Landfills' Environmental Impacts: Perspectives on Biomonitoring

Magdalena Daria Vaverková[1*], Evan K. Paleologos[2], Venkata Siva Naga Sai Goli[3], Eugeniusz Koda[4], Arif Mohammad[5], Anna Podlasek[6], Jan Winkler[7], Aleksandra Jakimiuk[8], Martin Černý[9], Devendra Narain Singh[10]

[1]Professor, Institute of Civil Engineering, Warsaw University Life Sciences – SGGW, Warsaw, Poland, Faculty of AgriSciences, Mendel University in Brno, Brno, Czech Republic; https://orcid.org/0000-0002-2384-6207

[2]Professor, College of Engineering, Abu Dhabi University, Abu Dhabi, UAE, https://orcid.org/0000-0002-3582-2288

[3]Research Scholar, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India, https://orcid.org/0000-0003-1916-725X

[4]Professor, Institute of Civil Engineering, Warsaw University of Life Sciences – SGGW, Warsaw, Poland, https://orcid.org/0000-0002-3895-960X

[5]Postdoc, Department of Civil Engineering, School of Engineering, Cardiff University, Cardiff, UK, https://orcid.org/0000-0002-1815-5073

[6] Assistant Professor, Institute of Civil Engineering, Warsaw University Life Sciences – SGGW, Warsaw, Poland, https://orcid.org/0000-0003-0326-5672

[7]Assistant Professor, Department of Plant Biology, Faculty of AgriSciences, Mendel University in Brno, Brno, Czech Republic, https://orcid.org/0000-0002-5700-2176

[8]PhD Student, Institute of Civil Engineering, Warsaw University Life Sciences – SGGW, Warsaw, Poland, https://orcid.org/0000-0002-4444-2260

[9]PhD Student, Department of Plant Biology, Faculty of AgriSciences, Mendel University in Brno, Brno, Czech Republic, https://orcid.org/0000-0002-0651-4219

[10]D.L. Shah Chair Professor for Innovation, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India, https://orcid.org/0000-0003-3832-1507

*Corresponding author: Magdalena Daria Vaverková, magdalena_vaverkova@sggw.edu.pl; magdalena.vaverkova@mendelu.cz

Abstract

Environmental regulations on landfills contain detailed instructions for the monitoring of pollution from leachate on water, air, and soil. However, references to the impact of landfills on the landscape and the need to monitor the surrounding vegetation are described only in general terms. Studies have indicated that near-surface pollution events, which are not necessarily captured by existing regulatory monitoring schemes, have affected the vegetation in the vicinity of landfills. Indications for the effects of pollution emanating from landfills include the retreat of sensitive and native plant species, the abundance of halophytes or nitrophilous plants, and the prevalence of other invasive plant species, which can spread to adjacent ecosystems. To the best of the authors' knowledge, a comprehensive synthesis of landfill plant-based biomonitoring results has not yet been reported. The advantage of biomonitoring lies in its ability to assess the quality of the environment as perceived by living organisms. This would facilitate the determination of the response of plants to departures from natural conditions, detection of trends occurring in ecosystems, and adoption of management practices to prevent or mitigate degradation of the environment. Thus, to detect such effects on the flora surrounding a landfill, this article recommends that biomonitoring is utilized in environmental regulations to complement existing monitoring techniques.

Keywords: Landfills; Biomonitoring; Municipal solid waste regulations; Vegetation impacts from pollution; Active biomonitoring; Passive biomonitoring

1. Introduction

Despite significant efforts to recycle and compost municipal solid waste (MSW) the amount of MSW generated continues to increase globally. Although MSW management practices have made significant progress over the last 60 years, the problem of MSW disposal, instead of being alleviated, has become more severe. As indicated by Paleologos et al. (2016) this increase in

MSW over the years cannot be simply attributed to the population increase, but it is more complex, the result of modern lifestyle factors. It is therefore apparent that although modern MSW management practices can partially mitigate the effect of modern habits of consumerism, to reverse the trends of increased MSW, a significant change in material utilization and waste generation needs to take place, as envisioned by the circular economy approach. Given that landfilling is still the prevalent way of disposing MSW in advanced countries, and the only way of waste disposal in less developed ones, and the fact that existing landfilled waste will continue to decompose for several decades, while engineered measures at the landfill will deteriorate, and also that, globally, the generated per capita MSW rate is projected by the World Bank to increase from 1.2 kg/person/day to 1.42 kg/person/day by 2025 (Hoornweg & Bhada-Tata, 2012), monitoring and taking measures to reduce the impact of landfills on the environment becomes of paramount importance (Koda, 2012).

Municipal solid waste landfill facilities' (MSWLF) technical specifications, liability requirements, protection of public health and the environment, monitoring, enforcement and penalties, remediation, and post-closure care and redevelopment of landfilled sites have been the focus of several laws, policies, regulations, and practices worldwide (Mohamed & Paleologos, 2017; Vaverková, 2018; Koda et al., 2021). Enhanced landfill mining (LFM), the utilization of generated residues, popularly known as landfill mined residues (LMRs), has emerged as a practice to recover useful materials, such as landfill-mined-soil-like-fractions (LFMSF), combustibles/synthetic polymers (plastics, textiles and rubber waste), and recyclables, such as glass, metals, construction and demolition (C&D) waste, and wood waste (Hernández Parrodi et al., 2018; Mohammad et al., 2021; Goli et al., 2022b).

Monitoring the ecological status of the area around a landfill has drawn little attention both in the US and European landfill regulations. Given that the siting of a landfill follows the selection of a site where an aquifer system is found at a depth, it cannot be argued that groundwater monitoring wells can provide information on pollution incidents close to the ground surface, which may affect the flora and fauna of the area surrounding the landfill. Additionally, ambient air monitoring at landfills concentrates on CH_4, CO_2, non-methane organic compounds (NMOC), volatile organic compounds (VOC), hydrogen sulfide, particulate matter (PM), and emissions from combustion products of LFG (flares, engines, etc.), such as NOx, and CO (EC, 1999, Annex III; US EPA, 1999, 2008). Although, there may exist toxicological and epidemiological studies on the effects of several of those gases on human health, relationships with the wellbeing, growth, and development of plants are at best tentative. Finally, despite measures, precipitation and lateral water inflows enter a landfill body hence, they contribute to pollutant migration through the unsaturated zone. **Figure 1** from MSWLF sites clearly shows the presence of vegetation at these locations and summarizes also the threats from landfills to the environment. It seems that biomonitoring - the practice of monitoring the impact of landfills on the health of organisms and ecosystems, as well as the structure and function of the surrounding landfill landscape - is an area where current landfill regulations need to be updated (Vaverková, 2019; Vaverková et al, 2019 a, b; Vaverková et al., 2020; Vaverková et al., 2022).

The development of bioindication methods dates to the beginning of the 20th century. In the 1960s, interest of the scientific community in issues related to the reactions of living organisms to pollutants increased (Pott & Turpin, 1996; Holt & Miller, 2011). The use of bio-indicators has emerged as a valuable tool for assessing the impact of landfills and other pollution sites on the environment. Bio-indicators are identified through differentiation of response methods, such as changes in color, shape, and size of the organism, initial reaction to pollution, and correlation of population size with type of pollutant (Mahmood et al., 2019; Korbut et al., 2021).

Although bioindicators are used to assess the quality of air, soil, and water in many scientific publications, only few studies have focused on their application in landfills. The current article addresses biomonitoring as a technique in the context of geoenvironmental pollution caused by landfills by considering the principles, potential, and future perspectives of biomonitoring. Emphasis is placed on the plant species that are used in environmental surveys to evaluate anthropogenic pollution. Furthermore, this paper describes commonly used candidates for biomonitoring in the field of environmental pollution, with a special emphasis on the landfill environment. To the best of the authors' knowledge, no comprehensive review has been published to date that would describe the biomonitoring of landfill vegetation. The current article aims to close this research gap and to provide suggestions for amending monitoring regulatory requirements.

2. Bioindication and bioindicators

Bioindication, the determination of changes in the environment by means of biological indicators, which include plants (phytoindicators) or animals (zooindicators), or even whole biocoenoses, is one of the methods used to monitor industrial pollution and environmental contamination (Wolterbeek, 2002; Parmar et al., 2016; Al-Alam et al., 2019). Knowledge of the life requirements of fungi, plants, and animals, as well as their tolerance to different external factors, allows the study of the state of the environment (Begu, 2014; Parmar et al., 2016; Urbat et al., 2004; Yu et al., 2018). Thus, the responses of living organisms to positive or negative environmental changes can be used in environmental pollution assessments.

2.1. Information value of plants (phytoindicaton)

The earliest application of phytoindication as a diagnostic tool to assess the abiotic conditions in an environment involved identifying the presence or absence of plant species with known ecological and site-specific requirements (Zadorozhna, 2017; Kunakh & Fedyay, 2020). It has been demonstrated that the ecological amplitude (range of tolerance) of plant communities is as a rule greater than that by individual species. Thus, several studies (e.g., Zverev, 2014; Holyk & Goncharenko, 2017) have indicated that communities appear to be more sensitive indicators of environmental conditions than are individual species.

Phytoindication employs plants as bioindicators to track alterations in the environment, serving not only to diagnose habitat conditions (including climate, soil factors, and hydrological conditions) but also to determine the type and intensity of human activities affecting such plants, such as the presence of landfills (Zhukov and Potapenko, 2017; Glibovytska & Mykhailiuk 2020). Phytosociological analysis (analyzing plants) in a certain area is important when studying the environment on a large scale, such as whole landscapes or ecosystems (Gianguzzi and Bazan, 2020; Ighbareyeh et al., 2021).

Existing scientific work has primarily focused on the relationship between vegetation and environmental conditions that are not influenced by human activities. However, environmental conditions may gradually change due to human activities, resulting in the entry of a wide range of pollutants into the environment and leading to changes in living conditions ultimately affecting vegetation. Plants have several mechanisms for adapting to anthropogenic pollution (Winkler et al., 2022; Winkler et al., 2023). Vegetation responds to pollution first by retreating sensitive plant species, and then by new species, which are resistant to the presence of pollutants, penetrating the vegetation over time. Vegetation responds to the degree of toxicity by changing its species composition (Koda et al., 2022). The effects of anthropogenic pollution on vegetation is complex. The influence of diverse pollutants on plants and the synergistic and antagonistic relationships between different chemicals make the interpretation of the results problematic. The changes in the species composition of vegetation in the vicinity of a landfill is the first sign that indicates the presence and degree of toxicity of pollutants.

Landfill sites with leachate seepage are characterized by high salinity. Biomonitoring of plant communities in leachate seepage points represent a new approach to the assessment of the actual condition of a landfill (Koda et al., 2022). The presence of pollutants in leachate increases soil salinity, which translates to a higher abundance of halophytes (plants that naturally inhabit saline environments, such as salt marshes, salt flats, and steppes) in the vegetation (Ellenberg et al., 1991; Chytrý et al., 2018; Koda et al., 2022).

N compounds and other nutrients (P, K, Mg, etc.) are also released from MSW at high rates, as reported by Ellenberg et al. (1991) and Chytrý et al. (2018). Elevated N and other nutrient contents were reflected by the presence of a higher proportion of nitrophilous plant species. The abundance of readily available nutrients leads to a higher proportion of species employing ruderal life strategies. The rate of change in the environment due to the presence of pollutants here is indicated primarily by the abundance of diaspores of nitrophilous species in the vicinity of the pollution.

2.2. Screening of living organisms used as bioindicators

Biological indicators have been widely used to assess the degree of environmental pollution (Wolterbeek, 2002; Holt and Miller, 2011; Parmar et al., 2016; Adams et al., 2018; Azizi et al., 2018; Al-Alam et al., 2019). The criteria that can facilitate the suitability of living organisms as bioindicators are as follows: (i) relatively sedentary lifestyle (stationary) of selected organisms to meet the requirement of representativeness of the studied ecosystem (collecting specimens); (ii) wide geographical distribution for easy identification and collection of samples; (iii) potential to collect a representative sample of material; (iv) a certain tolerance of the selected organisms to pollutants (heavy metals (HM), organic compounds); (v) easy transport of organisms to the laboratory, and (vi) stability of the population of the selected organisms, which would allow repeated sampling during a long period of time (research of trends) (Farias et al., 2018; Fossi et al., 2018; Vitanović et al. 2018; Manickavasagam et al., 2019; Puig-Gironès and Real, 2022). The advantages and disadvantages of using plants as bioindicators are summarized in **S1**.

The use of vegetation in biomonitoring is limited mainly by the slowness in species composition changes compared to animals or microorganisms. The analysis can be further complicated because the variety of waste and pollutants affect vegetation by acting as polyfunctional factors with complex inter-relationships. Nevertheless, there are opportunities to use vegetation around an MSWLF to identify leachate infiltration sites (Koda et al., 2022), while Winkler et al. (2021) have pointed out that soil degradation can be inferred from the composition of vegetation growing in MSWLF. Changes in conditions on the surface and inside the landfill present a significant challenge for vegetation, which must respond accordingly during succession (Álvarez-López et al., 2020).

Winkler et al. (2021) have noted that certain nitrophilous plant species, such as *Atriplex sagittata*, *Chenopodium album*, *Setaria viridis*, *Apera spica-venti*, *Urtica dioica*, *Sambucus nigra*, *Phragmites australis*, *Rubus* sp., *Elytrigia repens*, *Lolium perenne*, *Bromus inermis*, and others, are permanent members of landfill vegetation. Moreover, there is a notable trend towards an increase in the total number of species in landfill environments, driven in part by the growing prevalence of invasive species and neophytes, such as *Calamagrostis epigejos*, *Acer negundo*, *Conium maculatum*, *Solidago canadensis*, and others. Additionally, there is a trend of hydrophilous plant species such as *Phalaris arundinacea*, *Alnus glutinosa*, *Salix alba*, *Typha latifolia*, *Populus canescens*, *Typha angustifolia*, and others, being withdrawn from these environments (Winkler et al., 2021).

Vaverková and Koda (2023) focused on the geological, environmental, and ecological impacts of landfills. Plants, especially invasive plants, have the potential to adapt to various and ever-changing environmental conditions, as noted also by Winkler et al. (2023). The composition of vegetation on landfill surfaces often reflects the soil degradation caused by a landfill (Mao et al., (2018)). Landfill sites tend to harbor a diverse range of plant species, which are not commonly found in native vegetation, and are dominated by synanthropic flora, plant species that thrive in association with human activities (Koda et al. (2013), Bryant et al. (2017), Vaverková et al. (2019a)). Thus, development of new plant communities, consisting mainly of neophytes and invasive plant species, is favored by the anthropogenic conditions of landfills (Wania et al. (2006), Vaverková et al. (2019a) and Winkler et al. (2021), Vaverková and Koda (2023)).

2.3. Bioindicators classification

Plant indicators are classified into several groups: passive, active (exposure), accumulation, and reactive. In order to identify and quantify species composition of vegetation sampling is done with the following approaches. Transect sampling involves laying out a linear transect across the study area and recording all plant species and their abundance along the transect. This allows for the identification of changes in species composition across a gradient. Phytocenological relevés (vegetation plot) is a standardized method used to record and describe the plant species and their abundance in a specific area. It involves selecting a representative sample area and systematically recording the species and their cover or abundance. The information collected through phytocenological relevé can be used to identify the plant community, estimate species diversity and richness, assess vegetation dynamics, and compare vegetation composition among different sites. Finally, collected field specimens can be analysed using various analytical techniques, depending on the specific biomarker of interest. These include spectroscopy, chromatography, elemental analysis, and enzyme-linked immunosorbent assay. After quantification, the data are analyzed using statistical methods to determine the significance of the biomarker and to identify correlations between biomarkers and environmental pollution.

Passive bioindication use the ability of selective damage to a plant's parts (reaction bioindicator), or an accumulation of some substances in selected plants (accumulation bioindicator). This type of monitoring uses both cultural crops (*Brassica juncea*, *Brassica nigra*, *Helianthus annuus*, *Sinapis alba*, *Triticum aestivum*) and wild plants growing naturally in the area of interest (*Achillea millefolium*, *Daucus carota*, *Phragmites australis*, *Urtica dioica*, *Taraxacum officinale*, *Tanacetum vulgare*) (Polechońska et al., 2018; Benítez et al., 2019; Turkyilmaz et al., 2019; Mishra & Farooq, 2022).

Active monitoring is widely used throughout Europe to assess the pollution associated with heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other organic pollutants (Kosior et al., 2010; Świsłowski et al., 2021). Active biomonitoring is a process by which bioindicators are collected from relatively pristine habitats, transplanted into different environments, and used to monitor pollution. This was done by deliberately exposing bioindicators to polluted areas under study (Ndlovu et al., 2019). This method has been used in both urban and industrial setups (Capozzi et al., 2016). The technique has several advantages, such as well-defined exposure time, known elemental concentrations, flexibility in the choice of location and number of sampling sites, and homogeneity of the trapping area. The main limitation of this method is that the accumulation efficiency of bioindicators for different contaminants is unknown (Aničić et al., 2009).

Still, some other methods combine passive and active bioindication procedures (Parmar et al., 2016; Cozea et al., 2018; Świsłowski et al., 2021). For example, plots can be established with detailed physical and chemical soil analyses on which the selected susceptible plants are grown.

Such a procedure is particularly appropriate for capturing the movement of monitored substances in the atmosphere – soil – water complex.

Accumulation bioindicators can store contaminants in their tissues, and the extent of such storage can be used to measure the concentration of contaminants in the environment (Abas, 2021). Finally, reactive bioindicators take advantage of the fact that the physiological reaction of a plant to the action of a given factor is demonstrated in functional disorders, such as restricted flowering, dieback of some organs, reduction of overall plant life, or limitation of the most important life processes (Fränzle, 2006; Khalid et al., 2019; Veskoukis et al., 2019; Martínez and Barrera, 2021). Thus, reactive biomarkers indicate environmental changes or exposure to certain pollutants. For example, changes in flower colour or morphology can indicate exposure to air pollution or heavy metals. Changes in flower scents can indicate exposure to organic pollutants. Some plants may also produce fewer or no flowers in response to environmental stressors such as drought or soil pollution. The types and descriptions of plant bioindicators are summarized in **S2**.

The indication capacity of plants relates to excitations from elements of the environment that are ecologically relevant. Thus, climatic conditions, such as, light intensity affects the species *Asclepias syriaca*, *Helianthus annuus*, and *Pteridophytes*; air temperature affects *Artemisia tridentata*, and *Poaceae*, and the degree of continentality influences *Echinacea purpurea*, and *Rudbeckia hirta*. Soil characteristics, such as moisture content would provide excitations to *Asclepias incarnata*; acidity to *Vaccinium spp.*, and *Vaccinium macrocarpon*; and nitrogen content affects *Fabaceae*; *Trifolium spp*., and *Urtica dioica*. Finally, fertility, pH, CEC, and nutrient retention capacity directly affect plants, which can be excellent indicators of these factors (Plit & Roo-Zielińska, 1990; Bazanov et al., 2009). For example, wildflowers occurring spontaneously at landfill sites such as lupines (*Lupinus spp*.), prefer well-drained, slightly acidic soils, whereas ferns (*pteridophytes*) prefer moist, acidic soils with high organic matter content. It follows that knowledge of the structure of plant coverage, spatial distribution, and the quantitative and qualitative composition of plant species allows not only the determination of the actual conditions at a site, but also the environmental components that are ecologically important to them.

The bioindication function of plants is also increasingly being used to check the changes caused by environmental contamination. The most used bioindicators are called indication species, that is species with a very specific range of tolerance to certain ecological factors (Mahapatra et al., 2019; Nasser et al., 2020; Bayouli et al., 2021; Garg et al., 2022). For example, *Epilobium angustifolium* is a plant species that is tolerant to heavy metals and nitrogen, which makes it a useful bioindicator of soil contamination. *Taraxacum officinale*, which is a common weed occurring at landfill sites, is sensitive to soil pH, making it a useful bioindicator of soil acidity. Another example is *Viola odorata*, which is sensitive to soil moisture and pH and can be used as a bioindicator for changes in water quality and soil acidity. These are examples of plant species that can be used as bioindicators of landfill conditions owing to their specific range of tolerance to certain ecological factors.

Vegetation can express the variability of environmental conditions from local through zonal differentiation, and can therefore be used as an indicator in a wide range of situations, depending on needs. In places with disturbances from anthropogenic activities, studies need to concentrate on the effects not only on vegetation but also on the soil profile and the overall environment to obtain a holistic picture of the environmental effects of pollution events (Herben et al., 2016; Winkler et al., 2022).

3. Biomonitoring assessment of landfills environmental impacts

The environmental impact of landfills has been studied using phytosociological analyses that allow proper characterization of vegetation communities and linkages of habitat-environmental factors and environmental valorization (Vaverková and Adamcová, 2012; Vaverková et al. 2012 a, b). In the scientific literature, the biomonitoring of landfills has focused primarily on lichens. Lichens are symbiotic organisms composed of green algae and fungi. Their metabolism depends on mineral uptake from the atmosphere; therefore, these organisms effectively trap trace elements from the surrounding environment. They grow very slowly, do not have stomata or cuticles regulating air exchange, and accumulate contaminants over the entire surface (Paoli et al., 2015). Epiphytic lichens have been used as indicators of environmental quality because they obtain water and essential nutrients mainly from the atmosphere and not from the soil (Sujetovienė et al., 2019). Lichens are effective accumulators of pollution over an entire surface. Species diversity, bioaccumulation, and physiological status are indicators of air quality and pollution. Epiphytic lichens are used to assess air pollution around landfills (Paoli et al., 2012; Nannoni et al., 2015; Paoli et al., 2015; Sujetovienė et al., 2019), but they do not reflect the entire state of the environment in the vicinity of landfills.

Loppi et al. (2021) assessed the utilization of lichens (*Flavoparmelia caperata*) as bioaccumulators of air-borne microplastic materials. Higher plants for biomonitoring environmental pollution, namely pollution from MSWLF, are used less than lichens. In this context, Vaverková et al. (2012a, b) performed floristic research and established a list of vascular plants occurring around a landfill in the Czech Republic (CR). The purpose of study performed by Vaverková et al. (2019a) was the long-term monitoring of the plant community (floristic survey) on a MSWLF, the identification of changes in species composition, and the evaluation of the significance of the identified plant species for the surrounding ecosystem and the assessment of the landfill's safety. It was concluded that MSWLF create a distinct and specific environment that affects the composition of plant species present. The results indicated that the vegetation on MSWLF is unstable and undergoes specific plant succession. As a result, continuous monitoring is necessary to track changes in species composition and to assess the impact of MSWL on the environment.

Biomonitoring also helps to assess the efficiency of stabilization processes, as reported by Zapata-Carbonell et al. (2019), where a study site was subjected to tests for the stabilization of topsoil *in situ* using white birch. The goal of the reclamation work was to create a landscape that would be ecologically well-balanced, economically valuable, and socially acceptable. In study by Xiaoli et al. (2011), it was concluded that emissions of CH_4 and CO_2 from soil covered by vegetation were lower than those from soil not covered by vegetation. This not only confirms that efficient and proper biological reclamation is important to mitigate the impact of landfills on the environment but also the significance of plants in biomonitoring. **S3** summarizes recent biomonitoring studies on the effects of landfills on the geoenvironment.

Vaverková et. al. (2022) recommended that landfills, in addition to the mandatory monitoring of groundwater, surface waters, and of leachate and landfill gas, should be subjected to regular biomonitoring of vegetation species' composition. A difficulty in such a task is that vegetation in the area near landfills is not stable in terms of species composition, and hence should be continually monitored. Landfills have a high potential to promote the expansion of invasive plant species, altering the species composition of vegetation in the surrounding ecosystems. These authors focused their study on the effects of management methods and environmental risks at two landfills in the CR. The vegetation in these two landfills was subjected to long-term monitoring. The vegetation analysis showed significant differences between the landfills, with the vegetation of a site showing a high prevalence in neophytes, invasive and expansive species.. This could be attributed to climatic and geomorphological differences between the two landfills, but also to differences in landfill management. These ecologically problematic species can spread from landfills to adjacent ecosystems, gradually eliminating native plant species and degrading adjacent farmlands. The research data suggested that landfills should be regularly subjected to vegetation biomonitoring. Landfill management methods should focus on the regulation of undesirable plant species, creating conditions that would be favorable to native plant species, and providing for the restoration of filled landfill cassettes as soon as possible.

Some of the species identified by Vaverková et. al. (2022) at the landfill sites, which are problematic to surrounding farmland include *Arrhenatherum elatius*, *Calamagrostis epigejos*, *Impatiens parviflora* and *Tanacetum vulgare*. In addition, at the landfill site that exhibited a large number of invasive plants, observed species included *Erigeron annuus*, *Reynoutria japonica*, *Robinia pseudacacia*, *Senecio inaequidens,* and *Oenothera fallax*. Attention should be paid to the species composition of landfill vegetation or to the disappearance of some species.

As pointed out by Vaverková et al. (2019b), reclamation of MSWLF is a necessary step to return the area back to the landscape. Grass species are often used for re-vegetation because of their low cost (e.g., *Lolium perenne*, *Festuca rubra*, *Festuca ovina*, *Festuca pratensis*, *Arrthenatherum elatius*, *Poa pratensis*, *Cynosurus eristatus*, *Bromus inermis*, and *Bromus erectus*). However, plants can be a significant source of air pollution, mainly because of allergenic pollen. Long-term monitoring was conducted at three landfill sites in the CR from 2008 to 2018, where 298 plant species producing allergens were identified. Most allergenic pollen-producing species were common to all studied sites, demonstrating that landfill vegetation can be a significant source of allergenic pollen. It was also shown that plants appearing in landfills could be used for biomonitoring of air quality and its impact on human health.

Koda et al. (2022) studied the relationship between vegetation composition and leachate seepage points to determine the potential for the utilization of certain species in the assessment of the applied mineral sealing on landfill surfaces. The results confirmed that the presence of leachates altered plant species composition, increasing the representation of species tolerant to salinization, and decreasing the share of glycophytes in the leachate seepage points. Based on the relationship between glycophytes and salinization-tolerant plant species, a work procedure and index of leachate vegetation were created, which provided rapid identification of leachate seepage points. The results of these studies can be applied to reclamation works on landfills.

Plant indicators can be helpful in determining local environmental conditions and the optimum use of land resources for forests, pastures, and agricultural crops. The occurrence, nature, and behavior of plants are indicators of the combined effects of all factors in a habitat. It should be emphasized that plants are inappropriate quantitative tools. Based on bioindicators, it is not possible to determine the absolute value of a particular variable of the environment; however, bioindicators can draw attention, for example, to the need to enhance the availability of nutrients or the occurrence of pollutants at first sight. The advantages and disadvantages of plant bioindicators are that they provide an expression of the complex interaction of multiple environmental factors, and usually after a prolonged period of exposure.

4. Biomonitoring of landfill gas emissions and of mined waste

The appropriateness of a landfill for mining, which requires waste stabilization (Mohammad et al., 2021), control of landfill gas releases, such as CH_4, and of the concentrations of ammonia in leachates (Lubberding et al., 2012) needs to be established first because LFM can lead to excessive release of several pollutants, such as NH_3, CS_2 (Wang et al., 2021), and greenhouse gases (such as CH_4 and CO_2) (Raga et al., 2015), as well as leachate leakage (Moretto et al., 2017; Weng et al., 2015).

Thus, monitoring of CH_4 and NH_3 in the air near landfills and NH_4^+ concentrations in the leachate, as promulgated by the US and EU landfill regulations, is recommended. Pieri et al. (2015) found an inverse relationship between the lichen's biodiversity index and NOx and ozone concentrations in the atmosphere. It was also observed that the lichen communities were restricted by the presence of calcareous dust. Furthermore, the investigation carried out by Frati et al. (2007) revealed that NH_3 presence in the atmosphere near pig stock farms caused a shift in the neutro-nitrophytic to nitrophytic species. The growth of *physconia grisea*, a nitrophytic lichen, is positively correlated with airborne NH_3, indicating that this species could be a useful bioindicator for assessing NH_3 emissions from landfills.

However, it appears that biomonitoring of landfill gas emissions and leachate releases during LFM or LFMSF, which have the potential to decompose and release gases during their utilization as landfill biocover and geotechnical fill materials, has not attracted much attention. The long-term monitoring of LFMSF performance with lichen plant species, when LFMSF is utilized as a geotechnical fill material has the potential to be a cost-effective monitoring system for decomposition-induced settlements. In addition, several studies have revealed that landfills are sinks for micro/nano plastics (MNPs) (Wowkonowicz et al., 2021; Goli et al., 2022a); hence, LFM activity can act as a pollution source for MNPs (Su et al., 2019: Goli & Singh, 2023). MNPs can be adsorbed by vascular plants, exhibiting phytotoxic effects such as oxidative stress, while disturbing plant growth and photosynthesis (Yin et al., 2021). Such plants can be investigated for their suitability as species for conducting bioindication studies while evaluating the effect of MNPs present in LMRs on their post-mining utilization. Orupõld et al. (2022) conducted germination tests using lettuce (*Lactuca sativa*), perennial ryegrass (*Lolium perenne*), and timothy (*Phleum pratense*) seeds to evaluate the phytotoxicity of leachates from LFMSF of size <10 mm. This study concluded that timothy seeds are more sensitive to LFMSF. Masi et al. (2014) conducted germination and root elongation tests using *Lepidum Sativum* and *V. faba*, respectively, to evaluate the phytotoxicity of LFMSF. It was observed that the LFMSF did not adversely influence the growth of *L. sativa*, whereas *V. faba* got negatively affected with an increase in the dosage. Hence, these seeds or associated plant species show potential as biomonitoring sites where LFMSF is applied.

5. Conclusions

Landfill monitoring constitutes an integral part of global environmental regulations. Although groundwater, surface water, and air monitoring have received special attention, little emphasis has been placed on the effects of landfills on the vegetation surrounding a landfill's environment. Pollution events taking place at or near a landfill's ground surface and in close proximity to it do not appear to be captured by existing landfill monitoring schemes that either sample deep aquifers, or relatively distant surface water systems.

This article focuses on the utilization of bioindicators to assess the impact of landfills on their surrounding vegetation, which can also be used as a visual representation and warning signal of near-surface pollution incidents from landfills. Research in this area, in which the authors of this paper have been active participants, has provided fruitful insights, and the major conclusions are summarized as follows.

(i) Vegetation responds to pollution first by retreating sensitive plant species, and then by new species, which are resistant to specific pollutants dominating the vegetation.
(ii) The increase in soils salinity translates to a higher abundance of halophytes.
(iii) High nitrogen and other nutrient contents were reflected by the presence of a higher proportion of nitrophilous plant species in the landscape.

(iv) Vegetation responds to the degree of toxicity by changing its species composition. This change in vegetation species composition near a landfill is the first sign that indicates the presence and degree of toxicity of pollutants.

(v) Epiphytic lichens, which primarily obtain water and essential nutrients from the atmosphere, have proven to be good indicators of air pollution from landfills.

(vi) Landfills have a high potential to promote the expansion of invasive plant species, altering the vegetation species composition in the surrounding ecosystems.

(vii) Ecologically problematic species can spread from a landfill to adjacent ecosystems, gradually eliminating native plant species and degrading nearby farmland.

(viii) Plant communities appear to be more sensitive indicators of environmental conditions than individual species.

Extensive studies, as those presented here, and the decades-long experience of the authors of this article make it evident that landfills should be regularly subjected to vegetation monitoring. Vegetation species' changes can assist in early detection of pollution events at a landfill, potentially identifying even preferential pollution directions, and thus helping to direct more focused sampling campaigns. The predominance of certain plant species, as reported herein, can provide a strong indication of the type of chemical pollutant that has leaked and hence assist in the selection of appropriate remediation technologies. In addition to pollution detection, biomonitoring can act as a warning sign to near-a-landfill farming activities by indicating the spread of invasive and problematic species that may end up dominating and replacing productive crops. Thus, landfill management methods should focus on controlling undesirable plant species, creating favorable conditions for native plant species, and providing early restoration of closed landfill cells. Finally, biomonitoring presents the potential for the study of vegetation at sites other than landfill-polluted sites, such as degraded land areas or urban brownfields. The ample evidence of the utility of landfill biomonitoring makes it advisable to include it in municipal waste monitoring regulations, an act that will also give the impetus for the development of more targeted detection biomonitoring techniques.

References

Abas, A., 2021. A systematic review on biomonitoring using lichen as the biological indicator: A decade of practices, progress and challenges. *Ecological Indicators*, 121, p.107197. https://doi.org/10.1016/j.ecolind.2020.107197

Adams, S.M., Shugart, L.R., & Hinton, D.E. (2018). Application of bioindicators in assessing the health of fish populations experiencing contaminant stress. In *Biomarkers of Environmental Contamination* (pp. 333-353). CRC Press.

Al-Alam, J., Chbani, A., Faljoun, Z., & Millet, M. (2019). The use of vegetation, bees, and snails as important tools for the biomonitoring of atmospheric pollution—a review. *Environmental Science and Pollution Research*, 26(10), 9391-9408. https://doi.org/10.1007/s11356-019-04388-8.

Álvarez-López, V., Zappelini, C., Durand, A., & Chalot, M. (2020). Pioneer trees of Betula pendula at a red gypsum landfill harbour specific structure and composition of root-associated microbial communities. *Science of The Total Environment*, 726, 138530. https://doi.org/10.1016/j.scitotenv.2020.138530

Aničić, M., Tasić, M., Frontasyeva, M.V., et al. (2009). Active biomonitoring with wet and dry moss: a case study in an urban area. *Environmental Chemistry Letters*, 7(1), pp.55-60. https://doi.org/10.1007/s10311-008-0135-4

Azizi, G., Akodad, M., Baghour, M., Layachi, M., & Moumen, A. (2018). The use of Mytilus spp. mussels as bioindicators of heavy metal pollution in the coastal environment. A review. *Journal of Materials and Environmental Sciences*, 9(4), 1170-1181.

Bayouli, I.T., Bayouli, H.T., Dell' Oca, A., et al. (2021). Ecological indicators and bioindicator plant species for biomonitoring industrial pollution: Eco-based environmental assessment. *Ecological Indicators,* 125, 107508. https://doi.org/10.1016/j.ecolind.2021.107508.

Bazanov, V.A., Berezin, A.E., Savichev, O.G., & Skugarev, A.A. (2009). The phytoindication method for mapping peatlands in the taiga zone of the West-Siberian Plain. *International Journal of Environmental Studies*, 66(4), 473-484. https://doi.org/10.1080/00207230903303729

Begu, A. (2014). Lichens studies in the Republic of Moldova and their ecobioindication features. *Revista Botanică,* 8(1), 44-53.

Benítez, Á., Medina, J., Vásquez, C., et al. (2019). Lichens and bromeliads as bioindicators of heavy metal deposition in Ecuador. *Diversity,* 11(2), 28. DOI: 10.3390/d11020028.

Bryant, G.L., Kobryn, H.T., Hardy, G.E.S. and Fleming, P.A., 2017. Habitat islands in a sea of urbanisation. *Urban Forestry & Urban Greening*, 28, 131-137. https://doi.org/10.1016/j.ufug.2017.10.016

Capozzi, F., Giordano, S., Aboal, J.R., et al. (2016). Best options for the exposure of traditional and innovative moss bags: a systematic evaluation in three European countries. *Environmental Pollution*, 214, pp.362-373. https://doi.org/10.1016/j.envpol.2016.04.043

Cozea, A., Bucur, E., Lehr, C. B., et al. (2018). Aspects regarding the use of some species of plants as bioindicators in air quality assessment. *Revista de Chimie (Bucharest)*, 69(11), 4138-4140. http://hdl.handle.net/123456789/1356.

Chytrý M., Tichý L., Dřevojan P., et al. (2018) Ellenberg-type indicator values for the Czech flora. – *Preslia* 90: 83–103.

Conti, M.E. (editor) (2008). Biological Monitoring: Theory and Applications—Bioindicators and Biomarkers for Environmental Quality and Human Exposure Assessment. Boston: WIT Press, 228 pp. ISBN: 978-1-84564-002-6

Dunham, S.J., Neumann, E.K., Lanni, E.J., et al. (2019). Biomarker discovery with mass spectrometry imaging and profiling. *Proteomics for Biological Discovery,* 89-123. https://doi.org/10.1002/9781119081661.ch4.

Ellenberg, H., Weber, H.E., Düll, R., et al. (1991). Pointer values of plants in Central Europe – *Scr. Geobot*., 18, pp. 1-248.

European Commission (EC) (1999). Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31999L0031&from=en

Farias, D.R., Hurd, C.L., Eriksen, R.S., & Macleod, C.K. (2018). Macrophytes as bioindicators of heavy metal pollution in estuarine and coastal environments. *Marine Pollution Bulletin,* 128, 175-184. https://doi.org/10.1016/j.marpolbul.2018.01.023.

Fossi, M.C., Pedà, C., Compa, M., et al. (2018). Bioindicators for monitoring marine litter ingestion and its impacts on Mediterranean biodiversity. *Environmental Pollution,* 237, 1023-1040. https://doi.org/10.1016/j.envpol.2017.11.019.

Frati, L., Santoni, S., Nicolardi, V., et al. (2007). Lichen biomonitoring of ammonia emission and nitrogen deposition around a pig stockfarm. *Environmental Pollution* 146, 311–316. https://doi.org/10.1016/j.envpol.2006.03.029

Fränzle, O. (2006). Complex bioindication and environmental stress assessment. *Ecological Indicators*, 6(1), 114-136. https://doi.org/10.1016/j.ecolind.2005.08.015.

Garg, A., Yadav, B. K., Das, D. B., & Wood, P.J. (2022). Improving the assessment of polluted sites using an integrated bio-physico-chemical monitoring framework. *Chemosphere*, 290, 133344. https://doi.org/10.1016/j.chemosphere.2021.133344.

Gianguzzi, L., & Bazan, G. (2020). A phytosociological analysis of the Olea europaea L. var. sylvestris (Mill.) Lehr. Forests in Sicily. *Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology*, 154(5), 705-725. https://doi.org/10.1080/11263504.2019.1681532.

Glibovytska, N., & Mykhailiuk, Y. (2020). Phytoindication research in the system of environmental monitoring. *Ecological Sciences*, 28, 111-114.

Goli, V.S.N.S., Paleologos, E.K., Farid, A., et al. (2022a). Extraction, Characterization and Remediation of Microplastics from Organic Solid Matrices. *Environmental Geotechnics* 1–34. https://doi.org/https://doi.org/10.1680/jenge.21.00072

Goli, V.S.N.S., Singh, P., Singh, D.N., Tak, L.K., (2022b). Investigations on characteristics of landfill-mined-soil-like-fractions and their dependency on organic matter. *Process Safety and Environmental Protection* 162, 795–812. https://doi.org/10.1016/j.psep.2022.04.052

Goli, V.S.N.S., Singh, D.N., 2023. Extraction and characterization of microplastics in Landfill-Mined-Soil-like-Fractions: A novel methodology. *Chemical Engineering Journal* 452, 139217. https://doi.org/10.1016/j.cej.2022.139217

Herben T., Chytrý M. & Klimešová J. (2016). A quest for species-level indicator values for disturbance. *Journal of Vegetation Science* 27: 628–636.

Hernández-Moreno, D., Ramos, A., Romay, C.D., et al. (2021). Heavy Metals Content in Great Shearwater (Ardenna Gravis): Accumulation, Distribution and Biomarkers of Effect in Different Tissues. *Archives of environmental contamination and toxicology,* 80(3), 615-623. https://doi.org/10.1007/s00244-021-00828-0.

Hernández Parrodi, J.C. Höllen, D., Pomberger, R. (2018). Characterization of fine fractions from landfill mining: a review of previous investigations. *Detritus*, 2, 46-62. https://doi.org/10.31025/2611-4135/2018.13663

Hinojosa-Garro, D., Rendón-von Osten, J., & Dzul-Caamal, R. (2020). Banded tetra (Astyanax aeneus) as bioindicator of trace metals in aquatic ecosystems of the Yucatan Peninsula, Mexico:

Experimental biomarkers validation and wild populations biomonitoring. *Ecotoxicology and Environmental Safety*, 195, 110477. https://doi.org/10.1016/j.ecoenv.2020.110477.

Holt, E.A., & Miller, S.W. (2011). Bioindicators: using organisms to measure. *Nature,* 3, 8-13.

Holyk, H.M., & Goncharenko, I.V. (2017). Syntaxonomy, synphytoindication analysis and anthropogenic transformation of forest vegetation in Kyiv city. *Ecology and Noospherology,* 28(1-2), 49-63. https://doi.org/10.15421/031705.

Hoornweg, D., Bhada-Tata, P. (March 2012). What a Waste: A Global Review of Solid Waste Management. Washington D.C.: World Bank, Urban Development Series; pp. 116.

Ighbareyeh, J.M.H., Suliemieh, A.A.R.A., Ayash, A.M.A., et al. (2021). Biodiversity and Phytosociological Analysis of Plants in Wadi Al-Quf Nursery Reserve North-Western of Hebron City in Palestine. *Journal of Plant Sciences,* 9(1), 13-24. doi: 10.11648/j.jps.20210901.13.

Jaskulak, M., & Grobelak, A. (2019). Cadmium Phytotoxicity—Biomarkers. In *Cadmium Tolerance in Plants* (pp. 177-191). Academic Press.

Jmii, S., & Dewez, D. (2021). Toxic Responses of Palladium Accumulation in Duckweed (*Lemna minor*): Determination of Biomarkers. *Environmental Toxicology and Chemistry,* 40(6), 1630-1638. https://doi.org/10.1002/etc.5011.

Kaymak, G., Kayhan, F.E.E., & Ertuğ, N.D.Y. (2021). A biomonitoring study: Using the biomarkers in Cyprinus carpio for the evaluation of water pollution in Sapanca Lake (Sakarya, Turkey). *International Journal of Agriculture Environment and Food Sciences,* 5(1), 107-121. https://dergipark.org.tr/tr/pub/jaefs/issue/59741/823582.

Khalid, N., Masood, A., Noman, A., Aqeel, M., & Qasim, M. (2019). Study of the responses of two biomonitor plant species (Datura alba & Ricinus communis) to roadside air pollution. *Chemosphere,* 235, 832-841. https://doi.org/10.1016/j.chemosphere.2019.06.143.

Koda, E., (2012). Influence of vertical barrier surrounding old sanitary landfill on eliminating transport of pollutants on the basis of numerical modeling and monitoring results. *Polish Journal of Environmental Studies*, 21(4), 929-935.

Koda, E., Pachuta, K. and Osinski, P. (2013). Potential of Plant Applications in the Initial Stage of the Landfill Reclamation Process. *Polish Journal of Environmental Studies*, 22(6).

Koda, E., Rybak-Niedziółka, K., Winkler, J., et al. (2021). Space redevelopment of old landfill located in the zone between urban and protected areas: case study. *Energies,* 15(1), 146. https://doi.org/10.3390/en15010146.

Koda, E., Winkler, J., Wowkonowicz, P., et al. (2022). Vegetation changes as indicators of landfill leachate seepage locations: Case study. *Ecological Engineering*, 174, 106448. https://doi.org/10.1016/j.ecoleng.2021.106448.

Korbut, M., Malovanyy, M., Davydova, I., et al. (2021). Assessment of the Condition of Pine Plantations in the Area of Influence of Municipal Waste Landfills on the Example of the Zhytomyr Landfill, Ukraine. *Ecological Engineering and Environmental Technology,* 22 (5), 40-46. https://doi.org/10.12912/27197050/139411.

Kosior, G., Samecka-Cymerman, A., Kolon, K. and Kempers, A.J., 2010. Bioindication capacity of metal pollution of native and transplanted Pleurozium schreberi under various levels of pollution. *Chemosphere,* 81(3), pp.321-326. https://doi.org/10.1016/j.chemosphere.2010.07.029

Kunakh, O.M., & Fedyay, I.O. (2020). Are Heteroptera communities able to be bioindicators of urban environments? *Biosystems Diversity,* 28(2), 195-202. https://doi.org/10.15421/012025.

Loppi, S., Roblin, B., Paoli, L., & Aherne, J. (2021). Accumulation of airborne microplastics in lichens from a landfill dumping site (Italy). *Scientific Reports,* 11(1), 1-5. https://doi.org/10.1038/s41598-021-84251-4.

Lubberding, H.J., Valencia, R., Salazar, R.S., Lens, & P.N.L. (2012). Release and conversion of ammonia in bioreactor landfill simulators. *J Environ Manage* 95, S144–S148. https://doi.org/10.1016/j.jenvman.2010.08.030

Mahapatra, B., Dhal, N. K., Dash, A. K., et al. (2019). Perspective of mitigating atmospheric heavy metal pollution: using mosses as biomonitoring and indicator organism. *Environmental Science and Pollution Research,* 26(29), 29620-29638. https://doi.org/10.1007/s11356-019-06270-z.

Mahmood, K., Ul-Haq, Z., Faizi, F., et al. (2019). Monitoring open dumping of municipal waste in Gujranwala, Pakistan using a combination of satellite based bio-thermal indicators and GIS analysis. *Ecological Indicators,* 107, 105613. https://doi.org/10.1016/j.ecolind.2019.105613.

Manickavasagam, S., Sudhan, C., & Aanand, S. (2019). Bioindicators in aquatic environment and their significance. *Journal of Aquaculture in the Tropics*, 34(1/2), 73-79. http://doi.org/10.32381/JAT.2019.34.1-2.6.

Markert, B.A., Breure, A.M., & Zechmeister, H. G. (Eds.). (2003). *Bioindicators and Biomonitors: Principles, Concepts and Applications*. Oxford, UK: Elsevier. ISBN: 0-08-044177-7.

Mao, D., Wang, Z., Wu, B., Zeng, Y., Luo, L. & Zhang, B., 2018. Land degradation and restoration in the arid and semiarid zones of China: Quantified evidence and implications from satellites. *Land Degradation & Development*, 29(11), 3841-3851. https://doi.org/10.1002/ldr.3135

Martínez, D.N., & Barrera, E.D.L. (2021). Physiological screening of ruderal weed biomonitors of atmospheric nitrogen deposition. *Botanical Sciences*, 99(3), 573-587. https://doi.org/10.17129/botsci.2789.

Masi, S., Caniani, D., Grieco, E., et al. (2014). Assessment of the possible reuse of MSW coming from landfill mining of old open dumpsites. *Waste Management*, 34(3), 702–710. https://doi.org/10.1016/j.wasman.2013.12.013.

Mishra, A.K., & Farooq, S.H. (2022). Trace metal accumulation in seagrass and saltmarsh ecosystems of India: comparative assessment and bioindicator potential. *Marine pollution bulletin*, 174, 113251. https://doi.org/10.1016/j.marpolbul.2021.113251.

Mohammad, A., Goli, V.S.N.S., Chembukavu, A.A., & Singh, D.N. (2021). DecoMSW: A Methodology to Assess Decomposition of Municipal Solid Waste for Initiation of Landfill Mining Activities. *The Journal of Solid Waste Technology and Management* 47, 465–481.

Mohamed, A.–M.O., Paleologos, E.K. (2017). Fundamentals of Geoenvironmental Engineering: Understanding Soil, Water, and Pollutant Interaction and Transport. 1st Edition. Elsevier Butterworth-Heinemann**,** 708 pp.

Moretto, R.L., Siqueira Neto, A.C. de, Elis, V.R., & Miguel, M.G. (2017). Detection of leachate pockets in experimental cell of municipal solid waste with aid of geophysics, in: *Proceedings Sardinia 2017 / Sixteenth International Waste Management and Landfill Symposium*. CISA Publisher, Cagliari, Italy, pp. 2–6.

Nannoni, F., Santolini, R., & Protano, G. (2015). Heavy element accumulation in Evernia prunastri lichen transplants around a municipal solid waste landfill in central Italy. *Waste Management*, 43, 353-362. https://doi.org/10.1016/j.wasman.2015.06.013.

Nasser, N.A., Patterson, R.T., Roe, H.M., et al. (2020). Use of Arcellinida (testate lobose amoebae) arsenic tolerance limits as a novel tool for biomonitoring arsenic contamination in lakes. *Ecological Indicators*, 113, 106177. https://doi.org/10.1016/j.ecolind.2020.106177.

Ndlovu, N.B., Frontasyeva, M.V., Newman, R.T. & Maleka, P.P. (2019). Active biomonitoring of atmospheric pollution in the Western Cape (South Africa) using INAA and ICP-MS. *Journal of Radioanalytical and Nuclear Chemistry*, 322(3), pp.1549-1559. https://doi.org/10.1007/s10967-019-06823-z

Orupõld, K., Somani, M., Kaczala, F., et al. (2022). Ecotoxicity assessment of fine fractions obtained from landfill mining. *J Hazard Toxic Radioact Waste* 26. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000715

Paleologos, E.K., Caratelli, P., El Amrousi, M. (2016). Waste-to-energy: An opportunity for a new industrial typology for Abu Dhabi. Renewable & Sustainable Energy Reviews, 55, 1260-1266, http://www.sciencedirect.com/science/article/pii/S1364032115007455.

Paoli, L., Corsini, A., Bigagli, V., et al. (2012). Long-term biological monitoring of environmental quality around a solid waste landfill assessed with lichens. *Environmental Pollution*, 161, 70-75. https://doi.org/10.1016/j.envpol.2011.09.028.

Paoli, L., Grassi, A., Vannini, A., et al. (2015). Epiphytic lichens as indicators of environmental quality around a municipal solid waste landfill (C Italy). *Waste Management*, 42, pp.67-73. https://doi.org/10.1016/j.wasman.2015.04.033

Parmar, T.K., Rawtani, D., & Agrawal, Y.K. (2016). Bioindicators: the natural indicator of environmental pollution. *Frontiers in Life Science*, 9(2), 110-118. https://doi.org/10.1080/21553769.2016.1162753.

Pieri, L., Vignudelli, M., Bartolucci, F., et al. (2015). Integrated environmental quality monitoring around an underground methane storage station. *Chemosphere* 131, 130–138. https://doi.org/10.1016/j.chemosphere.2015.03.009

Plit, J., & Roo-Zielińska, E. (1990). Phytoindication methods in maps. *Geographica Slovenica*, (21), 77.

Polechońska, L., Klink, A., Dambiec, M., & Rudecki, A. (2018). Evaluation of Ceratophyllum demersum as the accumulative bioindicator for trace metals. *Ecological Indicators*, 93, 274-281. https://doi.org/10.1016/j.ecolind.2018.05.020.

Popovych, V., Stepova, K., Telak, O., & Telak, J. (2021). Heat Resistance of Landfill Vegetation. *Journal of Ecological Engineering*, 22(1), 267–273. https://doi.org/10.12911/22998993/130022.

Pott, U., & Turpin, D.H. (1996). Changes in atmospheric trace element deposition in the Fraser Valley, BC, Canada from 1960 to 1993 measured by moss monitoring with Isothecium stoloniferum. *Canadian Journal of Botany*, 74(8), 1345-1353. https://doi.org/10.1139/b96-163.

Puig-Gironès, R., & Real, J. (2022). A comprehensive but practical methodology for selecting biological indicators for long-term monitoring. *PloS One*, 17(3), e0265246. https://doi.org/10.1371/journal.pone.0265246.

Raga, R., Cossu, R., Heerenklage, J., et al. (2015). Landfill aeration for emission control before and during landfill mining. *Waste Management* 46, 420–429. https://doi.org/10.1016/j.wasman.2015.09.037

Su, Y., Zhang, Z., Wu, D., et al. B. (2019). Occurrence of microplastics in landfill systems and their fate with landfill age. *Water Res.* https://doi.org/10.1016/j.watres.2019.114968

Sujetovienė, G., Smilgaitis, P., Dagiliūtė, R., & Žaltauskaitė, J. (2019). Metal accumulation and physiological response of the lichens transplanted near a landfill in central Lithuania. *Waste Management,* 85, 60-65. https://doi.org/10.1016/j.wasman.2018.12.017.

Świsłowski, P., Kosior, G., & Rajfur, M. (2021). The influence of preparation methodology on the concentrations of heavy metals in Pleurozium schreberi moss samples prior to use in active biomonitoring studies. *Environmental Science and Pollution Research,* 28(8), 10068-10076. https://doi.org/10.1007/s11356-020-11484-7.

Turkyilmaz, A., Sevik, H., Isinkaralar, K., & Cetin, M. (2019). Use of tree rings as a bioindicator to observe atmospheric heavy metal deposition. *Environmental Science and Pollution Research,* 26(5), 5122-5130. https://doi.org/10.1007/s11356-018-3962-2.

Urbat, M., Lehndorff, E., & Schwark, L. (2004). Biomonitoring of air quality in the Cologne conurbation using pine needles as a passive sampler—Part I: magnetic properties. *Atmospheric Environment*, 38(23), 3781-3792. https://doi.org/10.1016/j.atmosenv.2004.03.061.

US EPA (1999). Municipal Solid Waste Landfills, Volume 1: Summary of the Requirements for the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills (EPA-453R/96-004). North Carolina: Office of Air Quality Planning and Standards U.S. Environmental Protection Agency.

US EPA (2008). AP-42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal 2.4 Municipal Solid Waste Landfills, Draft Section-October 2008. Available at: https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-fifth-edition-volume-i-chapter-2-solid-waste-0

Vaverková, M. & Adamcová, D., (2012). Potential impact of two landfills on the near vicinity with the use of bioindicators. Infrastruktura *i Ekologia Terenów Wiejskich,* (1/IV).

Vaverková, M.D., Adamcová, D., & Toman, F. (2012a). Verification of the occurrence of some plant species as indicators of landfill impact on the environment. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis,* 61(5), 1441-1450. doi: 10.11118/actaun201361051441.

Vaverková, M. D., & Koda, E. (2023). Why landfill deposits are a distinguishing feature of the Anthropocene. *The Anthropocene Review*, 0(0). https://doi.org/10.1177/20530196231170370

Vaverková, M., Toman, F., & Kotovicová, J. (2012b). Research into the occurrence of some plant species as indicators of landfill impact on the environment. *Polish Journal of Environmental Studies,* 21(3), 755–762.

Vaverková, M. D., Radziemska, M., Bartoň, S., Cerdà, A., & Koda, E. (2018). The use of vegetation as a natural strategy for landfill restoration. *Land Degradation and Development,* 29(10), 3674-3680. https://doi.org/10.1002/ldr.3119.

Vaverková, M.D. (2019). Landfill impacts on the environment. *Geosciences,* 9(10), 431. https://doi.org/10.3390/geosciences9100431.

Vaverková, M. D., Winkler, J., Adamcová, D., et al. (2019a). Municipal solid waste landfill–Vegetation succession in an area transformed by human impact. *Ecological Engineering,* 129, 109-114. https://doi.org/10.1177/0734242X221079304.

Vaverková, M.D., Adamcová, D., Winkler, J., et al. (2019b). Influence of a municipal solid waste landfill on the surrounding environment: Landfill vegetation as a potential risk of allergenic pollen. *International Journal of Environmental Research and Public Health*, 16(24), 5064. https://doi.org/10.3390/ijerph16245064.

Vaverková, M.D., Elbl, J., Koda, E., Adamcová, D., Bilgin, A., Lukas, V., Podlasek, A., Kintl, A., Wdowska, M., Brtnický, M., & Zloch, J. (2020). Chemical Composition and Hazardous Effects of Leachate from the Active Municipal Solid Waste Landfill Surrounded by Farmlands. *Sustainability*, 12(11), 4531.

Vaverková, M.D., Paleologos, E.K., Adamcová, D., et al. (2022). Municipal solid waste landfill: Evidence of the effect of applied landfill management on vegetation composition. *Waste Management and Research*, 0734242X221079304. https://doi.org/10.1177/0734242X221079304.

Veskoukis, A., Kerasioti, E., Priftis, A., et al. (2019). A battery of translational biomarkers for the assessment of the in vitro and in vivo antioxidant action of plant polyphenolic compounds: The biomarker issue. *Current Opinion in Toxicology*, 13, 99-109. https://doi.org/10.1016/j.cotox.2018.10.001.

Vitanović, E., Ivezić, M., Kačić, S., et al. (2018). Arthropod communities within the olive canopy as bioindicators of different management systems. *Spanish Journal of Agricultural Research*, 16(2), 7. http://dx.doi.org/10.5424/sjar/2018162-12385.

Wang, Y., Xu, R., Kai, Y., et al. (2021). Evaluating the physicochemical properties of refuse with a short-term landfill age and odorous pollutants emission during landfill mining: A case study. *Waste Management* 121, 77–86. https://doi.org/10.1016/j.wasman.2020.12.001

Wania, A., Kühn, I. and Klotz, S., 2006. Plant richness patterns in agricultural and urban landscapes in Central Germany—spatial gradients of species richness. *Landscape and Urban planning* 75(1-2), 97-110. https://doi.org/10.1016/j.landurbplan.2004.12.006

Weng, Y.-C., Fujiwara, T., Houng, H.J., et al. (2015). Management of landfill reclamation with regard to biodiversity preservation, global warming mitigation and landfill mining: experiences from the Asia–Pacific region. *Journal of Cleaner Production* 104, 364–373. https://doi.org/10.1016/j.jclepro.2015.05.014

Winkler, J., Vaverková, M.D. & Havel, L., 2023. Anthropogenic life strategy of plants. The Anthropocene Review, p.20530196221149120.

Winkler, J., Mazur, Ł., Smékalová, M., et al. MD (2022). Influence of land use on plant community composition in Vysocina Region grasslands, Czech Republic. Environment Protection Engineering. sv. 48, č. 4, s. 21--33. ISSN 0324-8828. URL: https://doi.org/10.37190/epe220402

Winkler, J., Koda, E., Skutnik, Z., et al. (2021). Trends in the succession of synanthropic vegetation on a reclaimed landfill in Poland. *Anthropocene*, 35, 100299. https://doi.org/10.1016/j.ancene.2021.100299.

Wolterbeek, B. (2002). Biomonitoring of trace element air pollution: principles, possibilities and perspectives. *Environmental Pollution*, 120(1), 11-21. https://doi.org/10.1016/S0269-7491(02)00124-0.

Wowkonowicz, P., Kijeńska, M., Koda, E. (2021). Potential environmental risk assessment of di-2-ethylhexyl phthalate emissions from a municipal solid waste landfill leachate. *PeerJ* **9**: e12163. DOI 10.7717/peerj.12163

Xiaoli, C., Xin, Z., Ziyang, L., et al. (2011). Characteristics of vegetation and its relationship with landfill gas in closed landfill. *Biomass and bioenergy*, 35(3), 1295-1301. https://doi.org/10.1016/j.biombioe.2010.12.051.

Yin, L., Wen, X., Huang, D., et al. (2021). Interactions between microplastics/nanoplastics and vascular plants. *Environmental Pollution* 290, 117999. https://doi.org/10.1016/j.envpol.2021.117999

Yu, K., Van Geel, M., Ceulemans, T., et al. (2018). Vegetation reflectance spectroscopy for biomonitoring of heavy metal pollution in urban soils. *Environmental Pollution*, 243, 1912-1922. https://doi.org/10.1016/j.envpol.2018.09.053.

Zadorozhna, G. (2017). Soil Ecomorphs as a Form of Adaptation to the Conditions of Biogeocenosis. *Notes in Current Biology*, 7(356), 94-103. https://doi.org/10.29038/2617-4723-2017-356-7-94-103.

Zapata-Carbonell, J., Bégeot, C., Carry, N., et al. (2019). Spontaneous ecological recovery of vegetation in a red gypsum landfill: Betula pendula dominates after 10 years of inactivity. *Ecological Engineering*, 132, 31-40. https://doi.org/10.1016/j.ecoleng.2019.03.013.

Zhukov, O.V., & Potapenko, O.V. (2017). Environmental impact assessment of distribution substations: the case of phytoindication. *Ukrainian Journal of Ecology*, 7(1), 5-21.

Zverev, A.A. (2014). Direct and mediate assessment of acidity in hydromorphic habitats in West Siberian Plain. *International Journal of Environmental Studies*, 71(5), 629-636. https://doi.org/10.1080/00207233.2014.942546.

Figures Captions

Figure 1. Vegetation at municipal solid waste sites.

List of Supplementary Material

S1. Advantages and disadvantages of plants as bioindicators (Markert et al., 2003; Conti, 2008).

S2. Types and description of plant bioindicators.

S3. Summary of recent biomonitoring studies regarding the effects of landfills on the geoenvironment.

S1. Advantages and disadvantages of plants as bioindicators (Markert et al., 2003; Conti, 2008).

Advantages	Disadvantages
Potential of sampling over a long time period	Necessity to consider the seasonal effect of the growth of plants
Low cost of sampling process	Growth can be disturbed by a large number of environmental parameters
Easy determination of relationship between the concentration in tissues and depositions (mosses and lichens)	Impact of environment pollution on growth rate makes the interpretation of result difficult
Change in species composition in response to pollution	Slowness of change, lack of scientific knowledge about the causes of change in vegetation biodiversity
Effortless vegetation assessment process	Specific knowledge of plant species identification and phytocenology

S2. Types and description of plant bioindicators.

Type of indicator	Description	References
Biomarkers	Respond to subcellular biochemical, immunological and genetic changes (DNA modifications) with no visible morphological and physiological changes	(Dunham et al., 2019; Jmii and Dewez, 2021; Jaskulak and Grobelak, 2019)
Reaction biomarkers	Physiognomic degree of damage depending on the acting factor physiological reaction of plants to the action of the given factor shows in functional disorders such as restricted flowering, dieback of some organs, reduction of overall life or limitation of the most important life processes	(Fränzle, 2006; Khalid et al., 2019; Veskoukis et al., 2019; Martínez and Barrera, 2021).
Accumulation bioindicators	Accumulation in plant tissues diverse substances that can be valued quantitatively	(Hinojosa-Garro et al., 2020; Hernández-Moreno et al., 2021; Kaymak et al., 2021).

S3. Summary of recent biomonitoring studies regarding the effects of landfills on the geoenvironment.

Reference	Location	Duration	Purpose	Dominate species/bioindicators	Summary
(Paoli et al., 2012)	Central Italy	14 years	Detection of Cd, Cr, Fe, and Ni	lichens	• An increase in HM in lichens was noticed • The diversity of lichen was reduced • Improved the assessment of ecological impacts
Sujetovienė et al. (2019)	Central Lithuania	3.5 month	Detection of HM	lichens	• Accumulation of HM, except Cd, were almost the same in samples from landfill and control • Potential quantum yield was less for samples located closer to the pollution source • Lichens revealed sensitivity even to small changes in environmental conditions
Nannoni et al. (2015)	Cà Mascio landfill, Central Italy	4 months	Detection of air borne heavy elements	Lichens (*Evernia prunastri*)	• Lichens showed great sensitivity to serve as “early warning” indicators for even small environment changes • Severe (EC>1.75) and moderate (1.25<EC<1.75) accumulation of HM in lichens and damage to their cell membrane, as well as reduced photosynthetic efficiency.
Loppi et al. (2021)	Tuscany, central Italy	-	Detection of air borne microplastics	Lichen (*Flavoparmelia caperata*)	• Lichens collected near the landfill clearly accumulated the highest number of anthropogenic microfibres (147 mp/g dw) and fragments (79 mp/g dw)
Vaverková et al. (2012a, b) Vaverková and Adamcová (2012) Vaverková et al. (2018)	Kojetín bioregion, Štěpánovice landfill Kuchyňky, CR	4, 6 and 8 years	Reclamation of landfill	Native Plants *Cladonia arbuscula*, *Juniperus communis*, *Epipactis helleborine*, *Populus tremula*, *Polygala chamaebuxus*, *Prunus spinosa* and *Crataegus* spp., *Rosa* spp.	• During the floristic research conducted in 2007 and 2010, 94 species and 88 plant species, respectively, were detected • Any alarming symptoms, such as chlorosis or leaf area necrosis, were not noticed due to sanitary MSW landfill operation • The floristic research made in 2010, 2011, 2012 and 2015 revealed respectively 88, 105, 105 and 195 vascular plant species that were compared with 94 plant species identified in 2007, which indicated that the impact of landfills on the environment can be minimized by appropriate management

					• Health condition of plants occurring at the landfill was good, which in turn contributed to and indicated the health of the landfill site
Zapata-Carbonell et al. (2019)	Eastern part of France			*Betula pendula*	• Despite the high abundance of some of the nutrients necessary for proper plant development, such as Ca, S, Mg, P and K, the substrate conditions of the landfill, such as high pH, limited nutrients' access to plants • The physical and chemical properties of the waste stored on the investigated landfill, such as fine texture, high mechanical impedance, extreme pH conditions, excessive salinity and elevated concentrations of metals and metalloids, were considered detrimental to plant growth
Xiaoli et al. (2011)	Shanghai landfill		Landfill cover	*Phragmites australis*	• Coverage (25 up to 90%), height (0.8-2.2 m) and species (5 to 12) of the vegetation increased with increasing landfill time closure. This was due to decreasing landfill gas emissions and improved environmental conditions for vegetation growth
Vaverková et al. (2019)	Petrůvky landfill and Zdounky site, CR	long-term	landfilling safety		• MSW landfill created a very specific environment, where the vegetation species composition was not stable but rather a place of specific plants succession
Popovych et al. (2021)	Lviv landfill, Ukraine		Heat resistance of vegetation	*Artemisia vulgaris* L., *Artemisia absinthium* L., *Chenopodium urbicum* L., *Arctium lappa* L., and *Plantago major* L.	• The most stable species were wormwoods (*Artemisia*) in all landfill locations, and the least heat-resistant was the city goosefoot • Study confirmed that plants can be used to monitor temperature changes at landfills
Winkler et al. (2021)	Otwock, Poland	20 years	Monitoring 127 plant species	*Phalaris arundinacea*, *Alnus glutinosa*, *Salix alba*, *Typha latifolia*, *Populus canescens*, *Typha angustifolia*	• Assessment of vegetation composition used the method of phytocoenological relevés • Changes in the vegetation composition at the landfill between native plant species and neophytes, as well as the development of a new spectrum of plant species was noticed over time • Anthropogenic activities not only affected the landscape but also facilitated the creation of new ecosystems

Koda et al. (2022)	Lipiny Stare, Poland	6 years	Leachate seepage	*Salt tolerant*	• A growing number of tolerant to salinization plant species (i.e., halophyte and oligohaline) and the decreasing share of glycophytes in places of leachate leakage demonstrated the diagnostic potential of plants for the identification and localization of leachate leakage points at the landfill • For fast identification of leachate leakage points, an index was proposed based on the relation of glycophytes to plant species tolerant to salinity

Figures

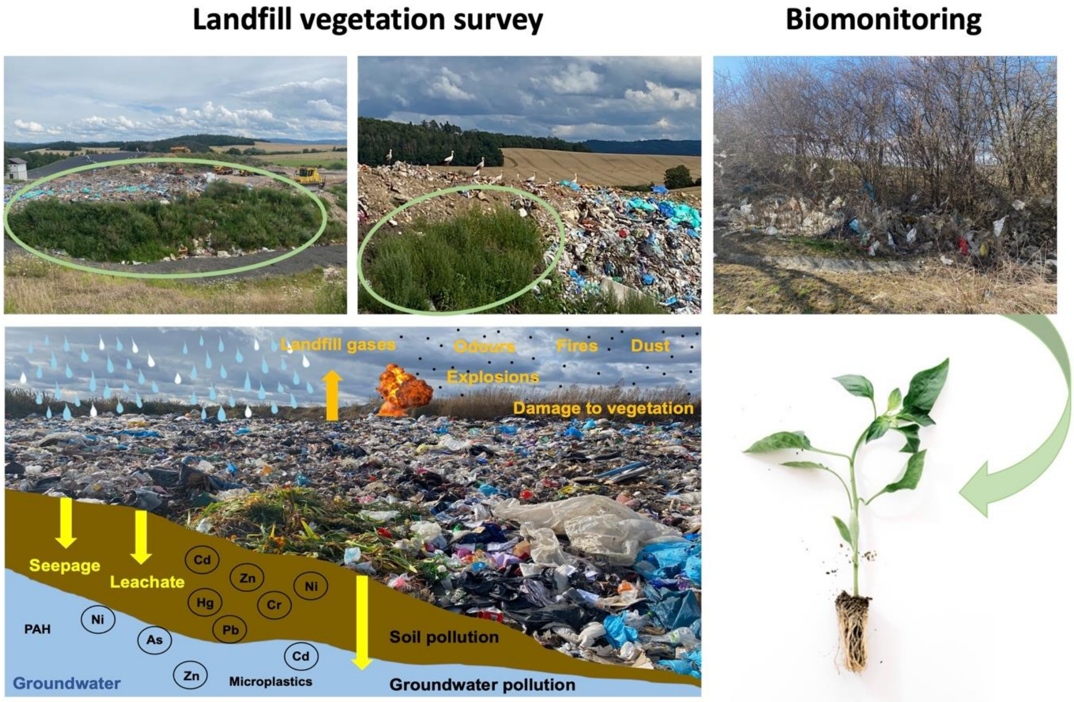

Figure 1. Vegetation at municipal solid waste sites.