Prospect to practice: field trials of phytoremediation at landfills

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Abstract

Human contamination poses environmental concerns at many different levels. One such level is in the waste we generate on a day-to-day basis, waste that usually ends up in a municipal solid waste (MSW) facility for long term storage, well beyond typical human life expectancy. To ensure these MSW's do not begin to pose environmental risk in the future we must develop ways to assist the Earth in self-cleaning these facilities after humans have closed them and moved on to post closure management. Phytoremediation is one such avenue that would provide a cost effective and eco-friendly approach to assisting in this management. This review looks at several recent phytoremediation projects that have been field applied at landfills around the world in pilot and full scales. Leachate and gas emissions combined to form the major components of landfill contamination, so hence this review will be limited to projects tackling these two contaminants. The author hopes that this review will serve as a guide to landfill workers to get ideas for potential phytoremediation options for their landfill before and after closure.

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Introduction

Human contamination poses environmental concerns in many different ways, one of which is in the solid waste that is generated by humans during their daily activities. To put into perspective the growing concerns of waste generation was revealed by a study at the University of Michigan in 2023 in which the researchers found that the amount of Municipal Solid Waste (MSW) generated per capita, within the United States has increased by 34% from 1980 to 2018. During the same time period, the total annual MSW generated in the United States had increased by 93% [1]. In Canada, as of 1999, roughly 50% of agricultural production in terms of value comes from within 80 km (about 49.71 mi) of major metropolitan areas [2]. This could eventually lead to direct competition with landfills as the need for land increases within proximity of urban locations. As this concern continues to rise in other countries around the world, there needs to be convenient and easily accessible solutions to limiting long term damage caused by MSW sites as well as places without established disposal facilities and locations.

A national overview conducted by the EPA in 2018 (and updated as recently as November 2023), looked to summarize recent data gathered over the last thirty-five plus years to determine what kind of waste is being generated and in what percentages they contribute to municipal solid waste landfilling. As of 2018, the EPA reported approximately 146.1 million tons of MSW entering landfills per year, which is approximately 50% of the total amount generated that year of 292.4 million tons [3]. It is worth mentioning that this is calculated after accounting for recycling, repurposing, and energy generation. While much of the waste in the landfill such as wood, paper, paperboard, food, and yard trimmings, may be biodegradable and will degrade provided oxygen is available. The other categories are not as readily broken down. In addition to the length of time required for decomposition, some of the contaminants might leach heavy metals and other chemicals into the ground and in countries that do not install proper landfill reclamation mechanisms, this can lead to soil and water contamination.

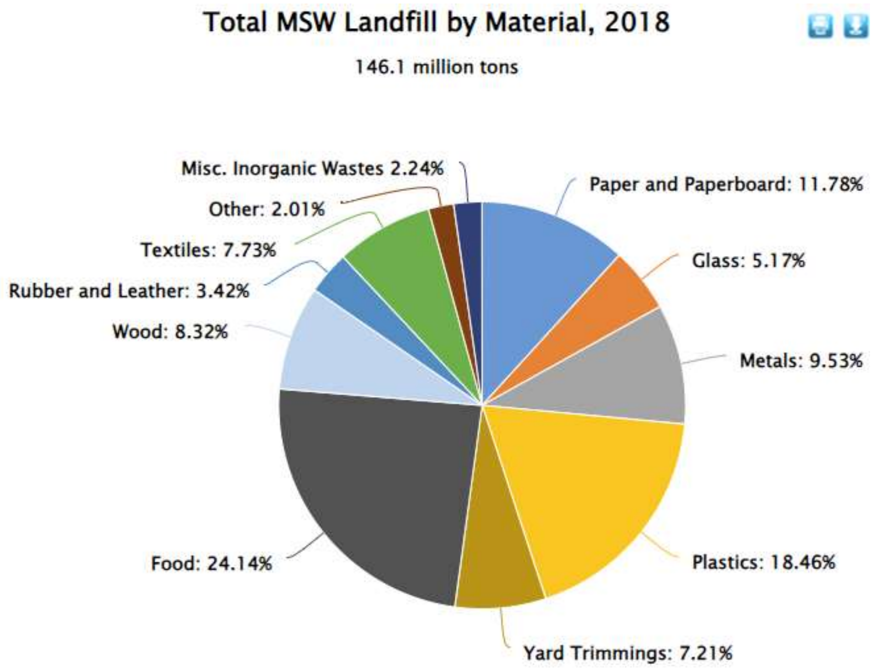

Figure 1: Total MSW Landfilled in the United States in 2018 [3]

The rapid population growth rate over the last several decades and the increased rate of urbanization and industrialization in India, reveals some trends about countries breaking through into the modern economic age and how waste generation for these countries could be anticipated. As of 2016, India was having trouble properly collecting its solid waste from urban locations and reported that, on average, only about 70% of the waste from each dwelling unit was collected and the other 30% gets lost in the city and into the ecosystem (rivers and water bodies). Of the waste collected only approximately 12.5% gets processed correctly for recycling and reuse, while the rest is sent to open air dumps for long term storage/disposal. Figure 2 shows the predicted land requirements to meet the projected needs for India through 2051. The estimated requirement for space in India is approximately three times that of 2021 [4]. If this model turns out to be true, then it is clear there is going to be a need to reclaim land at some point to meet future needs for the increased population.

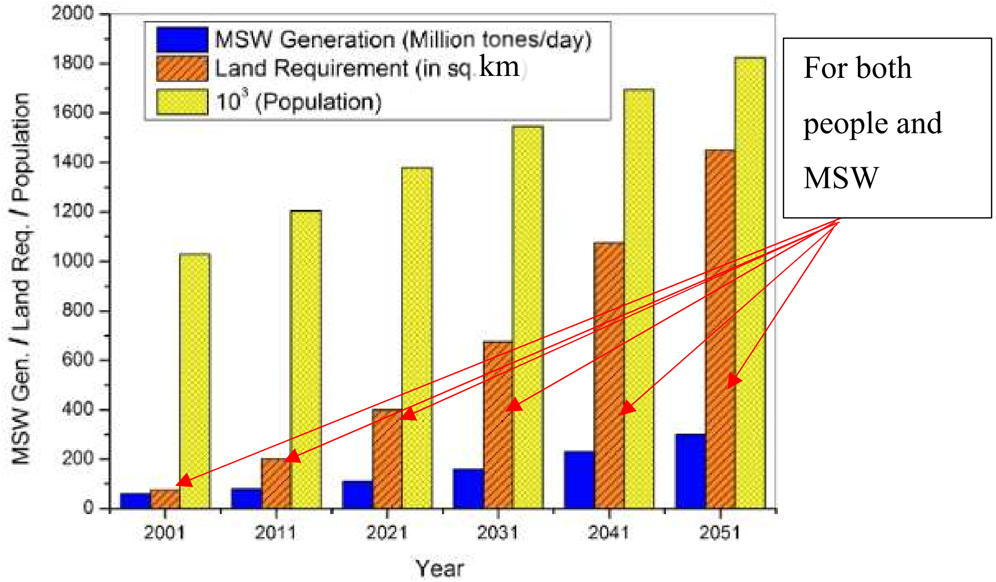

Figure 2: Predicted Requirements through 2051 [4]

Another key issue with MSW facilities is the hazardous chemicals and materials that are deposited in them either by accident or as part of the current "Best Management Practices." Batteries, petroleum hydrocarbons, diesel, chemicals, detergents, solvents, paints, e-waste, etc., can all be disposed of in landfills and once there it is extremely difficult to remove them. As they break down, they might form gases that escape through the topsoil or cap of the landfill and vent into the atmosphere. Methane and carbon dioxide are the most common landfill gases on average, accounting for roughly 50% (each) of all gas generated with trace amounts being non-methane containing gases [5]. The Intergovernmental Panel on Climate Change in 2014 put methane as an extremely potent greenhouse gas, estimating that it is 28 times more effective at trapping heat within the atmosphere than carbon dioxide over 100 years [6]. Hazardous chemicals and materials can find their way into leachate water and thus into groundwater for improperly installed landfills and therefore contaminate the nearby areas over time. Once landfills have been established and used for a long enough time it becomes difficult, if not impossible, to eliminate contamination at the source. This would require deep excavation in a landfill with the exact origin point unknown, which begs the question of what can be done to remediate or mitigate landfill contamination.

The best options for landfill contamination management are those that prevent waste from ever entering the landfills, recycling, reuse, incineration, etc. However, once the waste has made it to the landfill these options become extremely difficult. There are several manufactured methods to deal with landfill contamination such as liners, leachate reclamation, and gas reclamation systems but unfortunately, they are usually expensive, and several must be put in prior to the landfill construction. It is possible to excavate and remediate that way but this becomes expensive, time consuming, labor intensive and at the end the contaminants must be sorted and dealt with through other means which in turn further increases labor, time, and expenses [7]. To effectively manage and address landfill impact to humans and the environment we must organize and separate the environmental problems so that they can be thoroughly investigated, and effective strategies can be employed to deal with said problems. The biggest environmental issues associated with landfills can be organized by their effect on the environment and the surrounding populations of plants, wildlife, and people. Affecting these populations through water contamination is through leaching into the groundwater and surrounding surface waters via leachate breakout and seepage from the landfill. As the waste in the landfill breaks down gases might be released escaping from the soil into the atmosphere; these gases include methane, carbon dioxide, and trace amounts of various greenhouse gases that are unhealthy to most populations and, contribute to greenhouse gas emissions. Some important attributes to be considered in dealing with these impacts are cost effectiveness, minimal maintenance, ease of initiation/use. Most ways of managing the problems associated with landfills revolve around expensive and invasive methods in order to treat them. While this can temporarily alleviate the leachate and gas problems, it does not address the expensive or unappealing nature of the landfill. A technology becoming increasingly popular for dealing with environmental problems similar to what a landfill presents is phytoremediation and in this literature the author attempts to bring to light some recent phytoremediation projects that benefit landfills.

Review of the Literature

Phytoremediation

Phytoremediation is a technology that provides a route to environmental cleanup and remediation for landfill contamination/environmental impact. The broad overarching term phytoremediation has been around since approximately 1991 and includes all plant related ways of restoring or remediating environmental contamination or concerns with, for those curious, the name coming from the Greek prefix *phyto* (plant) and the Latin root *remedium* (to correct or remove evil) [8,11]. While phytoremediation is not necessarily a modern technology, the application of it for environmental cleanup is relatively new and is garnering the interest of scientists around the world. Phytoremediation is a biotechnology utilizing living organisms as the chief component in the process. However, phytoremediation does not just involve the plant but it also applies to the micro-organisms and small animals (such as earthworms and small bugs) that make their homes near the plant [9]. The combination of these organisms creates a biosystem that, under the right conditions, could be able to handle contamination from a landfill in a multitude of pathways. Plants are complex organisms and thus it would follow that the mechanisms involved in treating contamination would be varied. There are six main pathways plants could utilize for remediation of landfills and dumpsites: phytoextraction, phytovolatilization, phytostabalization, phytodegradation, rhizofiltration, and rhizodegradation. Each of these mechanisms provides a route of cleanup by either containing, eliminating (i.e., removal), or transforming a contaminant into an inert byproduct [9]. Figure 3 shows a simplified version of the various pathways under which phytoremediation can operate. Rhizodegradation is pictured here as phytodegradation because it operates similarly to phytodegradation taking place in the rhizosphere.

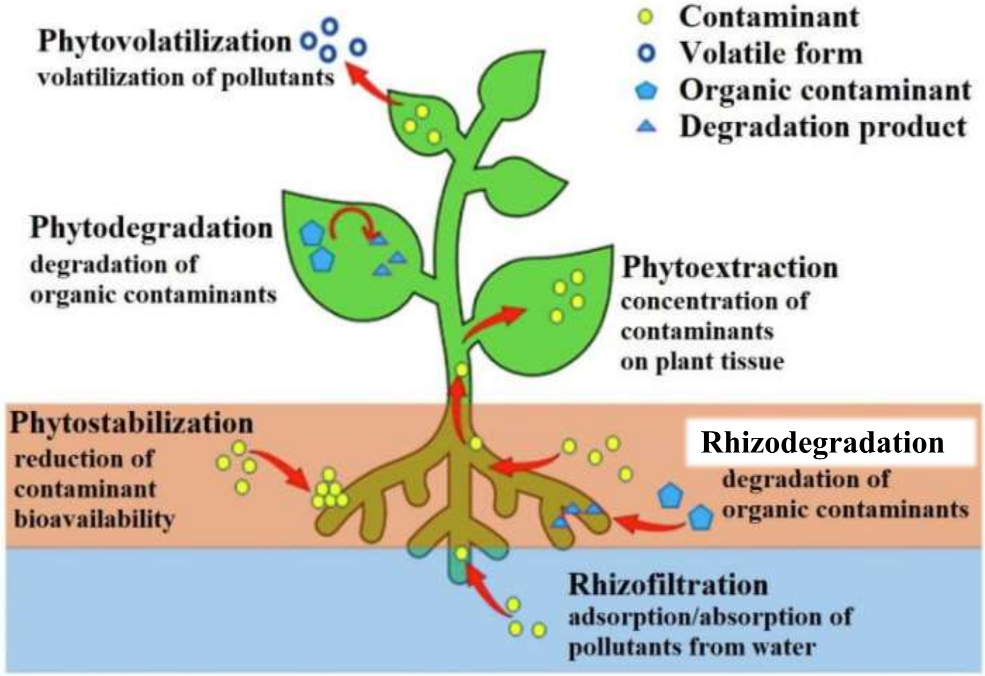

Figure 3: Simplified view of Phytoremediation pathways. Ohio State University [12]

There is plenty of information available about how phytoremediation has and is being applied to a multitude of different contaminants ranging from organic, inorganic, and heavy metals [15]. Table 1 provides a summary of some common contaminants with their corresponding cleanup pathway and typical plant associated with said pathway. An important observation that should be made from reviewing Table 1 is that each pathway is better suited for different applications because not all contaminants pollute in the same way or interact directly with the plant species. A few plant species are also useful for more than one phytotechnology route which provides valuable information when cleaning up complicated sites like landfills. These facts reveal the importance of plant selection when beginning a cleanup project. A brief introduction into each pathway along with the processes involved is important to gain understanding for use of phytoremediation for remediating landfills and dumpsites.

Table 1: Phytoremediation process route, mechanism, typical pollutants, and plants most associated with the process [15].

Phytotechnology	Mechanism	Pollutants	Plants
Phytoextraction	Hyperaccumulation in harvestable parts of plants	Inorganic: Co, Cr, Ni, Pb, Zn, Au, Hg, Mo, Ag, Cd Radionuclides: Sr, Cs, Pb, U	*Brassica juncea*, *Thalspi caerulescens*, *Helianthus annus*
Rhizofilteration	Rhizosphere accumulation though sorption, concentration and precipitation	Organics/Inorganics: Metals like Cd, Cu, Ni, Zn,Cr Radionuclides	*Brassica juncea*, *Helianthus annus*, Tobacco, Rye, Spinach and Corn
Phytovolatilization Rhizodegradation	Volatilization by leaves through transpiration In the rhizosphere	Organics/Inorganics: Chlorinated solvents, inorganics (Se, Hg, As)	*Arabidopsis thaliana*, Poplars, Alfalfa, *Brassica juncea* Calotropis
Phytodegradation	Pollutant eradication	Organic compounds, Chlorinated solvents, Phenols, Herbicides, Munitions	Hybrid poplars, Stonewort, Black willow, Algae
Phytostabilization	Complexation, sorption and precipitation	Inorganics: As, Cd, Cu, Cr, Pb, Zn, Hs	*Brassica juncea*, Hybrid poplars, Grasses

Phytoextraction utilizes a plant's natural ability to uptake contaminants from the soil or water via the root system. The contaminant is then translocated into the upper biomass of the plant, to further isolation from the soil or water. Phytoextraction offers advantages for many cleanup applications because the contaminants of concern are absorbed into the plant and then the plant can either be extracted for incineration or processed to recover the contaminant if it is of economic use [15]. Incineration of these plants can also provide energy for populations provided the contaminant is rendered inert by the incineration process. Phytoextraction is especially useful for heavy metal contamination and in certain situations, radionuclides. When selecting a phytoextractor plant it is important to consider plants that have a high tolerance to the contamination of concern, and are able to transport them to the upper biomass. The growth rate and size of the plant must be high to facilitate contaminant uptake effectively [16]. Plants that can either accumulate high amounts of metals with low biomass or produce high amounts of biomass, but low metal accumulation are called hyperaccumulators and are highly desired in phytoremediation projects for the ability to take in high amounts of contaminants [17].

Phytoextraction can provide benefits to landfills by being implemented in soils that have been contaminated by landfill leachate or at dumpsites that are known to be locations of metals in high concentrations.

Another method plants utilize for remediation is volatilization of organic and certain inorganic contaminants from the soil or water and release them into the atmosphere, this process is known as phytovolatilization. For some contaminants, the plant has a pathway to metabolize the contaminant and convert it into a gaseous form inside the leaves or stem to then releases it into the atmosphere. Phytovolatilization offers several benefits for remediation such as preventing the plant from accumulating the contaminant to toxic levels and/or transforming certain metal contaminants into their gaseous form. There are two methods of phytovolatilization, direct and indirect, both providing remediation potential. Direct phytovolatilization is the physical uptake of the contaminant into the plant to be then released above ground. Indirect phytovolatilization comes from the plants natural water uptake and transpiration cycle of the plant to lower water levels, which promotes gas fluxing within the soil [18].

While phytovolatilization can be considered removal of a volatile contaminant from the location, phytostabalization would be the opposite. Phytostabalization occurs within the plants' root zone in which a contaminant (usually a heavy metal) is absorbed and thus immobilized preventing it from traveling with underground water [19]. By immobilizing the contaminant, the bioavailability goes down and thus reduces exposure potential. Certain plants have also been known to produce special redox enzymes that can bind to heavy metal contaminants and convert them into a less harmful or even inert form [17]. This also limits extreme events from pulling the contaminant out of the soil; events like erosion or leachate runoff [19].

The term phytodegradation refers to the uptake and enzymatic breakdown of pollutants by plants, as well as the degradation of pollutants in soil, ground water, or surface water. To transform organic pollutants like 2,4,6-trinitrotoluene (TNT), polychlorinated biphenyls, herbicides, and pesticides from toxic to nontoxic forms, this process uses plants and related microorganisms [20,21]. One of the most prevalent contaminants, trichloroethylene, can be broken down by hybrid poplars [22]. In some instances, the resulting products from phytodegradation can prove to be environmentally harmful as well which implies the need for performing field studies at multiple locations with multiple different types of contaminants [23].

Rhizofiltration works similar to phytoextraction in that it entails the accumulation of metals and certain organic compounds but operates on groundwater, surface water, and wastewater. When contaminated water flows through the root zone, plants selectively absorb and accumulate pollutants. The process primarily targets toxic metals, such as lead, cadmium, and zinc. Suitable plant species for rhizofiltration include sunflowers (*Helianthus annuus*), mustard (*Brassica juncea*), and water hyacinth (*Eichhornia crassipes*). These plants have robust root systems and can efficiently translocate metals from the surrounding water to their roots. There are several advantages to rhizofiltration such as its cost-effectiveness for treating large volumes of water with low contaminant concentrations and its applicability to various settings, including landfills, industrial sites, and wastewater treatment facilities. At landfills, rhizofiltration can help manage leachate-contaminated liquid that seeps from waste piles [24, 25].

Rhizodegradation is a phytoremediation process that relies on the interactions between plant roots and soil microorganisms to break down organic contaminants. When plants grow in contaminated soil, they release various compounds through their roots. These compounds include organic acids, enzymes, and other metabolites. As a result, the rhizosphere—the soil region influenced by root exudates—becomes enriched with these substances. Soil microorganisms, particularly bacteria and fungi, thrive in this nutrient-rich environment. They utilize the exudates as a carbon source and, in the process, degrade organic pollutants. Enzymes produced by microorganisms play a crucial role in breaking down complex organic molecules into simpler, less toxic forms. Overall, rhizodegradation enhances the natural microbial activity in the soil, leading to the degradation of contaminants. Rhizodegradation has been studied extensively for its potential in cleaning up contaminated sites. Researchers have investigated various plant species, including grasses, legumes, and trees, to assess their effectiveness in promoting rhizodegradation. For example, poplar trees (*Populus spp*.) have been used to remediate soil contaminated with petroleum hydrocarbons. The roots of these trees release exudates that stimulate microbial growth and enhance the degradation of hydrocarbons [26].

It thus becomes clear that phytoremediation should be further investigated as a favorable alternative to more costly, invasive, and labor-intensive approaches. However, the information related to active, ongoing, and recently closed phytoremediation projects at landfills and dumpsites is scattered and difficult to track down efficiently. There is a need to study several phytotechnology projects that have been successfully employed in the field in order to gain actual field data on how plant technology can provide benefits to landfill operation and closure. These valuable studies would help other operators with the information needed to consider more phytoremediation processes in the future. The next section entails a review of literatures created for field applications of phytotechnology at dumpsites or municipal solid waste landfills (including laboratory support where needed) that can hopefully provide a starting point for future endeavors in said field. A brief intro into phytoremediation concepts will also be provided to understand how this process imparts usefulness to said landfill problems and/or environmental hazard.

Landfill Leachate Management

From the environmental hazards that landfills pose, leachate is arguably the most concerning, complicated, and common; along with its potential to produce explosive landfill gases [13]. Because landfills are too big to be covered or built indoors, leachate will always be generated regardless of the controls built prior to construction; the main difference being it either seeps deep into the ground or moves to a containment pond where it must be addressed by some means. Therefore, it becomes crucial to manage and contain any leachate that a landfill generates. Prior to the inception of Resource Conservation and Recovery Act (RCRA) in 1976, landfills did not require a liner to be preinstalled before the landfill could begin accepting waste [27]. This meant landfills relied on natural attenuation and dispersal into the environment through slow uncontrolled release of leachate in the geology and groundwater as the method of cleanup. This also meant the unavoidable generation of contaminating plumes. Another obvious take away here is that this means on old landfills contamination plumes are unavoidable. Post 1976, more efficient and cost-effective methods for dealing with landfill leachate have been developed; current methods for leachate treatment use anaerobic or aerobic biological treatments and physiochemical processes to reduce toxicity.

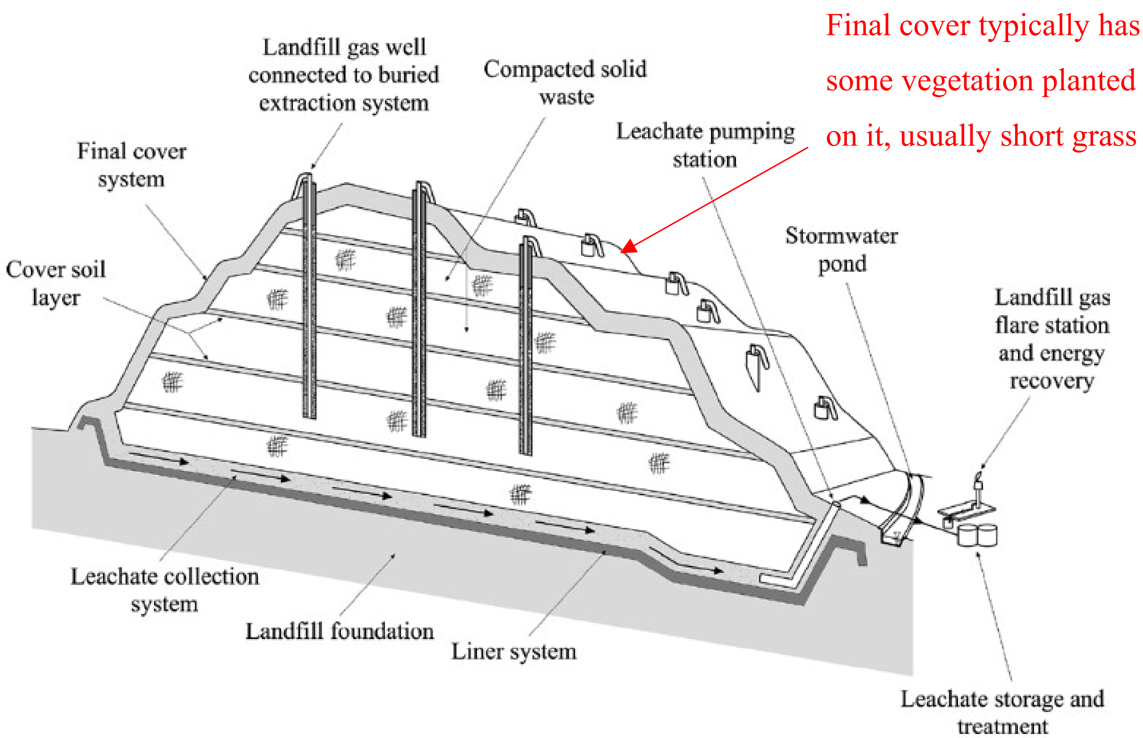

Figure 4: Modern (sanitary) Landfill Leachate Collection System, which also shows a gas collection system [14].

Modern leachate systems operate under three common practices: on-site pre-treatment followed by off-site post-treatment before use, off-site wastewater treatment, usually at a domestic wastewater treatment facility, or a complete treatment system onsite with discharge back to the site. While these techniques accomplish the job of prepping the leachate for reintegration into the public water cycle they prove expensive and/or not cost-effective to operate [14]. Figure 4 shows the simplified layout of how a modern landfill is typically constructed, utilizing a multilayer geosynthetic liner as the base and a series of collection pipes that route leachate to a collection area in order to be pumped for treatment.

Phytoremediation Application

It has been proposed that phytoremediation would provide a great option to support or replace current leachate treatment techniques, as it would be powered by the sun and would require low post-installation costs. Currently the literature is limited on peer reviewed publications for phytoremediation at full-scale or small-scale field trials, due to legislation and/or due to upscaling challenges. As a result, much field work related to phytoremediation of landfill leachate is at the pilot scale or limited application at landfills. For landfill leachate one of the most common techniques for leachate remediation involves constructing wetlands with specific plant species to treat the various contaminants within the leachate [28]. Another method currently gaining some attention is the use of leachate as an irrigation supply for planted trees in the soil, potentially on top of the landfill post closure [36]. Another potentially useful approach to phytoremediation techniques for landfills is to apply vegetation in areas that could be at risk for leachate seepage, utilizing the phytotoxicity relationship between plants and leachate, although case studies on this approach are limited. Constructed wetlands and irrigation buffer zones are two of the most popular and recent options for phytoremediation of landfill leachate and will be reviewed in more detail in the subsequent section.

Constructed Wetlands for Phytoremediation of Landfill Leachate

The first constructed wetland (CW(s)) in the United States was built in 1976 for a project in New York. In general, constructed wetlands provide several advantages: First, they are powered by the sun and are built to take advantage of gravity to filter and sediment out pollutants, dirt, sand, etc. Second, they are usually esthetically pleasing and do not require a large footprint in most cases. Finally, they require minimal maintenance once built (typically only requiring regular cleaning), which allows developing countries that lack the funding or regulation to push sanitary landfills for their MSW an accessible option [28]. Because of these features, CWs have gained traction in the phytoremediation community as a method to remediate landfill leachate as part of other remediation systems. CW operate under two basic mechanisms either free surface water or subsurface flow systems, as illustrated in Figure 5. Subsurface systems have two different modes of operation, horizontal and vertical: free surface water systems operate by pumping the leachate onto the surface of the CW and provide a porous media around the plants for phytoremediation to occur. To function efficiently, the substrate used for the CW must be carefully selected to ensure the porosity is good for the subject plants to uptake the contaminants effectively [30]. In some cases, a combination of the two may be employed. An in-depth review conducted by R. Bakhshoodeh, et al. found that the vertical flow subsurface CW proved the most successful at removing heavy metals from landfill leachate across the board from studies that were all conducted and published prior to 2017 [29].

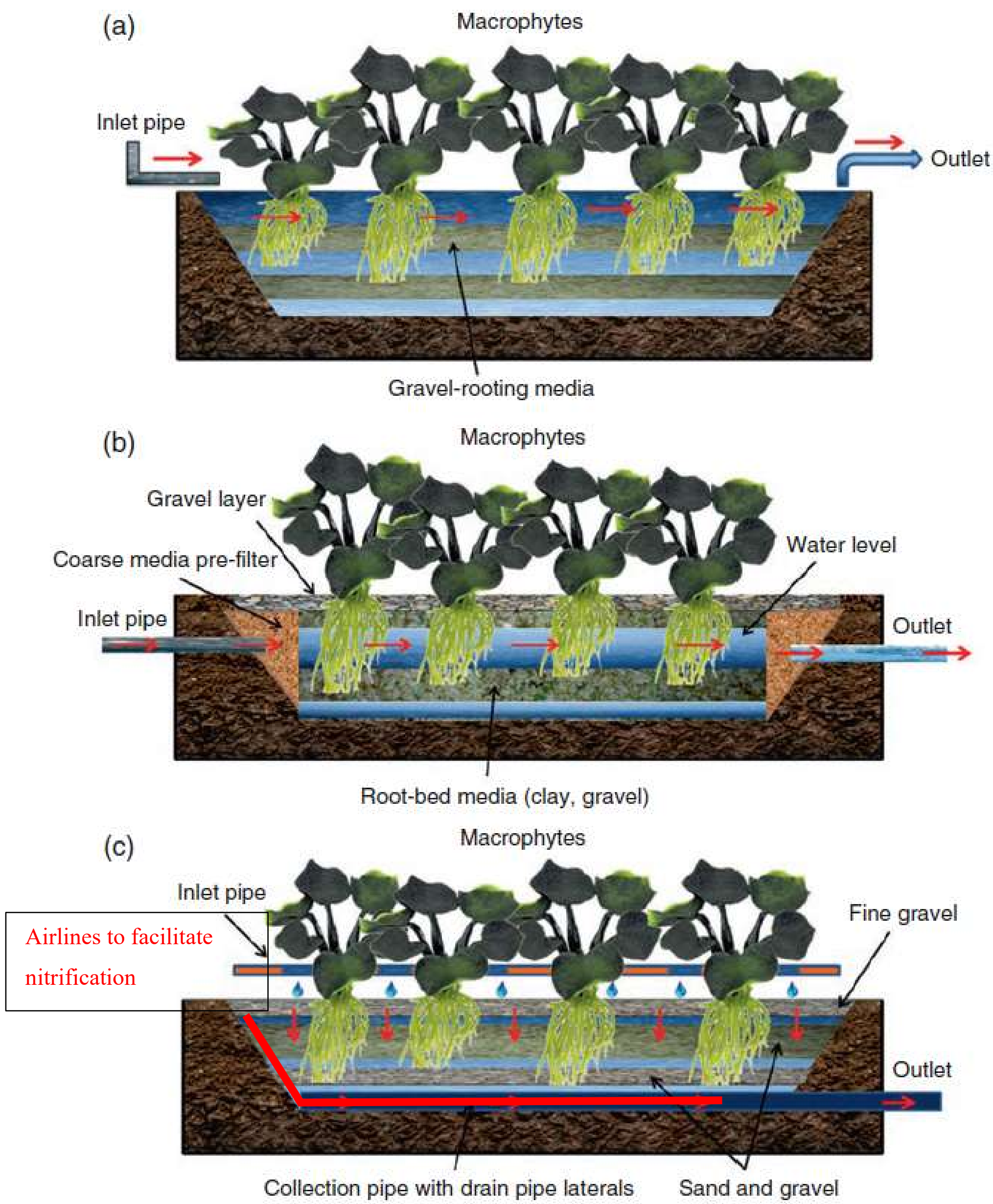

Figure 5: Different CW layouts. a - surface flow, b - subsurface horizontal flow, c - subsurface vertical flow [30]

Constructed wetlands have been shown to be highly effective at treating landfill leachate provided it is diluted properly to not overly stress the plants and microbe population. One such lab study investigated the efficiency of *Cattail* and *Bulrush* to remediate common leachate pollutants under various retention times and found that removal efficiency was as high as 91% for total solids and 65% for nitrates. Optimal retention time was approximately 4 hours as after this removal had reached equilibrium [28].

Looking into large-scale projects of CW is of incredible value to understanding how effectively phytoremediation can operate in real world scenarios. Most of the work done over the past several decades has been conducted at lab scale usually in greenhouses to control the environment. A brief look into recent literature published related to phytoremediation using CWs is important for the understanding of where the work is trending and, how much of it is being conducted and shared. A book published by Springer in 2017 and written by A. Ansari, et al. provided a comprehensive list of lab and field scale phytoremediation projects from around the world up to this date [42]. Therefore, the scope of this review will be limited to field studies of the application of phytoremediation via constructed wetlands of landfill leachate from 2017 to present.

In March of 2017, a hybrid leachate treatment system was installed to treat landfill leachate in Patro, Italy, as part of a tertiary treatment system, utilizing a hybrid subsurface flow CW for the final treatment state prior to discharge to the local wastewater treatment plant (WWTP). The goal behind this installation was to reduce chemical oxygen demand (COD) prior to entry into the WTP. The system was set up with two sets of CW beds, the first being vertical and the second being horizontal. Sampling wells were located at the end of both beds to determine efficiency. Common reed plants (*P. australis*) were used as the macrophyte (water loving plants) for both beds. *P. australias* has been studied previously to be a suitable candidate for phytoremediation techniques due to its ability to sequester heavy metals at an effective rate and efficiently reduce COD, both objectives of treatment prior to release to the WWTP [31,32, 33].

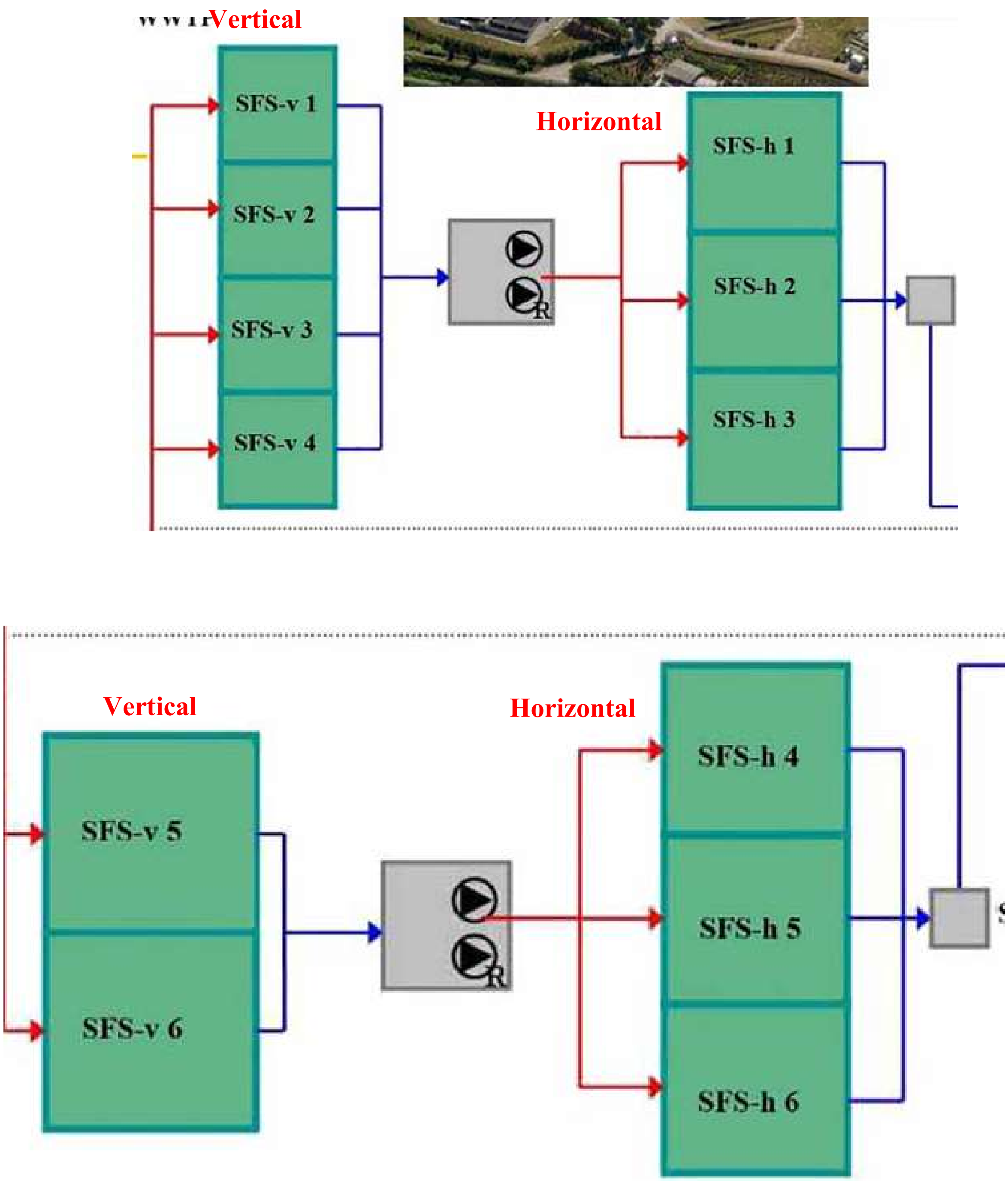

Figure 6: Schematic of the tertiary treatment setup [33].

Figure 7: CW bed layout [33].

Feeding of leachate was done intermittently 12 times a day for the vertical flow and continuously for the horizontal flow. This was important for establishing theoretically optimal retention times. Important findings from the process displayed both promise and certain drawbacks. The vertical flow constructed wetlands showed 100% and 50% growth and activation for phytoremediation by the end of the first year of operation and the horizontal flow showed 100% and 40% respectively between lines A and B. It was found that operation problems including mechanical and hydraulic lead to uneven distribution of leachate and nutrients within the horizontal system [33].

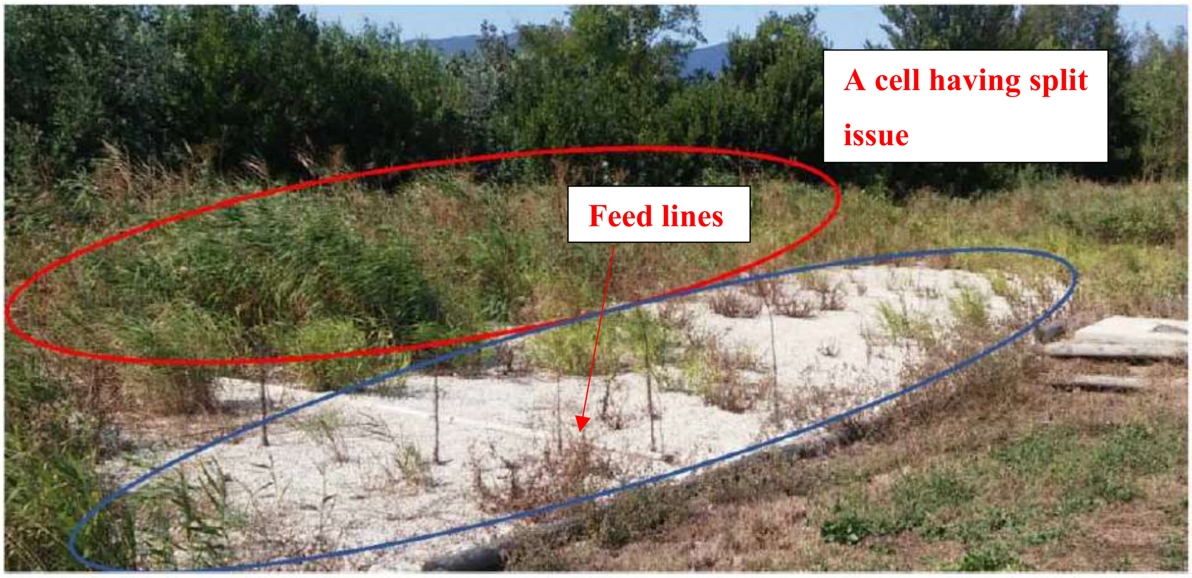

Figure 8: Uneven growth of horizontal CW [33].

Key takeaways from this system are detailed below:

1. COD reduction of up to 30% was achievable with the system; however, some of the COD lacked biodegradability coming out of the other stages of the system.
2. During the second year the vertical CW showed reductions of 15% COD, 89% ammonia N, 14% Nitrite N, and 12% for Phosphorus.
3. The horizontal setup showed the most promise for removing Nitrite N, as it increased the removal by 22%. All others were negligible.
4. The removal of metals such as Al, Fe, B, and Cr was approximately 9.25% on average.

The study concluded that while there was a positive effect on the leachate waste stream before entry into the WWTP, more research would be necessary to optimize the system and more time would be needed for the plants to grow more mature. Optimization options to consider may include an additional pre-treatment of the leachate prior to entry into the CW, an increase in the hydraulic residence time, and the use of different plants.

Another study conducted in Sri Lanka investigated compost leachate on different plants for a potential future subsurface vertical constructed wetland for already pretreated MSW leachate [34]. While the study does not actually take place at a landfill it is important for the effect of leachate on different plants in real climate weather conditions. Utilizing drums for the vertical CW in parallel, the plants were exposed to different dilutions of leachate. The success of each plant is shown below in Table 2 [34].

Table 2: Summary of plant performance from Sri Lanka study [34].

Plant Species	Type	Dilutions	Successful
E. crassipes (water hyacinth)	Free-Floating	75% 50%	Yes No
P. stratiotes (water cabbage)	Free-Floating	75%	No
T. angustifolia (narrowleaf cattail)	Emergent Macrophyte	75% 50% 0%	Yes Yes Yes
C. zizanioides (vetiver)	Emergent Macrophyte	75% 50% 0%	Yes Yes Yes

What is clear from the study is that the emergent macrophytes were better able to manage the raw leachate than the free-floating macrophytes. At no dilution, the macrophytes were the only plants capable of sustaining phytoremediation. A control was added that could be considered a CW without plants and it performed well (see Figure 9). However, the addition of plants improved the efficiency of remediation of every constituent [34]. It is possible that the additional soil layer for the emergent macrophytes plays a crucial role in assisting the plants through rhizofiltration/degradation or simply slowing the transfer rate as compared to free floating macrophytes. Studies of this nature should continue to be conducted to look at different plants and should also include the analysis of heavy metals and other trace contaminants in the future.

Parameter	Units	T^0_1 (*T. angustifolia*)	T^0_2 (*C. zizanioides*)	Control (C^0)
EC	µS/cm	41.53 ± 0.52^b	47.96 ± 0.55^a	35.86 ± 0.95^c
Turbidity	NTU	90.30 ± 0.19^a	91.76 ± 0.16^a	88.77 ± 0.18^b
BOD	mg/L	92.36 ± 0.15^a	93.60 ± 0.12^a	90.21 ± 0.20^b
COD	mg/L	88.48 ± 0.23^b	90.55 ± 0.26^a	86.30 ± 0.30^c
TSS	mg/L	59.96 ± 1.72^b	65.10 ± 1.15^a	54.13 ± 1.70^c
PO_4^{3}	mg/L	98.34 ± 0.15^a	98.82 ± 0.93^a	97.62 ± 0.11^b
NO_3^-	mg/L	63.97 ± 1.11^b	67.42 ± 1.12^a	54.69 ± 0.97^c
NH_4^+-N	mg/L	77.52 ± 0.55^b	81.60 ± 0.51^a	69.08 ± 1.20^c
SO_4^{2-}	mg/L	69.41 ± 1.05^b	74.13 ± 0.76^a	60.13 ± 3.74^c
Color	Platinum Cobalt Units	92.13 ± 0.15^b	93.71 ± 0.18^a	89.38 ± 0.14^c

Red box indicates favorable results

Figure 9: Results of no dilution of leachate on emergent macrophytes, in percentages [34].

Unfortunately, there is a lack of any additional field-testing reports on constructed wetlands since 2017. It would be interesting to know if this can be attributed to the pandemic in any way or legislative changes that have made them less appealing for landfills. There are numerous lab-scale models that are currently being evaluated for various plant types and contamination ranges; however, they have yet to be verified in field-scale models. Given the success of previous field applications of wetlands for leachate management, additional field studies are encouraged and recommended.

Terrestrial Irrigation

When a landfill closes and begins its post operation life cycle it will leave a large barren footprint that will require cover to prevent erosion and the potential escape of leachate and landfill gas. This leads to increased interest in finding ways to maintain cover as economically and eco-friendly as possible. For example, using woody plants such as poplar and willow trees for these covers could be a "Phyto" approach to remediation of landfill leachate in soils as opposed to wetlands [36]. The benefit of using terrestrial or woody plants is that it allows for the ability to recycle the leachate back onto the landfill thus creating a cycle that could provide faster landfill stabilization and keep the leachate away from sensitive environmental receptors.

Terrestrial plants such as trees provide evapotranspiration of some of the water in the leachate, which reduces the amount to recycle. Terrestrial plants can also be used to create buffer zones around landfills to prevent the escape of rogue leachate and contamination [56]. Field trials for terrestrial plants usually involve small plantations (1 ha) of willow or poplar trees to carry out phytoremediation investigations of landfill leachate. Leachate is usually brought in and applied via irrigation (spray or trickle) onto the trees.

Of the terrestrial plants studied thus far, poplar (*Populus*) and willow (*Salix*) trees are two of the most investigated. This is because of their fast growth, ease of rooting, high biomass, rapid and high-water uptake, and wide diversity of species that can provide opportunities to experiment with different subspecies for cross breeding and selective contaminant cleanup trait [35]. When these plants have been established and have grown sufficiently, they can be harvested for energy or if the contaminant is valuable, phytomined for reclamation. These beneficial factors have led to the great interest in these trees for phytoremediation purposes. Further investigations into the capabilities and limitations of these trees have continued over the years and plantations for long term studies have been established and evaluated over the years for various remediation applications [57]. As discussed below, a couple of full scale projects demonstrate that offer some favorable results for phytoremediation applications to landfill leachate.

A study conducted in Tuscany, Italy (2021), an investigation into the abilities of poplar and willow trees to survive and thrive in the Mediterranean Sea while being exposed to landfill leachate. The trees were subjected to a two-year study under different concentrations of leachate (with the same leachate dilutions and the same lysimeter setups for both species). The lysimeters (Figure 10) were setup out by the landfill in an unused closed section to get atmospheric conditions. Leachate was diluted more the first year and concentrated more by the end of the second year. After the two-year study it was concluded that both plant species showed a positive response to landfill leachate as opposed to a water-based treatment. Willow showed a stronger response to the leachate treatment, being as much as 25% taller than the poplar in the study. All plants subjected to the leachate treatment (high or low dilution) showed greater growth than that of the controls (water based) [37].

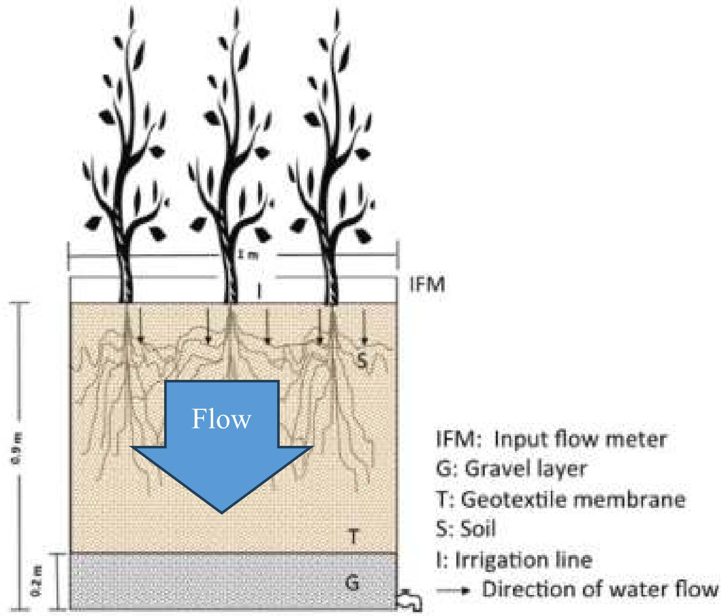

Figure 10: Lysimeter setup for poplar and willow treatment [38].

Phytoextraction capacities of the trees were studied as well and provided promising results, as shown in Figure 11. Trace element concentrations for As, Cd, Cu, Ni, Zn, N, and P were measured in the stem and leaves of the trees at the end of each growing season. Both species were able to move trace elements to the above ground biomass, but poplar displayed a better ability overall in extraction of Cu and Ni from high leachate concentrations. In any case, both plants were able to extract As to ranges below limit of detection (LOD). Ammonia removal was very efficient in poplar plants but only about half as effective in willows. BOD and COD were managed efficiently by both plants as well, but poplar more effectively remediated these [37]. A key issue discovered in this study was that high salinity continues to be a problem, showing a buildup towards the end of the study. This has been a well-known issue for poplar and willow trees; a study conducted by Justin in 2010 reported similar issues when comparing the growth of poplar clones and native willow trees [38].

Solving the long-term buildup of salt concentration in the soil must be a goal to continue long-term phytoremediation efforts. This is being investigated by potential cross breeding of plants or finding more salt tolerant species of current well-known plants [59]. Pre-treatment is the immediate solution; however, there are companies looking to perform saline agriculture to utilize salt tolerant plants to leach salt out of the soil, but this requires that low salt irrigation water be applied [39]. More studies into utilizing multiple plant species in one phytoremediation scenario could prove a favorable option but more testing would still be required.

Plantations of short rotation coppice have been of interest for leachate treatment for several years. The idea of harvesting the upper portion of the plant for energy provides a profitable outlet for landfills that have ceased operation. In terms of using plantations as buffers and leachate treatment fields, a study was conducted in eastern Canada at an old, closed landfill. Benoist et. al. was interested in seeing if willow trees planted on the cap of an old landfill could serve as a place to treat the leachate without killing the plants and providing extraction capabilities for the trace elements in the leachate. The site utilized was an old landfill in Southern Quebec that had been closed in the early 80's with a 1 m clay liner. One-year-old willow plants were transplanted to cover about 0.5 ha used. Four different leachate strength tests were conducted, one without leachate addition, one diluted (percent not provided), and two are half as diluted as the first and one doped with phosphorus. The leachate used is from an older landfill therefore it is classified as old leachate. Again, this test saw that under leachate treatment the size of the willows above ground biomass growth was better than under water treatment alone; up to 2.5 times higher biomass in the weakest dilution (strongest leachate) doped with phosphorus. This indicates the leachate doped provided good fertilizer for the plants and was not detrimental for most of the plantation; a few trees died but it was not disclosed under which treatment they were subjected to. Another positive outcome of the study was that COD and nitrogen were efficiently managed by the plantation for the most part. As the concentration of the leachate got higher the buildup of COD in the soil was apparent. Properly diluted leachate could counter this and render it less of an issue in future experiments [40].

Parameters	Treatment	D0	D1	D2	D2P
COD	Influent (mg L^{-1})	9.8 ± 6.1	288 ± 43	288 ± 43	288 ± 43
	Effluent (mg L^{-1})	28.0 ± 18^{a}	58 ± 20^{b}	198 ± 69^{d}	111 ± 42^{c}
	Efficiency %	−185.0	$\boxed{79.8}$	$\boxed{31.2}$	$\boxed{61.6}$
NTK	Influent (mg L^{-1})	0.22 ± 0.06	221 ± 37	221 ± 37	221 ± 37
	Effluent (mg L^{-1})	0.90 ± 0.68^{a}	2.3 ± 1.6^{b}	5.6 ± 4.0^{c}	3.8 ± 2.0^{c}
	Efficiency %	−309.1	$\boxed{99.9}$	$\boxed{97.5}$	$\boxed{98.3}$
NH_4-N	Influent (mg L^{-1})	0.23 ± 0.05	218 ± 35	218 ± 35	218 ± 35
	Effluent (mg L^{-1})	0.06 ± 0.04^{a}	$0.07 \pm 0.08^{a,b}$	$2.29 \pm 3.53^{b,c}$	0.82 ± 1.30^{c}
	Efficiency %	74	$\boxed{100}$	$\boxed{99}$	$\boxed{99.6}$

Red box indicates favorable results

Note: Different letters in rows indicate significant differences ($p < 0.05$); ± indicates standard deviation.

Figure 11: Results of application at the willow plantation [40].

Parameter	Units	Influent		Effluent							
		Water	Leachate	D0		D1		D2		D2P	
				August	October	August	October	August	October	August	October
Ca	mg/kg	78.7	232	139.3 ± 28	$\underline{151 \pm 39}^{a}$	344.0 ± 77	$\underline{368 \pm 101}^{b}$	396 ± 80	$\underline{386 \pm 108}^{b}$	433.0 ± 111	$\underline{456 \pm 116}^{b}$
Fe	mg/kg	1.45	34.5	3.8 ± 4.3	$\underline{2.7 \pm 1.8}^{a}$	0.09 ± 0.07	$\boxed{\underline{0.06 \pm 0.01}^{b}}$	0.10 ± 0.09	$\boxed{\underline{0.15 \pm 0.14}^{b}}$	0.04 ± 0.02	$\boxed{\underline{0.04 \pm 0.02}^{b}}$
K	mg/kg	4.5	267.7	8.4 ± 5.7	$\underline{10 \pm 1.6}^{a}$	38 ± 22	$\boxed{\underline{35 \pm 11}^{a}}$	87 ± 42	$\boxed{\underline{119 \pm 89}^{b}}$	49 ± 19	$\boxed{\underline{55 \pm 36}^{a}}$
Mg	mg/kg	39.2	122.4	62 ± 19	$\underline{63 \pm 22}^{a}$	194 ± 63	$\underline{190 \pm 66}^{b}$	210 ± 15	$\underline{201 \pm 27}^{b}$	212 ± 82	$\underline{220 \pm 73}^{b}$
Na	mg/kg	21.7	333	12 ± 3	$\underline{11 \pm 5}^{a}$	262 ± 180	$\boxed{\underline{250 \pm 99}^{b}}$	396 ± 129	$\underline{467 \pm 172}^{b}$	371 ± 209	$\underline{377 \pm 210}^{b}$
P	mg/kg	0.0008	0.006	0.17 ± 0.11	0.09 ± 0.02	0.50 ± 0.55	0.07 ± 0.05	0.14 ± 0.05	0.07 ± 0.04	0.24 ± 0.15	0.13 ± 0.09

Red box indicates favorable results

Note: underlined numbers are significantly different. Different letters in rows indicate significant differences ($p < 0.05$
± indicates standard deviation.

Figure 12: Results of application at the willow plantation continued [40].

In this study the leachate clearly functioned as a fertilizer providing the plants with good growth support. Figure 11 shows the results for COD and nitrogen loading (including ammonia) loading on the soil around the plants. COD and nitrogen were managed well by the highest dilution but saw diminishing returns at the more concentrated leachate, which could be alleviated by increasing the plantation size. Figure 12 shows the results of sampling the soil after a few months near the end of the growing season. When the dilution was high the phytoextraction of Fe, Mg, Na, and K was good. However, there was a limit as the stronger leachate application left the soil with higher concentrations of these trace elements, which means that buildup would be inevitable [40]. What has become apparent from the work compiled in this review is that finding out the proper loading of leachate is key. If added too strongly it creates a toxic environment for the plants that as it worsens, it deems the plants becomes less efficient.

Conducting a test on this scale is what is desired for this review; however, the test also provides understanding as to the difficulty and complexity that arises when attempting large-scale applications. As can be seen from the results in Figures 11 & 12, not everything is phytoextracted evenly. Some elements potassium for example, were kept in check by the willow plants but others; calcium for instance, were not affected very well by it. More work is needed to improve the efficiency of willow plants, but this is a step in the right direction and shows they can be used with the right application of leachate.

Phytocapping

Another phytoremediation technique that is gaining traction is phytocapping. Phytocapping is the use of specifically selected plants to be planted on the final cap for landfills and landfill cells. Typically, the method for closing a landfill entails applying an approximately 1-m thick clay layer which is then seeded with local grass vegetation. If the landfill soil is highly contaminated, a more sophisticated cover could be geomembrane or a combination of geomembrane and clay with vegetation [43]. Landfill caps are important because they seek to prevent water from entering the landfill refuse through percolation.

Landfill gas is generated by the decomposition of organic matter over time [45]. There are two types of gas generation in landfills, namely aerobic (with oxygen) and anaerobic (without oxygen). Aerobic decomposition occurs in a greater capacity when the landfill is younger as there is more oxygen readily available for reacting. As the landfill ages and the presence of oxygen decreases anaerobic conditions appear in some locations. While during aerobic breakdown the byproduct is predominantly carbon dioxide, anaerobic decomposition leads to the formation of methane. When water percolates through landfills carbon dioxide generation goes back up due to the reinsertion of oxygen [46]. As stated in the introduction both are greenhouse gases with methane being a more formidable greenhouse gas. Methane needs to be managed appropriately to prevent its escape into the atmosphere.

Sanitary landfills are equipped with gas collection systems, see Figure 4, designed to capture and route gas to incineration points or collection points for use. However, this requires that the gas does not escape by other means. If the cap is inefficient then the possibility of gases venting elsewhere on the landfill is likely. Geomembrane and clay caps can deteriorate over time, leading to inefficiency and gas escape. Phytocapping looks to solve these problems by utilizing plants that create a canopy layer over the landfill cover to catch and prevent moisture from entering the landfill and aid in stabilizing the soil cap in order to prevent degradation and eventual failure of gas and leachate containment. Albright *et al.* in 2004 concluded that clay liners are not an effective way to limit the percolation of water through a landfill long term [44]. Because developing countries are unlikely to utilize sophisticated closure strategies, it is important to consider economically feasible and easy to install systems, which is what phytocapping, seeks to do.

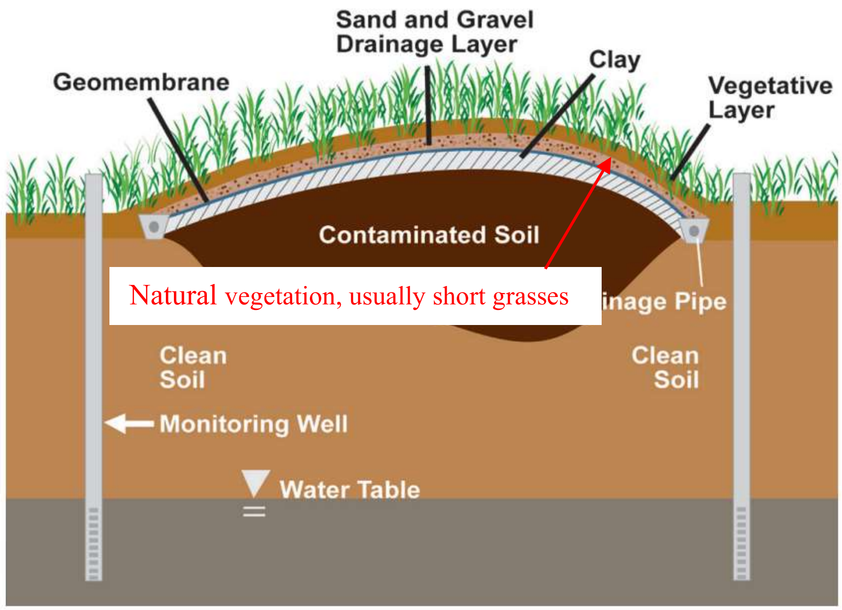

Figure 13:Typical landfill closure setup [44].

A recently published study that was conducted from 1990 to 2020 found that 17% of the United States total methane emissions originated from landfills [47]. As shown in Figure 14, Cusworth, *et al.* conducted a study from 2016 to 2022 across the United States spanning 20% of all open landfills and found that over 50% of them were off gassing methane from uncontrolled points [48]. An important observation is how many point detections were in highly populated areas, with the entire California coast as an example. These studies highlight the importance of proper capping and control of landfill gases. Unfortunately, there have not been any full-scale studies in recent years (2018 to present) that were easily accessible from publications. Hauser reported in 2009 that the construction of a phytocap could be as much as 72% lower than a conventional cover, which should make them an economically appealing choice for landfill closure [49]. It is theorized by this reviewer that many landfills do not want to take the risk of implementing a seemingly unproven technology, given that after a landfill closes the income drops off dramatically if not completely.

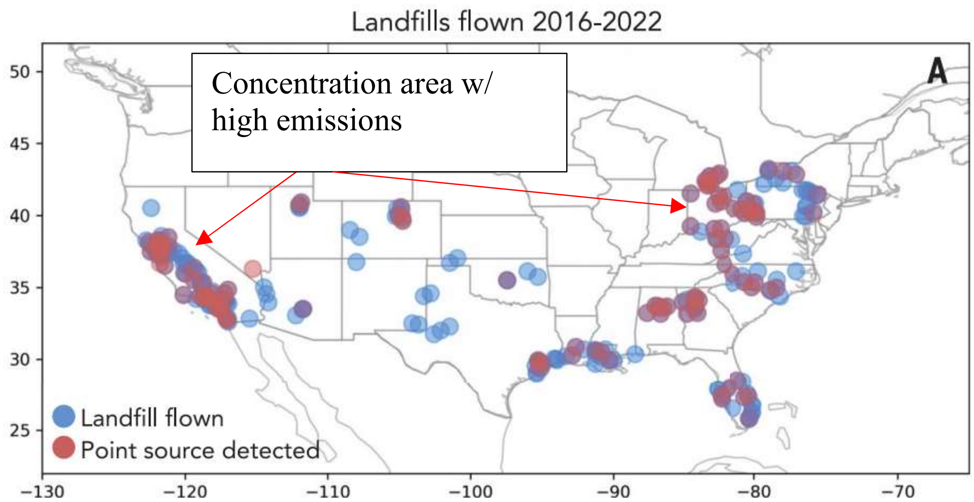

Figure 14: Landfills with methane leaks detected [48].

There is a study that was published in 2009 that looked at a large scale phytocapping in Australia for a MSW that provides ample groundwork to justify the use of phytocapping here in the United States. Using higher order plants (i.e., trees) trees, and two different cover thicknesses (0.7 m and 1.4 m) the researchers investigated of which system would provide the best methane control over a plain clay liner. Trees were planted in a 6 m x 6 m array over ½ of the liner and the other ½ was left bare. What was found was that the thicker cover layer coupled with the trees provided approximately 80% reduction in methane gassing. It turns out that the tree roots system resulted in an effective methane reduction layer by providing methanotrophic bacteria a fertile ground to grow plentiful enough to reduce methane levels substantially (Figure 15). The presence of the tree roots created a porous soil that allowed oxygen to be supplied to the rhizosphere where the bacteria are present. They also found, back in 2009, that this technique could cut the remediation costs of the landfill in half [50]. Phytocapping has been shown to stabilize, extract contaminants, and degrade contaminants while also facilitating hydraulic control.

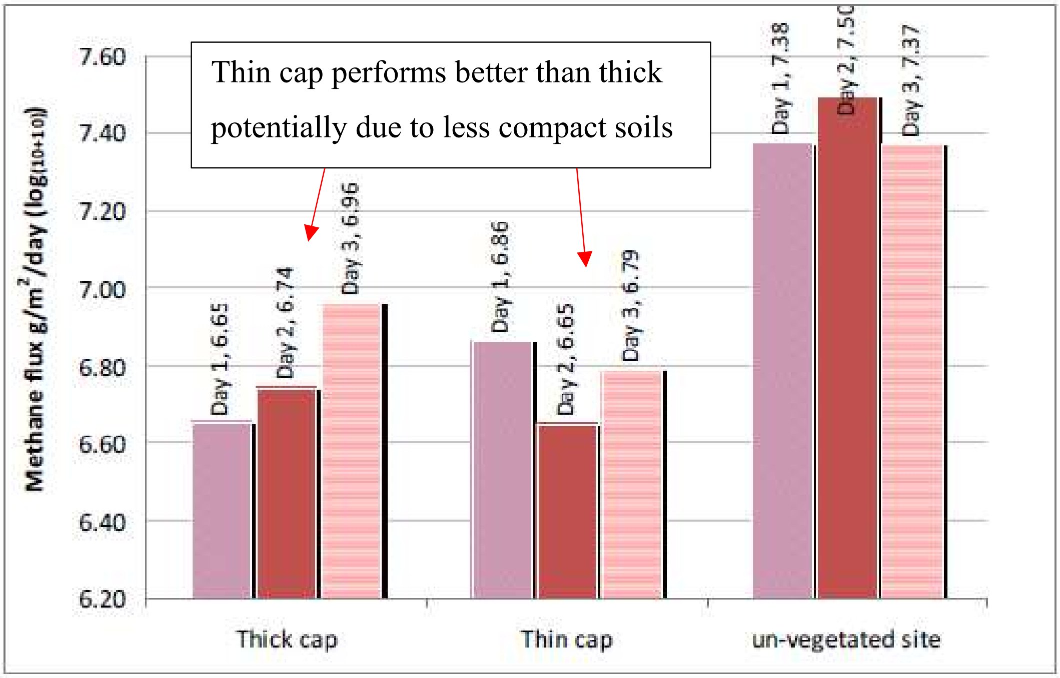

Figure 15: Daily Methane Flux with & without Phytocap [50].

A recent study was conducted to assess the ability of lysimeter scale models to accurately represent full-scale phytocapping. It was found that they could potentially be unreliable for showing how phytocapping works at the large scale. Australia requires phytocap performance to be demonstrated via lysimeter prior to installation [51]. This could reduce the acceptance of phytocapping in the future if these tests remain a requirement. This is amplified by the fact that another study conducted in Australia utilized a lab scale phytocap setup and showed that 60%-63% methane reduction was highly achievable [52]. While phytocapping lags behind leachate techniques in terms of full-scale applications, numerous lab-scale studies indicate that phytocapping is worth pursuing with estimated cost reductions of up to 72% it is further enticing [57].

Discussion and Conclusions

Phytoremediation offers many benefits to leachate and gas control and remediation for landfills. Constructed wetlands have been shown to be good strategies for effective leachate management and water control, while providing aesthetically pleasing scenery when located near populated areas.

Figure 16: Constructed Wetlands near a city [53].

Terrestrial applications provide an alternative route of remediation that can be applied to the cover of landfills potentially enhancing gas capture abilities, in the right circumstance. With the added benefit of providing biomass for energy production there is a synergistic nature to cleanup that can provide added economy to an otherwise depleted source.

A need for more phytocapping studies in the field has been highlighted in this review and hopefully they will become more prevalent in the near future. With the ability to regulate water input into the landfill and mitigate landfill gas emissions trees provide good coverage for aging landfills.

There are limitations to phytoremediation at landfills that will require solutions in the future. When not effectively managed leachate can be toxic to plants and severely hinder phytoremediation ability or kill the plants outright. Too much methane in the soil can create an anoxic environment that could asphyxiate the plants and kill them as well. Root zone contact is also important to consider as deeper contamination might not be reachable by the plants [54]. It is also a young technology that requires much more research in order to implement properly. Plant selection is highly dependent on the environmental factors associated with the landfill location and thus finding plants that can achieve effective phytoremediation could prove challenging in certain climates. Temperate zones and polar regions will have dormant seasons where plants are not active. Phytoremediation drops dramatically in winter without winter plant species and therefore leachate must be stored or handled in other ways during winter months. Uncontrolled gas production becomes more likely then as well. Phytoremediation also takes longer than conventional means which limits its applicability in certain situations.

Even with the drawbacks phytoremediation still offers an ecofriendly and cost-effective approach to landfill remediation and closure. Benefits up to 72% cost savings for phytocapping and anywhere from 50%-98% cost savings for leachate are incentives to at least try it as an option [55]. Further investigation into phytoremediation is necessary to unlock and optimize all the benefits it has to offer, but as shown in this review, phytoremediation is an endeavor worth pursuing.

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Glossary of Terms

Macrophyte - A macrophyte is a plant that grows in or near water and is either emergent, submergent, or floating. In lakes and rivers, macrophytes provide cover for fish, substrate for aquatic invertebrates, produce oxygen, and act as food for some fish and wildlife.

RCRA- Resource Conservation and Recovery Act

CW – Constructed Wetlands

MSW – Municipal Solid waste

Leachate - water that has percolated through a solid and leached out some of the constituents

WTP – Wastewater Treatment Plant

Short Rotation Coppice (SRC) – Trees that are repeatedly cut down to near ground level in order to harvest biomass over many years.

COD – Chemical Oxygen Demand – a measure of the amount of oxygen that can be consumed by reactions in a measured system. In our case here, it is used to measure the level of organic pollutants in water. High COD can be detrimental to aquatic life.

LOD – Limit of detection – the lowest quantity or concentration of a component that can be reliably detected.