APPLICATION OF ECOLOGICAL ENGINEERING IN LANDFILL REMEDIATION

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Abstract: *Ecological engineering is a new branch of engineering based on ecology that emerged in the 1960s from the growing need for more sustainable biological solutions to environmental problems. It is based on the design of natural ecosystems for the benefit of both nature and human society, and its techniques can be applied to a range of environmental problems, from the restoration of degraded ecosystems to the removal of pollutants. One of the major environmental problems worldwide is waste disposal in the form of landfills, with its various negative impacts on the environment, living beings and human health. Conventional landfill closure and remediation techniques have proven to be economically and energetically challenging and are not sufficiently effective in reducing leachate formation and removing pollutants. For this reason, this article presents several ecological engineering techniques that can be used in landfill remediation. Phytocapping is an alternative to conventional cover systems that uses plants to control and limit water infiltration into waste, leachate formation, stabilize landfills, control erosion, and reduce methane emissions. Phytoremediation is an environmentally friendly technology for soil remediation through natural processes, in two forms: phytoextraction and phytostabilization. Phytoextraction uses plants to extract and remove pollutants from waste and soil, while phytostabilization is used to immobilize pollutants in the root zone. Constructed wetlands, designed and constructed according to the principles of natural wetland ecosystems, can be used to clean leachate. Natural attenuation uses natural biological processes to mitigate pollution without taking specific action. All of these techniques are based on viable natural solutions that can reduce remediation costs and further maintenance of the landfill. Although they are increasingly being considered in developed countries, there are few examples of their application in landfill remediation in Croatia.*

Keywords: *ecological engineering, landfills, phytocapping, phytoremediation, constructed wetlands, natural attenuation*

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1. INTRODUCTION

Nowadays, environmental problems are becoming increasingly complex and the resources available to solve them are limited. Practical experience has shown that many of these problems (soil, water and air pollution, waste problems, habitat degradation, etc.) cannot be solved only by conventional technological methods, which are often economically very demanding and ecologically unsustainable. In many cases, solving one pollution problem leads to other problems, and little attention is paid to ecologically healthier approaches that consider direct and indirect impacts on the environment and human health (Mitsch, 1996; Mitsch & Jørgensen, 2003).

In response to the growing need for a more sustainable approach, a new branch of engineering based on ecology, called ecological engineering, emerged in the 1960s (Mitsch, 1996). Ecological engineering implies the assumption that environmental problems can be solved within ecosystems themselves, using their components and the natural processes that occur within them, and relying on the ability of natural ecosystems to organize and design themselves. In contrast to other conventional technological methods, it represents a better, more environmentally friendly and economically profitable strategy in the long term, since it uses already existing, free natural solutions. The goal is to create and restore ecosystems that are of value to both nature and human society, while protecting the goods and services provided by the natural environment, according to the principle of "use but not abuse" (Jørgensen, 2008). Ecological engineering techniques are now used around the world to solve a range of environmental problems, such as restoring degraded areas, adapting to climate change, controlling dispersed sources of pollution (e.g., from agriculture and mining), remediating landfills, treating wastewater, etc.

Despite the development of modern waste recycling technologies, landfills are still the most common option for waste disposal in many countries, as they are an easier and more profitable way to solve the waste problem. Landfills, and especially uncontrolled ones (i.e. open dumping), pose a high risk to the environment and human health by releasing various types of pollutants into the environment. Just for illustration, in 2020 32.2% of the total waste generated in the European Union was deposited in landfills (Eurostat, 2022). In Croatia, a total of 1,451,749 t of municipal and industrial waste was deposited in 93 active landfills (84 municipal and nine industrial waste landfills) in the same year; in addition to the active landfills, there were 228 closed landfills, of which 156 were remediated (Zavod za zaštitu okoliša i prirode Ministarstva gospodarstva i održivog razvoja, 2021).

As in many European countries, the problem in Croatia is the so-called uncontrolled landfills, where mainly construction and bulky waste and, to a lesser extent, municipal waste is deposited. A total of 10,723 such landfills across Croatia have been reported from October 2019 to the end of 2022 through the "Waste disposal location record" system (https://eloo.haop.hr/public/) established and managed by the Ministry of Economy and Sustainable Development (Ministarstvo gospodarstva i održivog razvoja, 2022). However, their actual number cannot be estimated, as new landfills are very often created by the irresponsible individuals.

The remediation of landfills reduces the negative impact of waste on the environment and natural resources. However, most of these projects use expensive conventional technological solutions with high maintenance costs that are usually ineffective in the long term because they depend on external energy, control, and management by humans. More and more attention is being paid to new nature-based ecological engineering techniques for landfill remediation, such as phytocapping (plant cover evapotranspiration prevents water infiltration into the waste and erosion, and reduces methane emission and leachate generation) (Ventrakaman & Ashwath, 2011; Lamb et al, 2014; Khapre et al., 2017), phytoremediation (allows remediation of pollutants using plants and stabilization of landfill cover) (Nagendran, et al, 2006; Kim & Owens, 2010; Pathak et al., 2012)., constructed wetlands (enable remediation of landfill leachate) (Madera-Parra & Ríos, 2017; Bakhshoodeh et al., 2020) and natural attenuation (mitigation of pollution without specific measures) (Bagchi, 1983; Christensen et al., 2000; Kisić, 2012). These techniques, alone or in combination with conventional technological solutions, can make a useful contribution to more successful and faster remediation and restoration of sites contaminated with waste.

The objectives of this paper are therefore as follows:

a) to give a brief overview of the new discipline - ecological engineering -, its definition, basic concepts and approaches that distinguish it from conventional engineering techniques for solving environmental problems, especially with regard to sites polluted with wastes;
b) to present potential applications of new ecological engineering techniques (phytocapping, phytoremediation, constructed wetlands, and natural attenuation) in the remediation of landfills and discuss their advantages and disadvantages;
c) to provide a brief overview of the existing ecological engineering techniques already used in Croatia for landfill remediation.

2. ECOLOGICAL ENGINEERING

2.1. History, definition and goals

The term "ecological engineering" was coined in the 1960s by Howard T. Odum, often called the father of ecological engineering. He defined it as "environmental manipulations by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural sources " (Odum et al., 1963; Mitsch & Jorgensen, 2003).

Mitsch and Jorgensen (1989), in their pioneering work "Ecological Engineering: An Introduction to Ecotechnology," define ecological engineering as "the design of human society with its natural environment for the benefit of both" while in later works they redefine it as the design of sustainable natural or artificial ecosystems that integrate human society with its natural environment for the benefit of both (Mitsch & Jørgensen, 2003; Jørgensen, 2008).

According to Jørgensen (2008), ecological engineering uses the knowledge of ecology as a basic science on one hand and the principles of engineering disciplines with quantitative approaches on the other. It is used to predict, design, restore and manage ecosystems or parts of them. Its main objectives are to restore ecosystems that have been significantly disturbed mainly by human activities and to develop new sustainable ecosystems that have social and ecological value (Mitsch & Jørgensen, 2003; Mitsch, 2012). The main tool of ecological engineering is the self-design of ecosystems whose components are all biological species of the world (Mitsch, 1996).

Ecotechnology is sometimes used as a synonym for ecological engineering. Straškraba (1993) describes it as "a new means for environmental management" and defines it as "use of technological means for ecosystem management based on deep understanding of principles on which natural ecological systems are built and on the transfer of such principles into ecosystem management in a way to minimize the costs of the measures and their harm to the global environment".

In China, under the leadership of Ma Shijun, the so-called agro-ecological engineering, defined as the application of ecological engineering to agriculture, was developed almost simultaneously with the development of environmental engineering in Europe and America (Yan et al., 1993; Mitsch & Jørgensen, 2003).

2.2. Comparison with other technologies

Unlike traditional ecology and its sub-disciplines (e.g. ecotoxicology, landscape ecology), which are primarily descriptive and limited to monitoring, environmental impact assessment, and natural resource management, ecological engineering provides applicable solutions to environmental problems. The feedback gained from the successes and failures of applying its methods in the real world can be used to support or refute many ecological theories (Mitsch, 1996).

Unlike bioengineering or biotechnology, it does not involve manipulation at the genetic level, but at a higher level of the biological hierarchy (species, populations, biocenoses, habitats, ecosystems).

Although it shares the same goal in terms of solving environmental pollution problems, ecological engineering is not the same as environmental engineering. Environmental engineering is a sub-discipline of civil engineering concerned with the design and construction of processes and facilities to reduce the impact of human activities on the environment. It is primarily concerned with the quality and protection of the non-living components of the environment (water, soil, air). Environmental engineering is mainly based on chemical, mechanical and material technologies, various technical devices and man-made objects (separators, filters, scrubbers) for the removal, transformation or retention of pollutants (Jorgensen, 2008). However, the application of these traditional techniques often results in inflexible systems that, unlike biocenoses in natural ecosystems, have difficulty adapting to changing conditions. Biotic material may be present in environmental engineering, often in the form of organisms used as a means to achieve a particular effect (Allen et al., 2003). These man-made systems require more maintenance and often rely on external, non-renewable energy sources, in contrast to ecological engineering, which relies on sustainable energy sources within the ecosystems themselves.

Although ecological engineering, which uses free natural solutions, is a more environmentally friendly and therefore better and more cost-effective strategy in the long term, in some cases it cannot fully replace conventional environmental engineering methods and solutions. Therefore, a synergy between the two disciplines is often required to better solve environmental problems.

2.3. Basic concepts and classification of ecological engineering

Mitsch and Jørgensen (2003) and Mitsch (2012) summarized five basic concepts that distinguish ecological engineering from conventional approaches to environmental problems: (1) it is based on the self-design capacity of ecosystems; (2) it can be the field (or acid) test for ecological theories; (3) it relies on systems approaches; (4) it conserves non-renewable energy sources; and (5) it supports ecosystems and biological conservation.

The same authors proposed the following classification of ecological engineering according to function: (1) ecosystems are used to reduce or solve a pollution problem, (2) ecosystems are imitated or copied to reduce a resource problem, (3) ecosystems are restored after significant disturbance, (4) existing ecosystems are modified in an ecologically sound manner, and (5) ecosystems are used for the benefit of humanity without destroying the ecological balance.

Applications in ecological engineering can be classified into three spatial levels: mesocosmos, ecosystems and regional systems (Mitsch, 1993, 1996). Mesocosmos means the replication or improvement of ecological processes in closed systems of smaller scale (~0.1 to hundreds of m^2) that simulate the conditions of the real environment, while allowing the manipulation of environmental factors. Examples are smaller plant systems for leachate treatment. The ecosystem level (1-10 km^2) has the most examples of water purification (e.g., constructed wetlands for wastewater treatment). Regional systems (>10 km^2) require the creation or restoration of a large number of ecosystems that are all interconnected, which is a complex and challenging task. Examples include restoration of large river basins, wetlands, forests, and coastal areas.

The methods of ecological engineering are not new. Ever since people realized that their health is related to the quality of their environment, they have been applying principles to improve both. In Asia and large parts of China, for example, polyculture and recycling have a long tradition (Yan et al., 1993). Methods in practice are diverse and their selection depends on the characteristics of the ecosystem and the nature of the problem to be solved. Applications range from the creation of new ecosystems to the ecologically sound use of existing ecosystems with the aim of eliminating pollutants, invasive species, returning to a natural state, landscape planning, water cycle management, etc.

3. ENVIRONMENTAL EFFECTS OF LANDFILLS

Landfills possess an extensive lifespan, often requiring maintenance for many decades. Throughout a landfill's lifecycle, from its inception to its operation and eventual aftercare, it can give rise to various environmental challenges. Such issues include air pollution (emission of greenhouse gasses, odor, and dust), groundwater contamination, deterioration of landfill cover, impairment of public welfare, loss of property value, decline in biodiversity, and so on (Lamb et al., 2014).

As mentioned above, landfills are a significant source of greenhouse gases (CH_4, CO_2, NO_2) generated by the microbiological decomposition of the organic components of the waste. In addition to CH_4 and CO_2, which account for more than 90% of the total composition of landfill gases, they emit a number of other gases (H_2S, H_2, NH_4, NO_x, volatile organic compounds) that are responsible for spreading unpleasant odours and affecting air quality. The amount and composition of gases depends on the type of waste deposited, moisture content, temperature, plant cover and age of the landfill (Lamb et al., 2014; Iravanian & Ravari, 2020). Due to the emission of flammable gases, there is also the possibility of explosions and fires at landfills, which can additionally release larger amounts of toxins into the atmosphere, soil and water (Vaverková, 2019).

Leachate generated at landfills poses a significant contamination risk to groundwater, surface water, and soil. It is a complex mixture of various substances that can be hazardous and toxic to human health and other living organisms. In general, the composition of leachate from landfills can be divided into four different groups: dissolved organic substances, inorganic macro-components (calcium, magnesium, sodium, potassium, ammonium, iron, chloride, sulfate and hydrogen carbonate), heavy metals and xenobiotic organic compounds (benzene, toluene, ethylbenzene, xylene, tetrachloroethylene and trichloroethylene) (Iravanian & Ravari, 2020). The composition of leachate depends on several factors, including the age of the landfill, seasonal weather variations, total precipitation, the type of waste, and its composition. For example, the concentration of organic compounds in leachate decreases with the age of the landfill, while the NH_3 concentration increases (Vaverkova, 2019).

Landfills not only consume valuable land but also disrupt and destroy natural ecosystems impacting the biodiversity of adjacent areas. Siddiqua et al. (2022) note that the creation of a landfill can result in a decline of 30 to 300 animal species per hectare, and this doesn't even take into account the myriad soil microbes affected. For example, gasses produced by landfills can penetrate the surrounding soil, displacing oxygen in the soil and subsequently harming both flora and fauna; this is underscored by the findings of Iravanian & Ravari (2020), which show the detrimental effects on plant roots and soil organisms. In addition, leachate, a toxic liquid that leaks from landfills, can cause similar damage. This environmental stress often causes shifts in local communities: some native bird and mammal populations are displaced by species adapted to the waste, such as crows or rats, and native plants are replaced by those with a higher tolerance to soil contamination. In addition, most landfills around the world cause serious sanitary and health problems, especially for local residents, due to their unpleasant odour, air pollution, and the settlement of vermin, pests, and infectious disease agents.

4. ECOLOGICAL EGINEERING TECHNIQUES FOR LANDFILL REMEDIATION

4.1. Phytocapping (evapotranspiration covers)

The three main environmental challenges associated with sustainable landfill management are: minimizing the impact of leachate on groundwater, controlling greenhouse gas emissions, and managing unpleasant odours (Lamb et al., 2014). Therefore, a mandatory part of any landfill remediation is to provide the landfill with a top cover after closure to prevent direct exposure to waste, reduce erosion and stabilize the landfill, minimize precipitation infiltration into the waste and reduce leachate formation, control gas emissions and odours, reduce the possibility of fires, prevent the occurrence of disease vectors, and meet aesthetic and other end-use purposes.

Conventional landfill cover systems are designed to minimize water infiltration into the landfill body by using low permeability layers (compacted clay and artificial materials such as geomembranes and geosynthetic sealing layers). The upper part of the cover is vegetated with grasses and other low and medium height plant species. This cover system can be used alone or in combination with other technologies (e.g., leachate or landfill gas collection systems). Their design depends on the characteristics of the landfill and the intended function of the final cover. Conventional landfill covers have several disadvantages. They are quite financially demanding and often impractical for small and medium-sized landfills. Recent studies based on long-term monitoring in various climatic regions of the U.S. have shown that clay covers are not durable in the long term because they deteriorate (dry out and crack) over time, especially when exposed to extreme weather conditions, and are therefore unable to completely prevent water infiltration into the waste (Albright et al., 2004; Venkatraman & Ashwath, 2011). Furthermore, clay covers do not allow optimal interaction of methane with oxygen, which is required for its efficient oxidation (Abichou et al., 2004; Venkatraman & Ashwath, 2011), and do not provide an opportunity to remove pollutants from the waste.

Evapotranspiration covers (hereafter ETCs) or phytocapping provide a nature-based alternative to conventional covers. In the literature, they have also been referred as water balance covers, alternative earthen final covers, vegetative landfill covers, soil-plant covers, and store-and-release covers (United States Environmental Protection Agency, 2011; Khapre et al., 2017). Phytocapping involves applying soil material to the landfill surface and planting it with dense plant covers (trees, shrubs, and herbaceous plant species). Soil serves to store rainwater, while vegetation acts as a "bio- pump" that, through the natural processes of evaporation and transpiration, removes stored water and retains precipitation, reducing rainwater infiltration into the landfill body and the formation of leachate (Yuen et al., 2010; Venkatraman & Ashwath, 2011, 2011; Lamb et al., 2014). In addition, the dense vegetation stabilizes the surface of the landfill cover and prevents erosion.

There are two general types of ETC systems: monolithic and capillary (United States Environmental Protection Agency, 2011). Monolithic cover systems, as shown in **Figure 1,** use a single fine-grained soil layer rich in organic matter necessary for vegetation development.

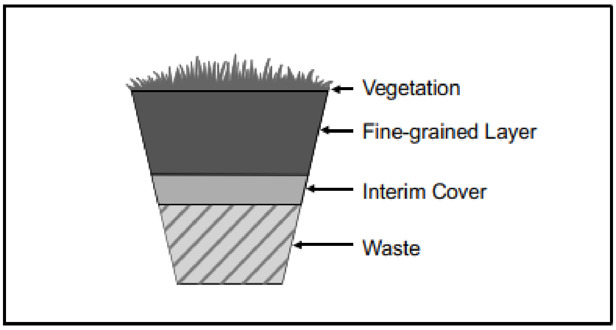

Figure 1. Conceptual design of monolithic ETC (United States Environmental Protection Agency, 2011)

Capillary cover systems are modified monolithic covers with an additional capillary layer beneath fine-grained soil layer, containing coarser granular material (usually sand or gravel). The discontinuity in pore size between the two layers creates a capillary break that causes water to be absorbed into the unsaturated pore space of the finer-grained soil, which can then absorb more water than a monolithic cover system of the same thickness. That can additionally encourage the establishment and development of a surface vegetation. The coarse layer can can act as a barrier against biointrusion, protecting against animal disturbances and root penetration and/or can also function as gas collection layer (Dwyer, 2005; United States Environmental Protection Agency, 2011). Conceptual design of a capillary ETC is shown in **Figure 2**.

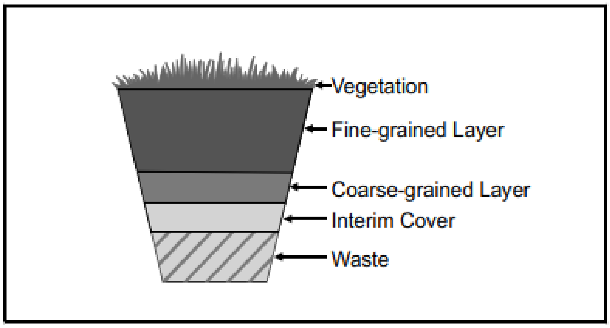

Figure 2. Conceptual design of capillary ETC (United States Environmental Protection Agency, 2011)

Depending on the type of landfill, it is also possible to add control layers (biobarrier, drainage layers and gas collection layers).

Soil texture is of key importance as it determines water retention capacity. Typical materials used for ETCs are clayey loam, silty clay, silty sand, clay, and sandy loam. Fine-grained materials such as silts and clayey silts, which have higher storage capacity compared to sandy soils, are often chosen for monolithic covers and the top layer of capillary cover systems. Sandy soils, on the other hand, are usually used for the bottom cover layer of capillary cover systems.

The thickness of the soil cover is also important. It depends on the water storage requirements of the site, which is determined by the local climate and takes into account both rainy and dry seasons. For monolithic layers, the thickness usually varies between 0.5 and 2 m. For combined layers, the thickness of the finer-grained upper layer is between 0.5 and 1.5 m, while the coarser-grained lower layer is between 0.2 and 0.6 m thick (United States Environmental Protection Agency, 2011).

Enrichment of soil cover layers with additives such as compost, biochar, biosolids, sawdust, and beneficial microorganisms is recommended, especially for sites with nutrient-poor soils (e.g., construction waste landfills) (Lamb et al., 2014). Soil nutrients, including organic matter, nitrogen, phosphorus, potassium and micronutrients, along with pH, play a critical role in promoting plant growth and ecological succession.

The selection of plant species requires a knowledge of the conditions prevailing at the site, such as weather and soil properties, as well as the intended remediation goals. Planting native species is recommended because they are more adaptable to local conditions, such as extreme weather or disease, and have less adverse impact on existing local ecosystems compared to non-native species (United States Environmental Protection Agency, 2011). Plant species adapted to poorly structured, shallow soils, clay, and other environmental stresses (e.g., *Salix* and *Populus* genera), and fast-growing grass species with deep roots (e.g., *Poaceae* family), that can form dense cover in a short period of time, are particularly desirable for reducing erosion and retaining moisture (Lamb et al., 2014). Although cover layers are relatively thin, studies in recent decades have shown that plant roots are unable to break up and penetrate clay or various synthetic materials, which would destabilize the landfill body (Lamb et al., 2014).

The limiting factors for the application of this technique in the remediation of uncontrolled landfills are the lack of high-quality substrate for the growth of plant species and their resistance to high concentrations of landfill gases and pollutants. Therefore, successful revegetation of such landfills also depends on the selection of plant species. So-called pioneer plant species are very suitable for open landfills, as they are tolerant to nutrient deficiency, drought, various pollutants and landfill gases (Wong, 2018).

The advantages of ETCs compared to conventional cover systems are faster stabilisation of waste, better erosion control (since they do not contain geomembrane layers that can cause surface slippage), and reduction of pollutants from waste (phytoremediation mechanisms), which ultimately allows faster rehabilitation of such areas for alternative uses (parks, recreational areas). In addition, studies have demonstrated that they are able to reduce methane emissions by 75-85% compared to areas without vegetation (Venkatraman & Ashwath, 2011), due to increased oxidation of methane in the rhizosphere, while plant species with large biomass effectively support the process of carbon sequestration. This technique is more financially viable in the final stages of remediation, as it can reduce the cost of installing expensive landfill gas collection and treatment systems and the cost of ongoing landfill maintenance (estimates suggest savings of up to 50% for locally available materials).

ETCs can also be used to reintroduce endemic and threatened plant species to a particular area, create wildlife corridors or habitats for local flora and fauna, and thus increase biodiversity. Another option is to establish "plantations" of plant species that have high biomass and from which various plant materials (e.g., woody biomass) can be obtained. When landfills are not contaminated with toxic substances, they can be seeded and planted with grass and other cultivated species for harvesting and use as animal feed (Simmons, 1999; Lamb et al., 2014). When landfills are contaminated, ETCs can be used for phytoremediation of soil and landfill leachate.

The main disadvantage of this technology is that such a system may not be effective in areas where evapotranspiration rates are lower than precipitation (e.g., cold and humid areas) (Lamb et al., 2014). Other disadvantages include the possible occurrence of phytotoxicity, pests, or destruction of plants due to adverse weather conditions, leading to a decrease in their effectiveness (Nagendran et al., 2006).

ETCs are very commonly used in the U.S. to remediate various sites with deposited waste, especially in areas where potential evapotranspiration is greater than precipitation. The use of this technique is also explicitly allowed and applied in some European countries with suitable climates. In Germany, for example, the use of this technique is prescribed by the Ordinance on landfills (Verordnung über Deponien und Langzeitlager, 2009), which emphasizes that the selection of appropriate vegetation must maximize evapotranspiration and protect the final recultivation layer from wind and water erosion.

4.2. Phytoremediation

Phytoremediation (Greek: φυτό - plant, Latin: remedio - to treat, remediate) is a technology that uses plants, their enzymes, and the microorganisms present in the root zone to isolate, transport, detoxify, and mineralize pollutants in the soil, thereby reducing their concentration, mobility, or toxic effect (Greipsson, 2011; Ali et al., 2013; Milčić et al, 2019).

Phytoremediation mechanisms include: (a) phytostabilization (reduction of mobility and bioavailability of pollutants by accumulation in the roots or immobilization in the rhizosphere) (b) phytodegradation (organic substances are broken down into less harmful substances) (c) phytovolatization (conversion of pollutants to a volatile form and release to the atmosphere), (d) phytoextraction (plants accumulate pollutants in the upper vegetative parts of the plant), (e) rhizodegradation (degradation by the combined action of secreted plant enzymes and microorganisms in the root zone), and (f) rhizofiltration (removal of pollutants from the water medium). Through these processes, plants can remove various pollutants from soils and wastewater (heavy metals and radionuclides as well as organic pollutants such as polynuclear aromatic hydrocarbons, polychlorinated biphenyls, and pesticides) (Ali et al., 2013).

Although phytoremediation, as an *in situ* technique, can save the cost of installing expensive systems for leachate collection and treatment and contaminated soil removal and disposal, its main disadvantage is that it takes more time compared to conventional methods. Therefore, this technique is not suitable for sites that pose an acute threat to human health or the environment, such as some toxic waste sites.

For landfill phytoremediation, two primary strategies can be employed: (a) phytoextraction/decomposition and (b) phytostabilization of pollutants (Nagendran et al., 2006; Kim & Owens, 2010).

4.2.1. Phytoextraction

In phytoextraction, plants extract pollutants from the soil through their roots and accumulate them in their above-ground parts, which are later harvested and removed from the landfill. This is particularly suitable for the remediation of larger areas contaminated with low or moderate concentrations of pollutants at shallower depths, as plant growth is limited at high pollutant concentrations and roots only develop to a certain depth (Kumar et al., 1995; Prasad & De Oliveira Freitas, 2003). The success of this technique depends on the ability of selected plant species to rapidly build up a large biomass and accumulate large amounts of pollutants. The efficiency of phytoextraction is generally measured by the bioconcentration factor (BCF), which is the ratio of pollutant concentration in plant tissue to soil. Plant species whose BCF is > 1 are considered good candidates for phytoextraction (Rascio & Navari-Izzo, 2011; Ali et al, 2013; Baker et al., 2020). Plant species with extremely high BCFs are called hyperaccumulators. Most hyperaccumulators are found in the plant families *Brassicaceae*, *Fabaceae*, *Lamiaceae*, *Poaceae*, and *Euphorbiaceae* (Kisić, 2012). In addition, the selection of plant species for phytoextraction depends on their resistance to certain pollutants and ability to rapidly translocate pollutants from the roots to the above-ground parts, adaptation to difficult soil conditions, ability to form a dense root system, resistance to pests and various diseases, and the possibility of easy maintenance (Prasad & De Oliveira Freitas, 2003; Kisić, 2012).

The disadvantage of this method is the long remediation time, which usually ranges from 1 to 20 years (Kumar et al., 1995; Prasad & De Oliveira Freitas, 2003). The time required for remediation depends on the type and extent of pollution, the length of the growing season, and the efficiency of pollutant removal by plants (Kumar et al., 1995; Prasad & De Oliveira Freitas, 2003). Hyperaccumulators are usually slow-growing plants with shallow root systems and relatively low aboveground mass (Prasad & De Oliveira Freitas, 2003) that must be removed from the site and then properly disposed of (composted or incinerated). In general, hyperaccumulators can effectively remove only one or a few pollutant types, but not the mixture of different pollutant types expected in landfills.

4.2.2. Phytostabilization

In phytostabilization, plants immobilize pollutants in the soil by absorbing and accumulating them in the root zone, thus preventing the spread of pollutants by wind and/or water erosion or by leaching to deeper layers. The basic requirement for the selection of plant species is the presence of a highly branched root system and the rapid formation of below- and above-ground plant biomass, as well as their tolerance to high pollutant concentrations in the soil. In general, species suitable for phytoextraction are also used for phytostabilization. For example, various willow species (*Salix spp.*) are used as canopy species because they rapidly develop abundant aboveground biomass, while alfalfa (*Medicago sativa* L.) is suitable for phytostabilization of polluted soils with an alkaline reaction (Kisić, 2012).

This technique is most commonly used to stabilize open pits, mine tailings, quarries, and landfill remediation, especially for loose waste, to reduce dust migration and control the stability of the surface layer. Woody and herbaceous species serve as physical barriers (phytobarriers) against the spread of particles (Sánchez-López et al., 2015, Stančić et al., 2022).

A widely used technique for stabilizing steep landfill covers is to seed a mixture of grasses and legumes. This can be used effectively as pioneer vegetation, for example, in the ecological remediation of hazardous industrial waste landfills. Greening enables the rapid and efficient creation of extremely strong covers, stabilization of the surface layer and enrichment of the soil with organic matter (Maiti & Maiti, 2015). The best results were obtained on soils contaminated with organic pollutants (Kisić, 2012). It can also serve to create an ecosystem with native flora and fauna, increasing the ecological value of the site.

The main disadvantage of this technology is that pollutants remain on site as they bind to soil particles and plant roots, and there is a possibility of increased decomposition and dissolution of pollutants and their subsequent leaching to deeper layers. In addition, vegetation can provide an exposure pathway for contaminants through which they enter the food chain.

4.3. Constructed wetlands for leachate treatment

Constructed wetlands (hereafter CWs) are designed and constructed according to the principles of natural wetland ecosystems and consist of an aqueous medium, substrate, plants, and microorganisms (Stančić et al., 2016). They belong to biological methods and use phytoremediation to treat polluted water. Wastewater treatment is achieved through a combination of physical, biological and chemical processes, which include the deposition and filtration of suspended solids, the degradation of organic matter by microorganisms, the assimilation of nutrients by plants and microorganisms, and various chemical reactions **(Figure 3)**.

Depending on how wastewater flows through them, they can be constructed as surface or subsurface wetlands. Subsurface wetlands are divided into vertical or horizontal flow wetlands, depending on the direction of water flow (Vymazal, 2010; Malus & Vouk, 2012). Hybrid constructed wetlands that combine different types of wetland systems (two or more horizontal and/or vertical CWs connected in series), are also often used in order to ensure higher treatment efficiency. CWs consist of one or more pools of various sizes, usually covered on the surface with aquatic and marsh plants. They are primarily used to treat wastewater from households and industry but can also be used to treat leachate from landfills.

Essential components of CWs are plant species that naturally grow in and near aquatic ecosystems. Their role is manifold: with their branched roots, they create a large area for the development of microorganisms, which play an important role in wastewater treatment; they conduct oxygen to the root zone, which enables microbial decomposition of organic matter; they bind most of the nutrients and pollutants from wastewater; they stabilise the surface of the constructed wetland with their roots; they act as thermal insulators during the cold period; they contribute to the aesthetic value of the system (Malus & Vouk, 2012), and so on. The selection of suitable plant species for CWs depends mainly on climate, chemical composition of wastewater, topography, and hydrology. Literature indicates that the most commonly used plant species in Europe are common read (*Phragmites australis* L.) and, to a lesser extent, broadleaf cattail (*Typha latifolia* L.), yellow iris (*Iris pseudacorus* L.), reed sedge (*Phalaris arundinacea* L.), lake sedge (*Scirpus lacustris* L.), as well as other aquatic and marsh plant species (Stančić et al., 2016).

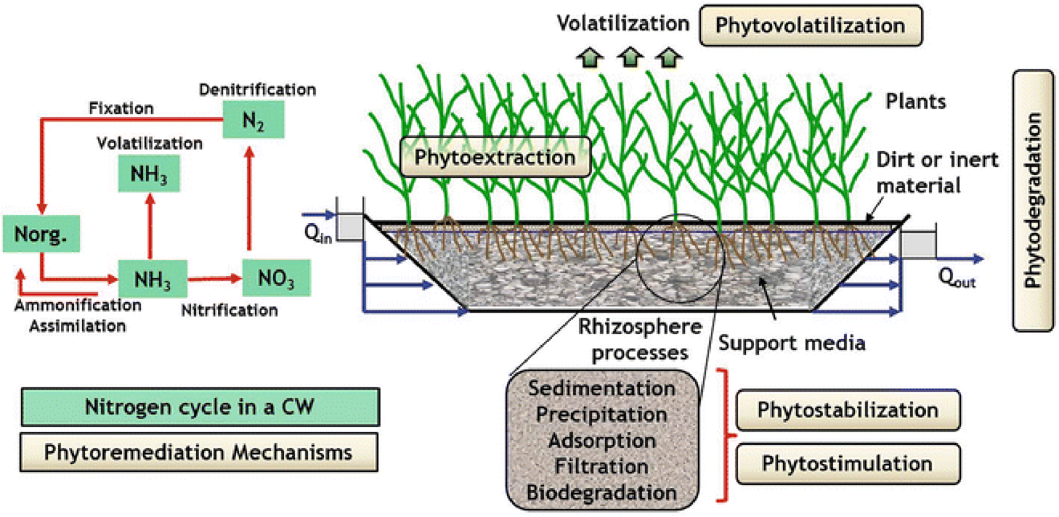

Figure 3. Phytoremediation processes and nitrogen fluxes in a constructed wetland (Salamanca et al. 2015)

All types of CWs are very effective in removing organic matter and suspended solids. Vertical flow CWs have higher oxygen transfer capacity than horizontal flow CWs, resulting in better removal of ammonia while horizontal flow CWs provide suitable conditions for denitrification (Gajewska et al., 2018; Bakhshoodeh et al., 2020). Some studies show that hybrid CWs generally have higher treatment efficiencies than nonhybrid systems, especially in removing total nitrogen and pathogens, but they generally require more space and are more expensive to construct (Vymazal, 2010; Bakhshoodeh et al., 2020). Removal of heavy metals has also been reported at 15-95%, with *Phragmites australis* plants proving to be the most successful species in removing heavy metals (Bakhshoodeh et al., 2020).

As natural systems, CWs require no chemicals, no energy, and no high-tech infrastructure; they are insensitive to runoff fluctuations; they function under a wide range of seasonal and climatic conditions with minimal maintenance; and they can operate for 20-30 years. Because they are often designed as dual- or multipurpose ecosystems, they can also provide other ecosystem services such as flood control, carbon sequestration, or wildlife habitat (Zhao et al., 2020).

On-site treatment with CWs is one of the most cost-effective methods of landfill leachate treatment and has been successfully applied in the United States and in some European countries (Norway, United Kingdom, Slovenia, and Sweden; Madera-Parra & Ríos, 2017). The main advantage of this technique is that it reduces the cost of landfill remediation because it does not require the construction of expensive facilities to collect and treat leachate or transport it to the treatment plant. The disadvantages of this technique are that a longer period of time is required to reach maximum efficiency (several seasons), and that the purification of wastewater takes longer than with conventional treatment plants.

4.4. Natural attenuation

Some authors (Bagchi, 1983; Christensen et al., 2000; Kisić, 2012) propose natural attenuation as one of the techniques for landfill remediation. Data collected at various municipal solid waste landfills around the world (particularly in Denmark) suggest that natural attenuation processes can be used to complement other management approaches (Christensen et al., 2000). Natural attenuation processes include a variety of *in situ* physical, chemical, or biological processes (biodegradation, destruction, decay, transformation, dispersion, dilution, sorption, volatilization, chemical or biological stabilization of contaminants) that, under favourable conditions (in the absence of human intervention), reduce the toxicity, concentration, mass, volume, or mobility of contaminants in soil or groundwater (Kisić, 2012). This technique can be used to treat leachate, but the best results have been obtained in the remediation of soils contaminated with volatile and semi-volatile pollutants (Kisić, 2012).

The main disadvantage of this technique is that it is a slow process that takes a long time (several years to decades). Furthermore, it is not recommended for hazardous waste sites because the toxicity and/or mobility of contaminants may be too high. This technique also necessitates more demanding site characterization and long-term, comprehensive monitoring (Christensen et al., 2000).

5. ECOLOGICAL ENGINEERING PRACTICES IN CROATIA

In Croatia, as in most other countries, conventional methods are used in the remediation of landfills, which include sealing layers, the construction of expensive systems for the drainage and treatment of leachate and rainwater, and systems for degassing. The foundation layer consists of impermeable materials such as clay, plastic film, asphalt, or bitumen, followed by a geomembrane and geotextile, and a drainage system. On top of landfill, a top sealing layer is applied, consisting of several natural and artificial layers (gas drainage layer, a layer of water-permeable geocomposite or an 80-cm-thick impermeable clay layer, geodren and an 80-cm-thick recultivation top layer of humus with plant cover) (Fond za zaštitu okoliša i energetsku učinkovitost, 2023).

The recultivation layer (humus with plant cover) is prescribed in the Ordinance on landfills (Official Gazette 4/23) as one of the requirements for the surface sealing of landfills for hazardous and non-hazardous waste. Other than a thickness greater than 1 m, there are no more detailed design requirements, such as planting native plant species that reflect the natural features of the landfill site and provide the evapotranspiration function, profile of the landfill slope, or other requirements.

Nevertheless, revegetation of the final layer is an integral part of any landfill remediation project and is usually done for aesthetic reasons with the goal of best integrating the remediated landfill into the existing landscape. In practise, grasses are often used to create a dense cover to protect against erosion and clovers to enrich the soil with nitrogen. It is recommended that native plant species be seeded and planted to maintain biodiversity. However, existing remediation projects do not pay sufficient attention to the evapotranspiration and phytoremediation potential of the final plant cover.

Although some studies have been conducted in Croatia in recent years on the phytoremediation potential of certain native plants and, in particular, on the phytoremediation of heavy metals (Stančić et al., 2015, 2022), there are few examples of actual application to landfills. One of these examples is the remediation of a phosphogypsum landfill near Kutina with CaF_2 and clay (as cover material), where the best results were obtained with the false indigo-bush plant (*Amorpha fruticosa* L.) and clover-grass mixtures (Kisić, 2012).

In Croatia, constructed wetlands are still an underestimated solution for wastewater treatment. While there is a growing trend to build wastewater treatment plants, especially for sanitary wastewater in areas such as car camps and smaller municipalities, there are few cases where they have been used for leachate treatment, with the Goričica landfill and a pilot project at the Jakuševec landfill being notable examples (Nadilo, 2013; Hudec plan d.o.o., 2021).

Currently, there is little use of ecological engineering techniques for landfill rehabilitation in Croatian waste management, and the potential for reuse of rehabilitated landfills for social purposes remains largely unexplored.

6. CONCLUSION

Ecological engineering, while an emerging branch of engineering, is evolving into a transformative approach. It harnesses nature-based and practical strategies on a large scale to solve myriad environmental problems, such as restoration of degraded ecosystems, wastewater treatment, pollution cleanup, landfill remediation, etc. Ecological engineering techniques such as phytocapping and phytoremediation hold immense potential for landfill remediation, arguably one of the most pressing environmental problems of our time. They have become an increasing focus of scientific research in recent years and are already being used in some countries to remediate controlled and uncontrolled (wild) landfills, either alone or in combination with conventional technologies. Because they rely on existing and available natural processes and energy, they are considered more cost-effective and environmentally sustainable than conventional methods.

Although ecological engineering is already showing promising results in solving landfill problems, it is crucial to understand that the field is still emerging. There is an urgent need for more extensive research, particularly in the area of phytoremediation. This research can serve as a catalyst for regulatory agencies to incorporate these remediation techniques into current laws and pave the way for broader application in the future.

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