soil. • Three Caterpillar 740 off-road articulating trucks hauling 30 loads per truck with a production of 20 loads per truck per 8 h (i.e., three trucks operating at 12 h/ha).
C. Dozer	2,912	• Two Caterpillar D6 dozers operating 20 h/ha.
D. Tractor	421	• One John Deere 5M tractor with box blade for access roadway management, operating about 70% of the time (i.e., 7 h/ha).
G. Water truck	445	• One water truck, 5,000 gal, operating 70% of the time (i.e., 7 h/ha).
6. Seeding, Lime, and Fertilizing		
A. Seed mix, lime, fertilizer	7,010	• Use of 3,360 kg/ha of agricultural lime; 1,680 kg/ha of nitrogen-phosphorus-potassium (N-P-K) 6-12-12 fertilizer; and 84 kg/ha of N fertilizer for top dressing based on Georgia Soil and Water Conservation Commission (GSWCC) [18]. • Enhanced calcitic (EC) lime, weighted EC of N-P-K, and EC of N fertilizer from Table I.
B. On-road truck	43	• One on-road truck to transport material to the site with assumed distance of 16 km (one way).
C. Truck mounted HydroSeeder	491	• One Finn T330 HydroSeeder mounted on a truck, operating 8 h/ha.
Total	**100,370**	

III. Carbon emissions in kilograms of carbon dioxide equivalent per hectare (kg CO_2eq/ha) for traditional soil cover.

(typically addition of water) of the soil for workability and for achieving adequate soil density and moisture content to meet project specifications. Standard construction equipment for on-site hauling and construction was used. For the vegetative soil layer, appropriate soil was assumed to be available at an on-site source. Standard construction equipment for excavating, hauling, placement, and spreading was considered. For final cover systems, establishment of permanent vegetation is necessary. Seeding, lime, and fertilizer application are generally performed for initial establishment of permanent vegetation. Emissions associated with the production, transportation, and construction of permanent vegetation are calculated.

Table III lists the materials, vehicles, and construction equipment used, along with the corresponding estimated emissions for production, transportation, and construction of each of the final cover system components for Alternative 1. Table III further includes details relative to specific materials, vehicles, and construction equipment, as well as the operational time for hauling, construction, or installation per hectare. Various parameters used, such as material quantities, bulking factors, load quantities, and number of loads for different equipment per unit time are included in Table III. The operational time for each vehicle or construction equipment was estimated based on experience at similar earthwork and closure construction jobs. For instance, emissions from a sheepsfoot compactor used for construction of the clay layer included as Item 4E in Table III are calculated as such: one Caterpillar-815 compactor is estimated to operate 40 h/ha to compact soils. Using the fuel consumption rate in Table II and the emission factor for diesel fuel, emissions from this particular activity were estimated as: 42 L/h X 40 h/L X 2.71 kg CO_2eq/L = 4,546 kg CO_2eq/ha. Additional estimations and assumptions used are included in Table III.

Description	CO_2eq Emissions, kg CO_2eq/ha	Estimations and Assumptions
1. Subgrade Preparation		
A. Dozer	2,041	• One Caterpillar D6 dozer operating 28 h/ha.
B. Motor grader	1,690	• One Caterpillar 140 AWD motor grader operating 28 h/ha.
C. Compactor	2,273	• One Caterpillar 815 smooth drum compactor operating 20 h/ha.
2. Geomembrane		
A. Embodied carbon (EC)	21,311	• Use 40-mil high density polyethylene (HDPE) liner • EC of HDPE from Table I.
B. Flatbed	541	• Assume distance of 800 km from manufacturing plant to site. Add 20% or 160 km for flatbed origination and destination. • One flatbed carries 12 rolls of geomembrane.
C. Telehandler	1,137	• One Caterpillar TH255C Telehandler to unload and stockpile rolls of geomembrane; subsequently to transport to application area and deploy geomembrane; operating 30 h/ha.
3. Engineered Turf		
A. Embodied carbon (EC)	22,759	• Engineered turf consisting of polypropylene (PP) geotextile backing and polyethylene tufting • EC of PP and HDPE from Table I.
B. Enclosed box truck	920	• Assume distance of 500 miles or 800 km from manufacturing plant to site. Add 20% or 160 km for flatbed origination and destination. • One enclosed box truck carries 27 rolls of engineered turf.
C. Telehandler	1,137	• One Caterpillar TH255C telehandler to unload and stockpile rolls of engineered turf; subsequently to transport to application area and deploy engineered turf; operating 30 h/ha.
4. Sand Infill		
A. Sand	1,178	• EC of sand from Table I. • Sand infill thickness of 0.5 in. or 13 mm.
B. On-road dump trucks	528	• Distance from sand source to site – 16 km (one-way) • Estimated payload of 11.5 cubic meters/load, with about 12 trucks or truck trips required to haul 140 cubic meters of soil.
C. Air Pump truck	1,229	• One Air Pump sand deployment truck operating 20 h/ha.
Total	**56,750**	

IV. Carbon emissions in kilograms of carbon dioxide equivalent per hectare (kg CO_2eq/ha).

Total emissions for Alternative 2: Engineered turf cover

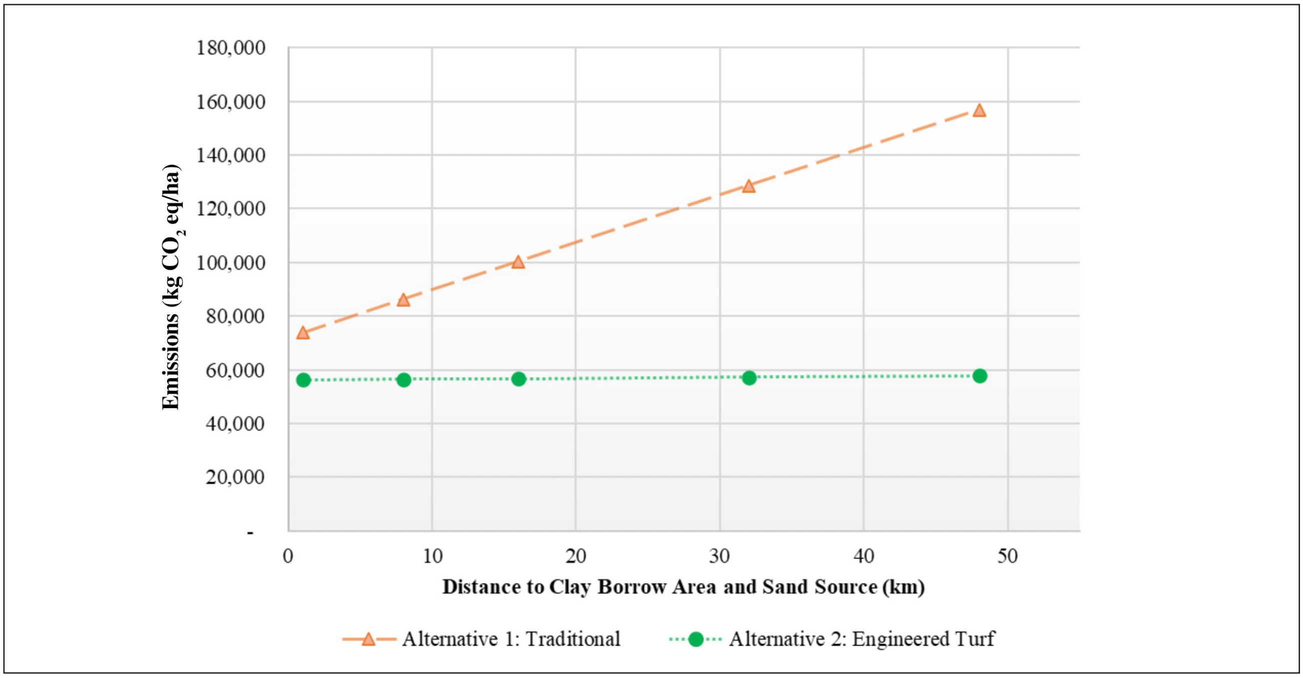
Production, transportation, and construction emissions for all components of Alternative 2 were calculated. **Table IV** shows the aggregate emissions for construction of one hectare of Alternative 2. Similar to Alternative 1, it was assumed that soils on site can be used to perform contouring and grading on top of waste to achieve a prepared subgrade. Subgrade preparation prior to deployment of geomembrane generally involves a little more effort. Subgrade preparation specifications generally require that the subgrade surface be smooth, uniform, unyielding, and free from rocks, debris, and protrusions. The specifications can generally be met by compacting the soil using a smooth drum compactor. This additional effort and associated emissions were considered for Alternative 2 subgrade preparation. The EC values for geomembrane, engineered turf, and sand infill noted in Table I were used. The quantities of the geomembrane and engineered turf per hectare were calculated based on weight and surface area per roll of the geosynthetics, as noted on material product data sheets [19]. For transportation of the geosynthetics, a distance of 800 km (50 times that of clay) was assumed from the manufacturing plants to the project site. Standard construction equipment was considered for deployment and installation of the geosynthetics. The distance of the sand infill source for Alternative 2 was assumed to be 16 km (similar to that of clay) from the project site. The sand infill was assumed to be hauled to the project site using dump trucks and then loaded onto specialized trucks for installation. Installation of sand infill was assumed using a specialized truck capable of pneumatically deploying sand media over the turf using pumps and hoses.

Table IV lists the materials, vehicles, and construction equipment used, along with the corresponding estimated emissions for production, transportation, and construction of each of the final cover system components for Alternative 2. Table IV further includes details relative to specific materials, vehicles, and construction equipment, as well as the operational time for hauling, construction, or installation per hectare.

Results and findings

Alternative 1 produces 100,370 kg CO_2eq/ha. For Alternative 1, it is observed that hauling of soil, both from offsite borrow area and on-site, makes a relatively large contribution to the emissions. About 28% of the total emissions for Alternative 1 are from off-site hauling of clay, and about 18% are from on-site hauling of soils. Alternative 1 is earthwork construction intensive, and the sum of construction emissions is about 47% of the total emissions, including construction activities in the borrow area. The EC for materials account for about 7% of the total emissions.

Alternative 2 produces 56,750 kg CO_2eq/ha. In contrast to Alternative 1, it is observed that majority of the emissions (about 80%) for Alternative 2 come from the EC or production of the geosynthetics. This is intuitive, since production of geosynthetics is an intensive process consisting of many steps, such as extraction and refinement of crude oil, production of raw materials, and manufacture of the geosynthetic product. Transportation emissions account for only 3%, as the number of trucks is drastically reduced due to



5. Carbon emissions in kilograms carbon dioxide equivalent per hectare (kg CO_2eq/ha) for Alternatives 1 and 2, relative to distance to borrow area.

use of geosynthetics instead of soil. Construction emissions are also drastically reduced, since much less construction equipment is needed and construction with engineered turf is faster. Construction emissions account for about 17% of the total emissions for Alternative 2.

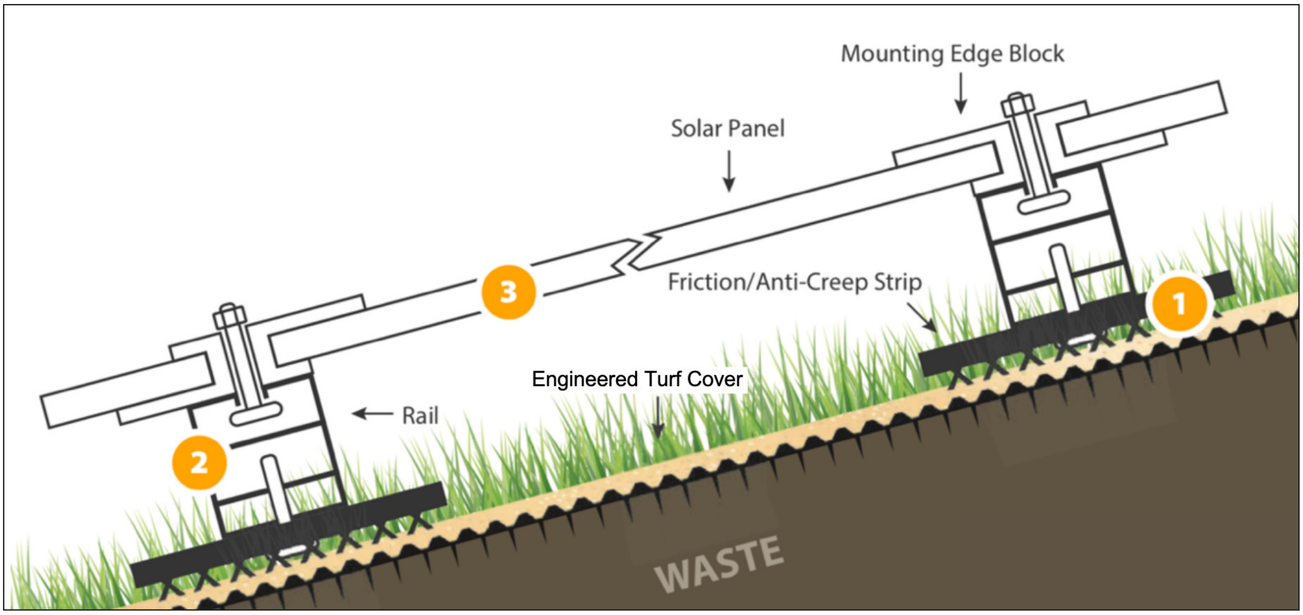
The results show that Alternative 2 (i.e., engineered turf final cover system) produces significantly lower carbon emissions, about 56% less, than that of Alternative 1 (i.e., traditional soil final cover system) per hectare of closure. Overall, the engineered turf final cover offers a reduction in emissions of 43,620 kg CO_2eq/ha of construction. For a 10-ha closure project, for instance, the reduction in carbon emissions offered is 436,200 kg CO_2eq (or ~436 MT CO_2eq). For a 40-ha closure project, the reduction in carbon emissions is ~1,745 MT CO_2eq.

The results demonstrate that earthwork construction and hauling emissions are large factors for Alternative 1, whereas production emissions are a large factor for Alternative 2. For this study, the distance of clay borrow area from the project site was assumed to be 16 km, and the contributing emissions were calculated to be about 28%. For many sites, the distance of borrow areas may be different (greater or smaller) than the considered distance. The effect of the distance to the off-site clay borrow area was further assessed. **Figure 5** shows resulting emissions for Alternatives 1 and 2 with varying distances to the clay borrow area. It is noted that the distance to the sand infill source (for Alternative 2) is assumed to mimic the distance to the clay borrow area (for Alternative 1). In other words, for a clay borrow area located at 32 km, the sand infill source is also assumed to be located at 32 km. From Fig. 5, it is observed that traditional soil cover emissions drastically increase with increase in distance to the clay borrow area. For a distance of 48 km, for instance, the emissions for traditional soil cover are 270% of that for an engineered turf cover. Furthermore, for a distance of just 1 km, the emissions for traditional soil cover are 131% of that for an engineered turf cover. Practically, this indicates that for a site with an on-site clay borrow area, the emissions for traditional soil cover would still be higher than that for an engineered turf cover. As noted earlier, the transportation emissions for an engineered turf cover were calculated to be only 3%, assuming a distance to geosynthetics manufacturing plants of 800 km. Assuming this distance is quintupled (to 4,000 km, which would be the maximum likely transportation distance in the continental United States), the emissions for traditional soil cover with an on-site borrow area would be 118% of that for an engineered turf cover.

BENEFICIAL USE: SOLAR DEVELOPMENT ON LANDFILL CAP

In addition to the stated environmental benefits and quantified significant reduction in carbon emissions, an engineered turf cover can be beneficially used after landfill closures. One of the beneficial uses of the closure is converting the land into a solar farm to generate clean renewable energy. The engineered turf provides an ideal foundation for installation of a solar farm, as it requires minimal post-closure maintenance. A traditional soil cover generally requires more and frequent post-closure maintenance than an engineered turf cover such as:

- Installation of erosion and sediment control measures.
- Potential slope repairs due to erosion of soils and surface sloughs (especially after a site experiences large storm events).



6. Solar power generation system components: (1) friction strip connected to rail; (2) rail with mounting edge block; and (3) solar panel connected to mounting edge block.

7. Installation of solar system on a landfill slope.

- Potential soil replacement.
- Periodic reseeding and fertilizing, as well as mowing to manage overgrowth of vegetation.

Mounting solar panels on top of soil covers therefore presents multiple challenges. Use of solar panels on engineered turf, however, helps eliminate and/or minimize these challenges. For instance, since there is no overgrowth of vegetation, mowing is not necessary and the functions of the solar panels are not impeded by vegetation (e.g., casting shadows).

Solar systems may be installed directly on top of an engineered turf cover. An example three-component solar system consisting of friction strips, mounting rails, and solar panels is shown in **Fig. 6**. The solar system is mounted on top of the cover and does not require cover penetrations. Friction strips provide adequate interface friction with the engineered turf cover. The system can be deployed not only on relatively flat areas (such as top decks) but also on landfill side slopes. The system conforms to the grades of the underlying surface. The system does not involve any racking and hence is easier and faster to install than traditional solar racking systems supported using heavy ballast. **Figure 7** shows installation of the solar system on a landfill side slope.

Extensive wind tunnel testing of the solar panel system has been performed and the test results have demonstrated satisfactory performance relative to wind uplift due to its low-profile setup and aerodynamic boundary conditions associated with the underlying engineered turf cover.

SUMMARY AND CONCLUSIONS

In 2020, carbon emissions by the Waste Sector, which includes the industrial waste landfills and industrial wastewater treatment systems, summed to 105.5 MMT CO_2eq. Of those, the reporting industrial waste landfills accounted for 7.4 MMT CO_2eq direct emissions. Opportunities exist for owners of industrial waste landfills to use alternative solutions to reduce carbon emissions. An engineered turf final cover system provides a true green solution. The engineered turf cover provides various environmental benefits over traditional soil covers, including avoidance of land use change, avoidance of land disturbance and associated impacts, reduction in construction materials, conservation of water resources, and improved quality of water.

Analysis was conducted to compare carbon emissions from a traditional soil-only cover and an engineered turf cover. Detailed estimations of production, transportation, and construction emissions were performed. Based on the results, the engineered turf cover produced significantly lower carbon emissions, about 56% of that for traditional soil-only cover. The engineered turf cover offers a reduction in emissions of 43,620 kg CO_2eq/ha of construction. The results indicated that construction and hauling emissions were large factors for the traditional soil-only cover, whereas production emissions were a large factor for the engineered turf cover. The effect of distance to borrow areas on the emissions was further evaluated. It was found that the carbon emissions for a traditional soil-only cover would exceed those for an engineered turf cover even in the presence of an on-site borrow area. The quantification confirms the true green proposition of an engineered turf solution for industrial landfills.

Industrial facility and landfill owners likely have a business- or facility-specific carbon emissions baseline and reduction targets and goals. The quantification of reduction in emissions presented in this study provides important data to owners and brings forward the magnitude of emission reductions that can be realized in using green solutions like an engineered turf final cover system.

Owners are presented with an additional opportunity for generation of clean renewable energy on top of industrial waste landfills. Landfill closure lands, which remain unused otherwise, can be beneficially converted to solar farms. Energy generated using solar systems on landfills can be used for facility operations and/or could be distributed to local communities. **TJ**

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ABOUT THE AUTHOR

Carbon emissions and sustainability are very timely topics, and work on sustainability in geosynthetics is increasing. This study is complementary to such efforts and offers owners and operators of pulp and paper mills the opportunity to consider landfill alternatives that provide a reduction in carbon emissions.

It was quite a task to perform the detailed quantification of carbon emissions for this study, which was accomplished by a significant time commitment. It was interesting to find that engineering problems can be solved using a "greener" approach. It was also interesting to learn that transportation emissions are not always the largest contributor of emissions and that other processes need to be looked at as well.

Industrial landfill owners like pulp and paper mills can adopt more sustainable solutions — final covers for landfills, in this case — to align with their sustainability goals and potentially claim carbon credits. One of the next steps in this study would be to evaluate carbon credits from closing industrial waste landfills.

Joshi

Joshi is director of Technology for Watershed Geosynthetics in Alpharetta, GA, USA. Email Joshi at rjoshi@watershedgeo.com.

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