Tropical Aquatic and
Soil Pollution

Review
Volume 4(2), 2024, 111–126
https://doi.org/10.53623/tasp.v4i2.490

Environmental Impact and Decomposition of Polycyclic Aromatic Hydrocarbons (PAHs) in Urban Soils: Challenges and Future Directions

Mehmet Emre[1]*, Rubiyatno[2], Jovale Vincent Tongco[3], Rega Permana[4,5]

[1]Faculty of Science, Dicle University, Diyarbakır, Turkey
[2]Graduate Faculty of Interdisciplinary Research, University of Yamanashi, 4-3-11 Takeda, Kofu, Yamanashi 400-8511, Japan
[3]Department of Forest, Rangeland and Fire Sciences, University of Idaho, Moscow, ID, USA
[4]School of Geography, Earth and Environmental Science, College of Life and Environmental Sciences, University of Birmingham, Birmingham B15 2TT, United Kingdom
[5]Universitas Padjadjaran, Faculty of Fisheries and Marine Science, Raya Bandung Sumedang Street KM. 21 Jatinangor, Sumedang, 45363, Indonesia

*Correspondence: mehmetzemre21@gmail.com

SUBMITTED: 4 September 2024; REVISED: 20 October 2024; ACCEPTED: 24 October 2024

ABSTRACT: The rapid pace of urbanization and development has led to an increasing global concern over polycyclic aromatic hydrocarbons (PAHs) due to their persistent and widespread presence in the environment, posing significant threats to ecosystems and human health. PAHs originate from both natural and human-made sources and can be categorized based on their origin into pyrogenic, petrogenic, and biogenic products. Upon entering the environment, PAHs undergo various chemical and biological transformations, and their movement occurs through processes such as air-to-soil and soil-to-air transport. Composting, a green and cost-effective technology, offers a promising solution for PAH remediation. This process, which includes mesophilic, thermophilic, cooling, and maturing stages, can yield compost that is useful as fertilizer and soil amendment in agriculture. The success of composting depends on factors such as substrate bioavailability, oxygen levels, nutrient supply, and environmental conditions. While composting has shown effectiveness in reducing PAH levels, it is not without challenges, including the risk of weed infestation, greenhouse gas emissions, and odor pollution. The main obstacles in PAH remediation today are the limited bioaccessibility of PAHs and the insufficient focus on the formation of oxygenated PAHs during the process. Future research should address these challenges, particularly by improving PAH bioaccessibility and mitigating issues related to odor and greenhouse gas emissions.

KEYWORDS: Polycyclic aromatic hydrocarbons; composting; soil; fate and transport

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) were a group of organic chemicals consisting of two or more fused benzene rings composed of carbon and hydrogen atoms. Based on the number of benzene rings, PAHs were divided into light-molecular-weight PAHs (LMW PAHs), which had two to three rings, and high-molecular-weight PAHs (HMW PAHs), which had four or more rings. PAHs were generally colourless, white, or pale yellow solids and had high melting and boiling points but low vapour pressure and solubility in water. The solubility and vapour pressure decreased as molecular weight increased, while the melting and boiling points increased proportionally [1,2].

PAHs originated from both natural and anthropogenic sources. Natural sources included wildfires, volcanic activity, oil seeps, and tree exudates, whereas anthropogenic sources were primarily from the incomplete combustion of fossil fuels or other organic materials, incineration, and petroleum spills or discharges. Due to their physicochemical properties, PAHs were persistent and ubiquitous in the environment, and were frequently detected in air, soil, and water. Their presence posed significant risks to human health and the environment because of their toxicological effects, including carcinogenicity and mutagenicity. Soil, in particular, served as the primary repository for PAHs, making soil contamination a critical focus for remediation efforts. PAHs accumulated in soil over time, and without effective remediation, the contamination would continue to pose long-term threats to ecosystems and human health. Thus, the need for soil remediation became urgent to prevent further contamination and mitigate the adverse effects on the environment and public health. The United States Environmental Protection Agency (USEPA) classified 16 PAHs as priority pollutants among 126 priority contaminants, and their detailed physicochemical properties are presented in Table 1 [1, 2].

Table 1. Physiochemical properties of 16 priority PAHs [1, 2].

Name	Formula	Molar Mass (g/mole)	Rings	Solubility in water (mg/L)	Toxicity as per IARC
Naphthalene	$C_{10}H_8$	128.17	2	31	2B
Acenaphthylene	$C_{12}H_8$	152.19	3	16.1	3
Acenaphthene	$C_{12}H_{10}$	154.21	3	3.8	3
Fluorene	$C_{13}H_{10}$	166.22	3	1.9	3
Phenanthrene	$C_{14}H_{10}$	178.23	3	1.1	3
Anthracene	$C_{14}H_{10}$	178.23	3	0.045	3
Fluoranthene	$C_{16}H_{10}$	202.26	4	0.26	3
Pyrene	$C_{16}H_{10}$	202.26	4	0.132	3
Chrysene	$C_{18}H_{12}$	228.29	4	0.0015	2B
Benzo(a)anthracene	$C_{18}H_{12}$	228.29	4	0.011	2B
Benzo(a)pyrene	$C_{20}H_{12}$	253.32	5	0.0038	1
Benzo(b)fluoranthene	$C_{20}H_{12}$	253.32	5	0.0015	2B
Benzo(k)fluoranthene	$C_{20}H_{12}$	253.32	5	0.0008	2B
Indeno(1,2,3-cd) pyrene	$C_{22}H_{12}$	276.34	6	0.062	2B
Benzo(g,h,i)perylene	$C_{22}H_{12}$	276.34	6	0.00026	3
Dibenz(a,h)anthracene	$C_{22}H_{14}$	278.35	6	0.0005	2A

Given the growing concern over PAH contamination in soil, researchers and government agencies developed various remediation technologies, including physical, chemical, and biological methods, to address the issue. For example, thermal treatment, soil washing, chemical oxidation, electrokinetic remediation, and bioremediation were among the approaches explored. Physical and chemical treatments for PAH contamination, while effective at rapidly reducing pollutants, were often prohibitively expensive due to the complex machinery and energy requirements involved. These methods also generated secondary environmental impacts, such as hazardous byproducts or the depletion of soil nutrients, making them less sustainable for large-scale applications. Conversely, bioremediation, particularly composting, offered a low-cost and sustainable alternative by using natural processes involving microorganisms to break down contaminants. It required fewer resources and posed minimal risk to ecosystems, making it a more environmentally friendly option, especially for long-term remediation in soils impacted by PAH contamination [2, 3].

Among the bioremediation methods, composting stood out as a promising green technology. It involved the transformation of degradable organic waste into humus-like compost, which could be used as a fertilizer to improve soil quality. Composting not only reduced waste volume but also offered a cost-effective solution for organic waste management [3]. Additionally, composting using different raw materials proved effective in reducing PAH concentrations to minimal levels [4]. This paper examines the types, sources, fate, and transport of PAHs, with a focus on their current status in Malaysia. The mechanisms of composting, its advantages and disadvantages, and its societal impact are also discussed. Finally, future challenges and prospects are explored to ensure composting becomes an even more sustainable and viable approach for managing PAH contamination in the long term.

2. Types and Sources of Polycyclic Aromatic Hydrocarbons

According to different processes, PAHs were introduced into the environment in the form of pyrogenic, petrogenic, and biogenic sources. Pyrogenic PAHs were produced during pyrolysis processes, where organic materials were subjected to high temperatures ranging from a minimum of 350°C to over 1200°C, either with very little oxygen or without oxygen. Pyrolytic processes occurred both intentionally and unintentionally. Intentional pyrolytic processes included the destructive distillation of coal into byproducts like coke and coal tar, as well as the thermal cracking of petroleum oil to break down longer, heavier hydrocarbons into shorter, lighter ones [5, 6].

A study conducted in Poland revealed that coking plants contributed significantly to PAH contamination in surrounding soil areas. The study found that these plants released high concentrations of PAHs, particularly those with four and five aromatic rings, such as naphthalene and fluoranthene, which were among the most carcinogenic compounds [7]. In addition to industrial sources, unintentional pyrolytic processes also played a role, including the incomplete combustion of motor fuels in vehicles, fuel oils in heating systems, and wood in wildfires, all of which generated substantial levels of PAHs [5, 6]. For instance, motor vehicles alone contributed an estimated 28% of the total PAH emissions in urban areas [6]. Campos and Abrantes discovered that burnt soil contained significantly higher levels of PAHs compared to unburnt soil, with levels often spiking after wildfires. In cases of biomass burning, PAHs became bound to charcoal and ash, which deposited and accumulated on the soil surface, along with soil organic matter. A study in the United States reported that PAH levels in soils following wildfires increased by over 400%, primarily due to the formation of pyrogenic PAHs during combustion [8]. The concentration of pyrogenic PAHs was often proportional to population density. Higher-population urban areas tended to have significantly higher concentrations of PAHs than rural areas [5]. For instance, a study conducted in urban areas of China showed that PAH concentrations in the soil were up to 20 times higher than those in nearby rural regions, largely due to emissions from vehicles and industrial activities. In major cities such as Beijing, PAH concentrations in topsoil reached levels as high as 33 mg/kg, posing significant risks to both environmental and public health [9].

In contrast, petrogenic PAHs were formed at lower temperatures, around 100°C to 150°C, over long periods, sometimes extending millions of years during the crude oil maturation process. Sources of petrogenic PAHs included petroleum and its byproducts, such as crude oil, fuel, lubricants, oil spills, and leaks from both underground and aboveground storage tanks, as well as emissions from gasoline and motor oil during the transportation of hydrocarbons [9]. The 16 parent PAHs listed by USEPA, along with petroleum-specific alkylated homologues (PAH1-PAH4), were key components of petrogenic sources. The "alkylated five" or "five target" series, including fluorene, dibenzothiophene, and chrysene, were particularly common in petroleum sources. Typically, high-molecular-weight (HMW) PAHs dominated pyrogenic sources, while light-molecular-weight (LMW) PAHs prevailed in petrogenic sources [2, 10].

Biogenic PAHs were synthesized biologically by plants, microorganisms, algae, and phytoplankton through the slow biological conversion of organic materials, such as the breakdown of vegetative matter. These PAHs had both natural and anthropogenic origins. For instance, perylene was found in soil from natural sources, such as termite nests, but it could also be produced by coal pyrolysis and vehicular emissions. Similarly, retene originated from the microbial degradation of dehydroabietic acid but could also be released from heavy-duty fuel exhaust, coal burning, and effluents from pulp/paper mills, oil, and diesel operations [11]. Figure 1 summarizes the natural and anthropogenic sources of PAH formation.

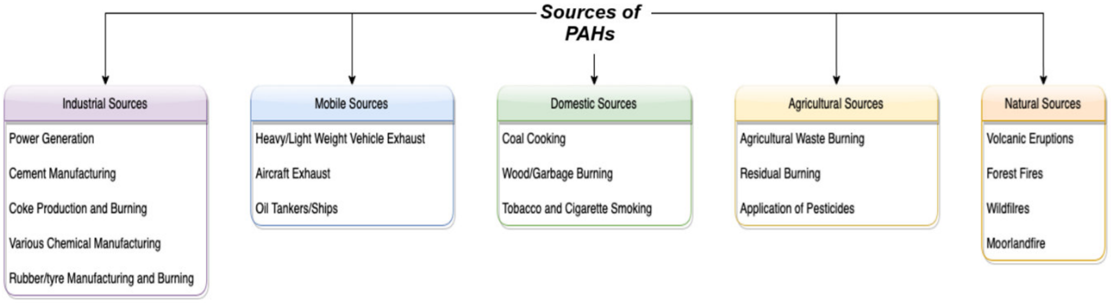

Figure 1. Sources of PAHs.

3. Fate and Transport of Polycyclic Aromatic Hydrocarbons

The transformation of the PAHs in the environment occurs via chemical and biological processes. Under the catalyzation of sunlight, PAHs can interact with the atmosphere by reacting with nitric acid and nitrogen oxide to form nitro-PAHs and undergoing oxidation to generate oxygenated PAHs (OPAHs). The halogenation and methylation of PAHs can only occur when fungal species catalyze them due to enzymatic activities. The conversion of PAHs depends on their chemical reactivity and molecular size. The bigger the size of the molecule, the greater the light energy is absorbed, therefore enhancing the photoreactivity. Besides, the PAHs with higher aromaticity tend to be more stable as they are less impacted by biological processes and have a longer half-life. Moreover, the transformation rate of a molecule into OPAHs and nitro-PAHs has a positive correlation with sp2-hybridization [12, 13].

Air is the primary transport medium for PAHs in the environment. Thus, the air is the key transport channel that is included in the environmental pathways on a regional and global level, consisting of air-to-soil and soil-to-air processes. The PAHs from the atmospheric particles are deposited into the soil as a result of gravity forces, wet deposition and adsorption to soil elements. The long-range transport from their origins, such as urban areas to urban peripheries, rural areas, and semi-rural areas, is facilitated by wind currents, storms and low-pressure systems. One of the factors that can affect the concentration of PAHs in air and soil is the temperature [12]. Based on the temperature, vapour pressure, solubility, size and surface area of the suspended particles, PAHs can be either in the form of gas or as a solid by attaching to aerosols or partitioned between two phases. Since surface deposition is the result of both wet and dry deposition that captures gas and particle phase pollutants in snow or rain, it is more susceptible to changes in climate and seasonality. The concentration of PAHs tends to be higher in winter than in summer as the low humidity leads to the greater deposition of PAHs and low temperature reduces the degradation rate and movement of PAHs [14]. A similar effect can be found in the equatorial countries where the PAHs level are decreased due to the monsoon seasons. On a daily basis, the number of PAHs is greater at night than in the daytime as well. Hence, the surrounding soil temperature greatly determines the mobility and leachability of PAHs in the soil environment. Vegetation also plays an important role in regulating the concentration of PAHs in the environment, shortening their airborne half-life and delivering them from the atmosphere to the soil. The trees can remove PAHs through evapotranspiration, adsorption and interception of airborne particle contaminants in the foliar canopy. The PAH volatilization from soils will probably be hindered by the stagnant atmosphere beneath the tree canopy [13, 14].

The soil-to-air fugacity factor is the key indicator of the rate of PAHs transference from soil to air controlled by temperature and organic carbon-to-water component. The organic carbon-to-water component is the parameter used to define the relative partition of PAHs in the aqueous and solid phases. The LMW PAHs are more likely to transfer from soil to the air than the HMW PAHs. It can be evidenced by a case study conducted in Turkey. The results show that the LMW PAHs, approximately 3 to 5 rings, were more prevalent in the gas phase than in the solid phase due to their high volatility. Previous study also proved that HMW PAHs have greater accumulation in the soil at a traffic site in Hanoi, Vietnam. The PAHs with high fugacity values have greater mobility to transport from soil to air in summer, whereas the migration is lowest during the winter [2, 15, 16].

4. Current Status of PAHs in Malaysia

Table 2 summarizes the occurrence of PAHs in Malaysia. Most of the research is done on the contamination of PAHs in aquatic environments in Malaysia. In contrast, the pollution in the soil environment has received less attention with only two studies found in Malaysia. A study on the distribution and source of PAHs has been carried out in the surface soil of five different locations in Klang Valley. The result indicated that there was 14 priority PAHs found in the sample and their total concentration ranged from 64 to 155 µg/kg. LMW PAHs contribute the majority of the PAHs profile in the soil. The combustion of biomass and petroleum in automobiles, factories, and non-point sources was the pyrogenic source of the PAHs found in the soils of the Klang Valley [17]. Mohd Radzi et al. [18] also conducted a study in five industrial areas around Kuala Lumpur by analysing the PAHs contamination level in roadside soils. The total PAH concentration in the soil sample from five sampling locations ranged from 2804 ± 2645 µg/kg to 18384 ± 12324 µg/kg. HMW PAHs are found to be dominant in all the sampling locations and the majority of them are contributed by petrogenic sources. In the case of sediment, sediment sampling was conducted in both Malacca and Prai Rivers to determine the source and distribution of PAHs. The total PAH concentration in the sediment of the Malacca River was 716 to 1210 ng/g while the Prai River had a concentration of 1102 to 7938 ng/g in the sediment. Pyrogenic sources like combustion predominated both through atmospheric input [19]. A similar study had conducted in surface sediments within aquaculture areas in Peninsular Malaysia. The collected samples were found to have a mean PAH concentration of 360 ng/g dry weight. According to the result, HMW PAHs were dominant in the samples, indicating the source was pyrogenic attributed to vehicle emissions, oil combustion, and biomass combustion [20]. For the sediment from Muar River and Pulau Merambong, the PAHs concentrations ranged from 212 to 440 ng/g and 151 to 412 ng/g dry weight respectively. Most of them were HMW PAHs, determining the pyrogenic sources like exhaust from vehicles and industrial expansion [21].

Table 2. Current status of PAHs in Malaysia.

Location	Sample	Concentration	Type	Sources	References
Klang Valley	Soil	64 to 155 μg/kg	LMWs	Pyrogenic	[17]
Kuala Lumpur	Soil	2804 ± 2645 μg/kg to 18384 ± 12324 μg/kg	HMW	Petrogenic	[18]
Malacca River	Sediment	716 to 1210 ng/g	-	Pyrogenic	[19]
Prai River	Sediment	1102 to 7938 ng/g	-	Pyrogenic	
Aquacultural areas in Peninsular Malaysia	Sediment	360 ng/g	HMW	Pyrogenic	[20]
Muai River	Sediment	212 to 440 ng/g	HMW	Pyrogenic	[21]
Pulau Merambong	Sediment	151 to 412 ng/g	HMW	Pyrogenic	[21]

5. Overview of Major Challenges

To date, co-composting is a promising technology widely applied to PAH-contaminated soil. Numerous research has shown that co-composting can greatly reduce PAHs, even the HMW PAHs. However, challenges could remain as a study demonstrated that the degradation of PAHs in long-term aged manufacturing gas plant field soils through co-composting was severely constrained under optimal mesophilic phase no matter how the ratio of soil to amendment or the application of surfactants had changed. It was believed that the bioaccessibility of PAH is the main issue that constrained the remediation process in these soils [22]. Although the chemical oxidation approach has been developed to address the limitation and achieve a certain success, the possibility of the occurrence of hydrocarbon decomposition activity cannot be excluded during the remediation process. The breakdown of hydrocarbon encourages the production of bounded residues as well as the release of PAHs from the soil, leading to a low or negligible net hydrocarbon removal. Hence, more research is required on the relationship between PAHs and organic matter, the remediation mechanism and their toxicity to enhance the performance [23].

The current research has much more attention on the remediation of PAHs whereas the co-contaminants of PAHs, specifically OPAHs do not receive much concern. The reason that OPAHs should be taken into concern as well is the comparatively high persistency in the environment and their formation through the degradation of PAHs may lead to a high accumulation of OPAHs on site. They pose a risk to both humans and the environment due to their toxicity, mutagenicity and carcinogenicity. Other than that, OPAHs have higher mobility in the environment because of the addition of carbonyl groups to the PAHs, resulting in high solubility and thus polarity of OPAHs. As the consequence, they have a greater propensity to disperse from the contaminated sites to the surrounding environment through surface water and groundwater [24].

6. Composting

6.1.Mechanism of composting.

Composting can be differentiated into aerobic composting, anaerobic composting and vermicomposting. However, this paper only discusses aerobic composting on PAHs since it has been widely studied and successfully implemented. Aerobic composting is the process that utilizes microorganisms to colonize and biodegrade the organic contaminants under the presence of oxygen and the final product is mature compost which is humus. Typical aerobic composting processes are windrow composting, aerated stack pile composting and in-vessel composting as illustrated in Figure 2, Figure 3 and Figure 4 respectively. Windrow composting, depicted in Figure 2, is a widely used method where organic waste is placed in long, narrow piles or "windrows." These windrows are regularly turned to maintain aerobic conditions, which are essential for the decomposition of organic matter. This method is cost-effective and simple but requires large areas of land and regular manual or mechanical turning to ensure proper aeration [3, 4, 22, 23].

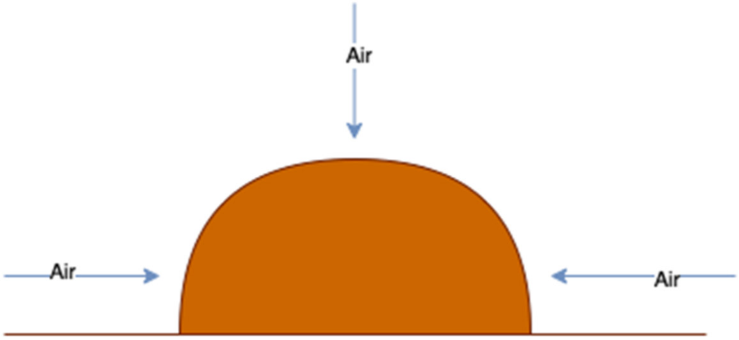

Figure 2. Windrow composting.

As shown in Figure 3, aerated static pile composting involves piling organic waste in large heaps that are aerated using a forced-air system. Unlike windrow composting, this method does not require regular turning, as air is supplied through perforated pipes or blowers. This system is more efficient in controlling temperature and moisture, which accelerates the composting process, but it requires a higher initial investment for the aeration system.

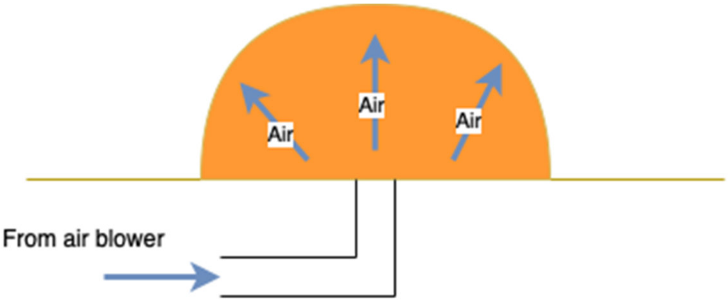

Figure 3. Aerated static pile.

Figure 4 illustrates in-vessel composting, a more controlled and advanced method where organic waste is processed in an enclosed container. This method allows for better control over environmental factors such as temperature, moisture, and aeration, resulting in faster composting times. In-vessel systems are ideal for handling large volumes of waste in limited space but tend to be more expensive to operate and maintain compared to other composting methods [23, 25].

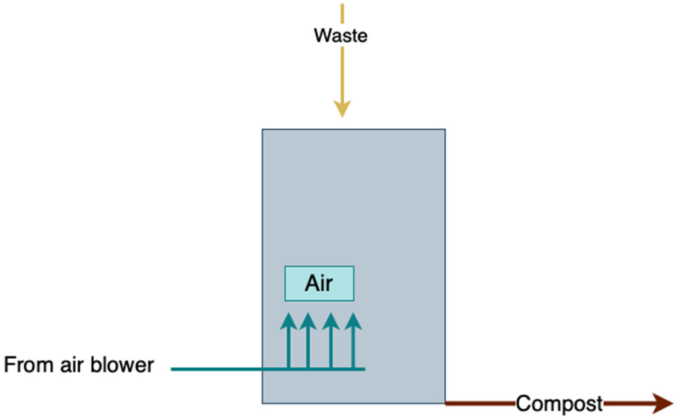

Figure 4. In-vessel composting.

The process controlling parameters such as temperature, oxygen and moisture must be regulated to the optimum values in order to obtain desired results within a reasonable time frame. Based on the rate of microbial metabolism and resultant heat production, composting can be classified into four stages: mesophilic, thermophilic, and cooling and maturing. The microorganism adapts to the environment in the mesophilic stage at the temperature of around 45°C and there is a rapid development of the microbial population as an abundance of degradable organic substrates is readily available as their food. It can be observed that the pH, temperature and carbon dioxide are increasing while the oxygen content drops significantly as a result of the enhanced microbial activity [22, 25]. The intensity of microbial activity reaches the greatest at the thermophilic stage, where the temperatures may approach a maximum of 70°C. The high temperature in this phase prevents mesophiles from growing and thriving and thus thermophiles predominate in the thermophilic stage. The high temperature may also lead to the sanitation of compost by removing the pathogens and accelerating maturation time. As a consequence of depleting organic substrates, the intensity of microbial activity is reduced, and the temperature steadily drops to 45°C in the cooling phase. When all the readily available organic substrates are exhausted, the microbial activity is decreased until the transformation of organic compounds has reached its minimum. At this point, the temperature falls to the ambient level and the compost reaches maturity. The chemical composition and properties of the mature compost rely on the composition of organic input material, the chemical interaction, and the metabolic processes that take place during the composting. It is vital to remove excess water generated from the metabolic activity and provide adequate oxygen in order to produce an ideal compost [3, 4].

6.2.Remediation of contaminated soil with polycyclic aromatic hydrocarbons.

Remediation of PAHs-contaminated soil by composting involves adding compost or other organic co-substrates to enhance the biodegradation rate of PAHs through microbial activity.

The bioavailability of the substrates, the oxygen concentration, the supply of nutrients and the environmental condition such as pH, moisture and temperature all contribute significantly to the effectiveness of the biodegradation process. The solubility of PAHs determines how they are assimilated and degraded by the microbial community. The greater the molecular weight and angularity, the lower the solubility of PAHs in water, and thus leading to a higher hydrophobicity of PAHs [25]. It can be proved by a soil-microcosm study conducted by Han et al. [26] regarding the effect of different agricultural wastes on the remediation of PAHs-contaminated soil. The results demonstrated that the PAHs with lower molecular weight had a higher degradation rate of 40.7% to 61.2%, which is higher than the degradation rate of 18.7% to 33.1% owned by the PAHs with a higher molecular weight. Besides, the octanol-water partition coefficient (log K_{ow}) also significantly impacts the biodegradation rates of PAHs. The log Kow has a positive relationship with the hydrophobicity of PAHs, leading to higher bioaccumulation potential and lower biodegradability of PAHs. Moreover, the degradation rate of PAHs is proportional to their concentration. The low concentration of PAHs in the soil can hardly be degraded as they cannot launch the degradation process because of low readily available nutrients to stimulate the microorganism. However, a high concentration of PAHs may release toxicity to the microbial community, disrupt the equilibrium of nutrients and inhibit microbial activity [25, 27].

In order to succeed in the biodegradation of PAHs, the process should be worked under optimum temperature. The solubility increases with the rising temperature, which eventually improves the bioavailability of the PAHs. It is, however, leading to a reduction in oxygen solubility and subsequently the decline of microbial activity. The PAHs are biodegraded throughout a wide range of temperatures, and each of the phases is dominated by different kinds of microorganisms. The enzymatic activity of microorganisms is more intense in mesophilic and thermophilic phases, particularly the mesophilic phase, due to the presence of a variety of microbial communities and their active participation in degrading hydrocarbon. Besides, it was discovered that composting of PAH-contaminated soil under various circumstances using various organic substrates is more favourable under the mesophilic phase [25]. Lukić et al. [28] proved that the PAHs have a higher degradation rate in the mesophilic range, especially LMW PAHs as there is a much lower residual concentration in the soil compared to that in the thermophilic range.

Organic co-substrate stability is also an important factor that determines the fate of PAHs. It is said that the compost with high stability is more efficient in remediating PAH-contaminated soil and its stability depends on the presence of substrates and humic substances. The function of the humic matter is to promote the bioavailability of the organic compound. The organic co-substrates served as nutrients for microorganisms during the composting process. Meanwhile, the humic matter aid in the accessibility of microorganism to PAHs by minimizing the binding affinity of humic matter and enhancing the heterogeneity of binding sites [29]. In addition, stable compost is preferable to fresh organic amendment as it accelerates the degradation of PAHs owing to its low biodegradable organic matter content and greater concentration of organic macromolecules. Furthermore, the organic matter with the highest humidity often comes with a finer size fraction, which can provide a larger surface area ratio to ease accessibility and produce more food for microorganisms [30, 31].

6.3.Advantages of composting.

Composting is a promising green technology that has successfully gained public interest due to its numerous advantages. It is both environmentally friendly and cost-effective [32]. Since composting utilizes organic matter as raw material, it offers an efficient way to convert organic waste into valuable products, such as biofertilizers and soil conditioners. This not only helps reduce the volume of organic waste sent to landfills but also minimizes the associated environmental impacts, such as methane emissions from waste decomposition in landfill sites. Additionally, composting prevents surface and groundwater contamination by significantly reducing pathogenic microbes that pose health risks, while also remediating chemical pollutants, including toxic PAHs, through microbial activity [33]. One of the most notable benefits of compost is its ability to serve as a biofertilizer, providing a sustainable alternative to synthetic fertilizers that can leach harmful chemicals into the environment and threaten biodiversity. Compost is rich in essential nutrients and beneficial microorganisms that enhance plant growth, improving soil fertility and, consequently, increasing crop yields. The high organic matter content in compost also boosts soil structure, leading to better water retention, enhanced soil aeration, and increased aggregate stability. This makes compost particularly effective in controlling soil erosion, as the humus it produces binds soil particles together, reducing the likelihood of soil degradation [34]. Moreover, composting contributes to plant health by fostering a diverse microbial ecosystem that can naturally suppress plant diseases. These microorganisms compete for nutrients with pathogens, engage in parasitism and predation, produce antibiotics, and generate lytic enzymes or other bioactive chemicals that inhibit the growth of harmful organisms [35, 36]. By integrating compost into agricultural and horticultural practices, not only can crop yields be improved, but there is also the potential to reduce the reliance on chemical pesticides and fertilizers, further promoting environmental sustainability..

6.4.Disadvantages of composting and its impact on society.

One of the disadvantages of composting is the possibility of weed infestation. This is because the raw material used may contain the fruits and seeds of various plant species. The widespread of invasive plants could harm the nearby ecosystem. In order to reduce the number of weeds in the compost, the compost should achieve the thermophilic phase in which most of the living things are killed due to the high temperature. Besides, adequate moisture should be provided through irrigation during composting to germinate the remaining seeds so they can be removed through shovelling. The application of compost in different regions should be avoided to limit the propagation of weeds [32]. Another drawback of composting is the emission of greenhouse gases (GHGs) which may exacerbate global warming and climate change. Figure 5 illustrates the microbial mechanism in GHG emissions during composting. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the main GHGs being released as a result of organic waste decomposition and breakdown of nitrogen-rich organic materials. The majority of GHGs emission results from high moisture content that provide an anaerobic environment for the generation of CH_4 and high temperatures that accelerate volatile substance volatilisation. Adding biochar reduces CH_4 emission as it reduces the anaerobic spots and increases the permeability, inhibiting the activity of methanogens but boosting the methanotrophs to lower the CH_4 emission. Besides, it is also effective in removing N_2O by absorbing the amount of inorganic nitrogen required by both nitrifying bacteria and denitrifying bacteria to produce N_2O and converting N_2O to N_2 through abiotic and biotic processes [37]. The majority of GHGs can be eliminated by properly mixing trash and maintaining ideal aeration and moisture content. Thus, effective aeration through forced aeration and a decrease in the pile size can substantially minimize CH_4 emission [38]. Moreover, the best available technologies should be implemented to treat GHG before emitting into the atmosphere. For example, carbon sequestration, chemical scrubber and biological reactor [37, 38].

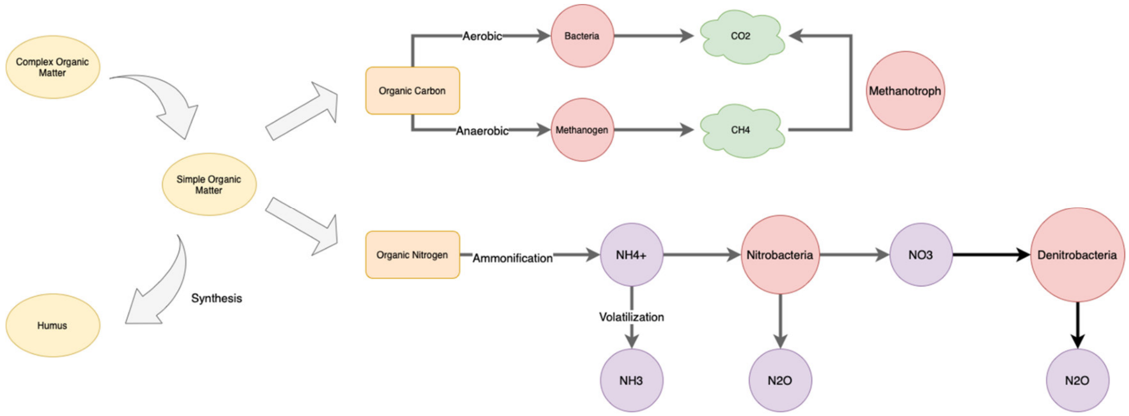

Figure 5. Microbial mechanisms associated with GHG emissions during composting.

Apart from GHG emissions, the composting process also produces an offensive smell that results in odour pollution. Volatile sulphur compounds (VSCs), volatile fatty acids (VFAs), ammonia (NH_3) and hydrogen sulphide (H_2S) are the primary contributor to the odorous gas emission from composting. The production of these odorous gases is due to the compost materials that have a low C/N ratio and insufficient oxygen supply, excessive moisture content, and low porosity that create anaerobic zones within the compost mixture. The gases are unhealthy to the workers and nearby residents as they can cause unpleasant olfactory organ activation and chronic exposure may lead to tension, headaches, anxiety, and depression. Numerous end-of-pipe treatment technologies, such as chemical (catalytic oxidation and ozonation), physical (absorption, adsorption, and thermal desorption), and biological (biofiltration, biotrickling, and bioscrubbing), can prevent odour emission [3].

7. Future Challenges and Prospects

Composting has an influence on the abundance, composition and metabolism of soil microorganisms, the fate and transport of PAHs, and the physiochemical properties of soil. Hence, the impact on the bioavailability of organic contaminants is the determining factor of how effective the composting is. In order to develop a more sustainable technology in the future, more research needs to be conducted regarding the effect of multiple factors such as compost quality and composition, compose dose, application methods as well as compost ratio on the bioavailability of PAHs to aid in managing the composting condition. Besides, further studies on temperature, pH, moisture, oxygen variation, the concentration of composting co-substrate and the introduction of exogenous microorganisms in relation to the bioavailability of PAHs are required to have a better insight into the overall composting mechanism. Presently, the establishment of standardized and uniform guidelines for organic pollutants is still in its infancy. It is crucial to develop an acceptable protocol to examine the bioavailability of various PAHs in the soil by comparing the existing bioavailability measuring strategies [39].

Since composting is inevitable in generating GHGs and odour, biological treatment of air such as bioreactor is introduced to transform inorganic and organic pollutants into non-toxic, odourless compounds through microorganisms. The research needs to focus on the media selection, design of the reactor, simulation of removal of gas components, and microbial structure analysis. Besides, the current method used to measure odour is dilution olfactometry. It is considered labour-intensive, time-consuming, expensive, prone to error, and results in delays between sampling and measurement. Thus, a better approach to odour determination should be delivered [40]. In the case of GHGs, it is more effective to adjust the operational parameters rather than the end-of-pie treatment. The experiment should be done in the actual field instead of on a lab scale to have a deeper understanding of the control parameters and strategies for reducing GHGs emissions throughout the composting process. Accurate monitoring of GHGs emissions during and after the process should also be taken into account [41, 42].

Conclusion

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds composed of multiple benzene rings, classified into pyrogenic, petrogenic, and biogenic types based on their formation processes. Pyrogenic PAHs arise from high-temperature combustion, such as from industrial activities or vehicle emissions, while petrogenic PAHs stem from low-temperature processes like oil spills or fossil fuel extraction. Biogenic PAHs are produced by the biological degradation of organic matter by plants and microorganisms. Once released into the environment, PAHs undergo various chemical and biological transformations, often accelerated by sunlight and microbial activity, leading to the formation of harmful derivatives such as nitro-PAHs and oxygenated PAHs (OPAHs). These compounds can persist in the environment and pose significant risks due to their toxicity and potential to form co-contaminants. PAHs are primarily transported through the atmosphere, with deposition processes facilitating their transfer from air to soil and volatilization allowing their re-entry into the atmosphere. Low-molecular-weight (LMW) PAHs are more volatile and thus more likely to vaporize, while high-molecular-weight (HMW) PAHs tend to adhere to soil and sediment particles due to their lower volatility. In Malaysia, research on PAHs has predominantly focused on sediments, particularly in areas like Klang Valley and Kuala Lumpur, with relatively less attention given to the presence and behavior of PAHs in soil environments. Composting is gaining recognition as an effective strategy for the remediation of PAH-contaminated soils. This process is environmentally friendly, cost-effective, and relatively simple, offering additional benefits such as improved soil fertility and reduced erosion. However, composting also presents several challenges, including the potential for greenhouse gas emissions, odor pollution, and the risk of introducing weeds. Managing these issues requires careful control of composting parameters like temperature, moisture, and oxygen levels, as well as the implementation of odor control technologies. One of the main obstacles in compost-based bioremediation is the limited bioaccessibility of PAHs in aged soils, which can reduce the efficiency of the process. Moreover, the formation of toxic OPAHs during composting remains a concern that needs to be addressed. To enhance the efficacy of composting for PAH remediation, future research should focus on optimizing the process conditions to increase PAH bioavailability, developing standardized protocols for monitoring and assessing PAH degradation, and exploring innovative uses for the heat generated during composting, such as for sustainable energy applications. Addressing these challenges will help ensure that composting becomes a more robust and widely applicable solution for managing PAH contamination in diverse environmental contexts.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Femi-Oloye, O.P.; Sutton, R.T.; Gordon, H.D.; Ain Das, A.; Morenikeji, G.O.; Odorisio, M.K.; Francestscu, O.D.; Myers, R.L.; Oloye, F.F. (2024). An Assessment of Polycyclic Aromatic Hydrocarbons Using Estimation Programs. *Toxics*, *12*, 592. https://doi.org/10.3390/toxics12080592.

[2] Mogashane, T.M.; Mokoena, L.; Tshilongo, J. (2024). A Review on Recent Developments in the Extraction and Identification of Polycyclic Aromatic Hydrocarbons from Environmental Samples. *Water*, *16*, 2520. https://doi.org/10.3390/w16172520.

[3] Tran, H.T.; Lin, C.; Bui, X.T.; Ngo, H.H.; Cheruiyot, N.K.; Hoang, H.G.; Vu, C.T. (2021). Aerobic composting remediation of petroleum hydrocarbon-contaminated soil: Current and future perspectives. *Science of The Total Environment*, *753*, 142250. https://doi.org/10.1016/j.scitotenv.2020.142250.

[4] Kästner, M.; Miltner, A. (2016). Application of compost for effective bioremediation of organic contaminants and pollutants in soil. *Applied Microbiology and Biotechnology*, *100*, 3433–3449. https://doi.org/10.1007/s00253-016-7378-y.

[5] Abdel-Shafy, H.I.; Mansour, M.S.M. (2016). A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. *Egyptian Journal of Petroleum*, *25*, 107–123. https://doi.org/10.1016/J.EJPE.2015.03.011.

[6] Patel, A.B.; Shaikh, S.; Jain, K.R.; Desai, C.; Madamwar, D. (2020). Polycyclic Aromatic Hydrocarbons: Sources, Toxicity, and Remediation Approaches. *Frontiers in Microbiology*, *11*, 2675. https://doi.org/10.3389/fmicb.2020.562813.

[7] Rachwał, M.; Magiera, T.; Wawer, M. (2015). Coke industry and steel metallurgy as the source of soil contamination by technogenic magnetic particles, heavy metals and polycyclic aromatic hydrocarbons. *Chemosphere*, *138*, 863–873. https://doi.org/10.1016/j.chemosphere.2014.11.077.

[8] Campos, I.; Abrantes, N. (2021). Forest fires as drivers of contamination of polycyclic aromatic hydrocarbons to the terrestrial and aquatic ecosystems. *Current Opinion in Environmental Science & Health*, *24*, 100293. https://doi.org/10.1016/j.coesh.2021.100293.

[9] Adly, H.M.; Saleh, S.A.K. (2021). Evaluation of Carcinogenic Polyaromatic Hydrocarbon Levels in Airborne Particulates Associated with Long-Term Exposure throughout the COVID-19 Pandemic in Makkah, Saudi Arabia. *International Journal of Environmental Research and Public Health*, *18*, 12745. https://doi.org/10.3390/ijerph182312745.

[10] Semenov, M.Y.; Marinaite, I.I.; Silaev, A.V.; Begunova, L.A. (2023). Composition, Concentration and Origin of Polycyclic Aromatic Hydrocarbons in Waters and Bottom Sediments of Lake Baikal and Its Tributaries. *Water*, *15*, 2324. https://doi.org/10.3390/w15132324.

[11] Patel, A.B.; Shaikh, S.; Jain, K.R.; Desai, C.; Madamwar, D. (2020). Polycyclic Aromatic Hydrocarbons: Sources, Toxicity, and Remediation Approaches. *Frontiers in Microbiology*, *11*, 562813. https://doi.org/10.3389/fmicb.2020.562813.

[12] Davletgildeeva, A.T.; Kuznetsov, N.A. (2024). Bioremediation of Polycyclic Aromatic Hydrocarbons by Means of Bacteria and Bacterial Enzymes. *Microorganisms*, *12*, 1814. https://doi.org/10.3390/microorganisms12091814.

[13] Tian, Y.; Wang, R.; Ji, M.; Tian, R.; Wang, R.; Zhang, B.; Wang, S.; Liu, L. (2024). The Degradation of Polycyclic Aromatic Hydrocarbons by Biological Electrochemical System: A Mini-Review. *Water*, *16*, 2424. https://doi.org/10.3390/w16172424.

[14] Wang, C.; Wu, S.; Zhou, S.; Shi, Y.; Song, J. (2017). Characteristics and Source Identification of Polycyclic Aromatic Hydrocarbons (PAHs) in Urban Soils: A Review. *Pedosphere*, *27*, 17–26. https://doi.org/10.1016/s1002-0160(17)60293-5.

[15] Li, C.; Zhang, X.; Wang, X.; Zhang, X.; Liu, S.; Yuan, T.; Qu, W.; Zhang, Y. (2022). Distribution Characteristics and Potential Risks of Polycyclic Aromatic Hydrocarbon (PAH) Pollution at a Typical Industrial Legacy Site in Tianjin, North China. *Land*, *11*, 1806. https://doi.org/10.3390/land11101806.

[16] Pham, C.-T.; Boongla, Y.; Nghiem, T.-D.; Le, H.-T.; Tang, N.; Toriba, A.; Hayakawa, K. (2019). Emission Characteristics of Polycyclic Aromatic Hydrocarbons and Nitro-Polycyclic Aromatic Hydrocarbons from Open Burning of Rice Straw in the North of Vietnam. *International Journal of Environmental Research and Public Health*, *16*, 2343. https://doi.org/10.3390/ijerph16132343.

[17] Lau, E. von; Gan, S.; Ng, H.K. (2012). Distribution and Source Apportionment of Polycyclic Aromatic Hydrocarbons (PAHs) in Surface Soils from Five Different Locations in Klang Valley, Malaysia. *Bulletin of Environmental Contamination and Toxicology*, *88*, 741–746. https://doi.org/10.1007/s00128-012-0527-9.

[18] Mohd Radzi, N.A.S.; Abu Bakar, N.K.; Emenike, C.U.; Abas, M.R. (2015). Polycyclic Aromatic Hydrocarbons (PAHs): Contamination Level and Risk Assessment in Urban Areas, Kuala Lumpur, Malaysia. *New Pub: Balaban*, *57*, 171–190. https://doi.org/10.1080/19443994.2015.1021103.

[19] Keshavarzifard, M.; Zakaria, M.P.; Shau Hwai, T.; Mohamat Yusuff, F.F.; Mustafa, S.; Vaezzadeh, V.; Magam, S.M.; Masood, N.; Alkhadher, S.A.A.; Abootalebi-Jahromi, F. (2014). Baseline Distributions and Sources of Polycyclic Aromatic Hydrocarbons (PAHs) in the Surface Sediments from the Prai and Malacca Rivers, Peninsular Malaysia. *Marine Pollution Bulletin*, *88*, 366–372. https://doi.org/10.1016/j.marpolbul.2014.08.014.

[20] Retnam, A.; Zakaria, M.P.; Juahir, H.; Aris, A.Z.; Zali, M.A.; Kasim, M.F. (2013). Chemometric Techniques in Distribution, Characterisation and Source Apportionment of Polycyclic Aromatic Hydrocarbons (PAHs) in Aquaculture Sediments in Malaysia. *Marine Pollution Bulletin*, *69*, 55–66. https://doi.org/10.1016/j.marpolbul.2013.01.009.

[21] Vaezzadeh, V.; Zakaria, M.P.; Shau-Hwai, T.; Ibrahim, Z.Z.; Mustafa, S.; Keshavarzifard, M.; Magam, S.M.; Alkhadher, S.A.A. (2015). Source Type Evaluation of Polycyclic Aromatic Hydrocarbons (PAHs) in Surface Sediments from the Muar River and Pulau Merambong, Peninsular Malaysia. *Environment Forensics*, *16*, 135–142. https://doi.org/10.1080/15275922.2015.1022839.

[22] Leech, C.; Tighe, M.K.; Pereg, L.; Winter, G.; McMillan, M.; Esmaeili, A.; Wilson, S.C. (2020). Bioaccessibility Constrains the Co-Composting Bioremediation of Field Aged PAH Contaminated Soils. *International Biodeterioration & Biodegradation*, *149*, 104922. https://doi.org/10.1016/j.ibiod.2020.104922.

[23] Medina, R.; Fernández-González, A.J.; García-Rodríguez, F.M.; Villadas, P.J.; Rosso, J.A.; Fernández-López, M.; del Panno, M.T. (2020). Exploring the Effect of Composting Technologies on the Recovery of Hydrocarbon Contaminated Soil Post Chemical Oxidative Treatment. *Applied Soil Ecology*, *150*, 103459. https://doi.org/10.1016/j.apsoil.2019.103459.

[24] Cao, W.; Yuan, J.; Geng, S.; Zou, J.; Dou, J.; Fan, F. (2023). Oxygenated and Nitrated Polycyclic Aromatic Hydrocarbons: Sources, Quantification, Incidence, Toxicity, and Fate in Soil—A Review Study. *Processes*, *11*, 52. https://doi.org/10.3390/pr11010052.

[25] Sayara, T.; Sarrà, M.; Sánchez, A. (2010). Effects of Compost Stability and Contaminant Concentration on the Bioremediation of PAHs-Contaminated Soil through Composting. *Journal of Hazardous Materials*, *179*, 999–1006. https://doi.org/10.1016/j.jhazmat.2010.03.104.

[26] Han, X.; Hu, H.; Shi, X.; Zhang, L.; He, J. (2017). Effects of Different Agricultural Wastes on the Dissipation of PAHs and the PAH-Degrading Genes in a PAH-Contaminated Soil. *Chemosphere*, *172*, 286–293. https://doi.org/10.1016/j.chemosphere.2017.01.012.

[27] Li, X.; Zhang, S.; Guo, R.; Xiao, X.; Liu, B.; Mahmoud, R.K.; Abukhadra, M.R.; Qu, R.; Wang, Z. (2024). Transformation and Degradation of PAH Mixture in Contaminated Sites: Clarifying Their Interactions with Native Soil Organisms. *Toxics*, *12*, 361. https://doi.org/10.3390/toxics12050361.

[28] Lukić, B.; Huguenot, D.; Panico, A.; Fabbricino, M.; van Hullebusch, E.D.; Esposito, G. (2016). Importance of Organic Amendment Characteristics on Bioremediation of PAH-Contaminated Soil. *Environmental Science and Pollution Research*, *23*, 15041–15052. https://doi.org/10.1007/s11356-016-6635-z.

[29] Plaza, C.; Xing, B.; Fernández, J.M.; Senesi, N.; Polo, A. (2009). Binding of Polycyclic Aromatic Hydrocarbons by Humic Acids Formed During Composting. *Environmental Pollution*, *157*, 257–263. https://doi.org/10.1016/j.envpol.2008.07.016.

[30] Staszel, K.; Lasota, J.; Błońska, E. (2022). Soil Organic Matter Fractions in Relation to Root Characteristics of Different Tree Species in Altitude Gradient of Temperate Forest in Carpathian Mountains. *Forests*, *13*, 1656. https://doi.org/10.3390/f13101656.

[31] Li, Y.; Li, Y.; Zhang, Y.; Wu, B.; Zhou, D.; Peng, H.; Li, F.; Wu, M. (2024). Conversion of Natural Soil to Paddy Promotes Soil Organic Matter Degradation in Small-Particle Fractions: δ13C and Lipid Biomarker Evidence. *Agronomy*, *14*, 818. https://doi.org/10.3390/agronomy14040818.

[32] Vaverková, M.D.; Adamcová, D.; Winkler, J.; Koda, E.; Petrželová, L.; Maxianová, A. (2020). Alternative Method of Composting on a Reclaimed Municipal Waste Landfill in Accordance with the Circular Economy: Benefits and Risks. *Science of The Total Environment*, *723*, 137971. https://doi.org/10.1016/j.scitotenv.2020.137971.

[33] Ayilara, M.S.; Olanrewaju, O.S.; Babalola, O.O.; Odeyemi, O. (2020). Waste Management Through Composting: Challenges and Potentials. *Sustainability*, *12*, 4456. https://doi.org/10.3390/su12114456.

[34] Epelde, L.; Jauregi, L.; Urra, J.; Ibarretxe, L.; Romo, J.; Goikoetxea, I.; Garbisu, C. (2018). Characterization of Composted Organic Amendments for Agricultural Use. *Frontiers in Sustainable Food Systems*, *2*, 44. https://doi.org/10.3389/fsufs.2018.00044

[35] Ahmed, T.; Noman, M.; Qi, Y.; Shahid, M.; Hussain, S.; Masood, H.A.; Xu, L.; Ali, H.M.; Negm, S.; El-Kott, A.F.; et al. (2023). Fertilization of Microbial Composts: A Technology for Improving Stress Resilience in Plants. *Plants*, *12*, 3550. https://doi.org/10.3390/plants12203550.

[36] Yao, X.; Wang, X.; Zheng, S.; Zhao, H.; Ju, J.; Wang, C. (2024). Research on Composting of Garden Waste and Its Application in Cultivation Substrates. *Sustainability*, *16*, 8216. https://doi.org/10.3390/su16188216

[37] Yin, Y.; Yang, C.; Li, M.; Zheng, Y.; Ge, C.; Gu, J.; Li, H.; Duan, M.; Wang, X.; Chen, R. (2021). Research Progress and Prospects for Using Biochar to Mitigate Greenhouse Gas Emissions During Composting: A Review. *Science of The Total Environment*, *798*, 149294. https://doi.org/10.1016/j.scitotenv.2021.149294.

[38] Yasmin, N.; Jamuda, M.; Panda, A.K.; Samal, K.; Nayak, J.K. (2022). Emission of Greenhouse Gases (GHGs) During Composting and Vermicomposting: Measurement, Mitigation, and Perspectives. *Energy Nexus*, *7*, 100092. https://doi.org/10.1016/j.nexus.2022.100092.

[39] Ren, X.; Zeng, G.; Tang, L.; Wang, J.; Wan, J.; Wang, J.; Deng, Y.; Liu, Y.; Peng, B. (2018). The Potential Impact on the Biodegradation of Organic Pollutants from Composting Technology for Soil Remediation. *Waste Management*, *72*, 138–149. https://doi.org/10.1016/j.wasman.2017.11.032.

[40] Onwosi, C.O.; Igbokwe, V.C.; Odimba, J.N.; Eke, I.E.; Nwankwoala, M.O.; Iroh, I.N.; Ezeogu, L.I. (2017). Composting Technology in Waste Stabilization: On the Methods, Challenges and

Future Prospects. *Journal of Environmental Management*, *190*, 140–157. https://doi.org/10.1016/j.jenvman.2016.12.051.

[41] Yaman, C. (2024). A Review on the Process of Greenhouse Gas Inventory Preparation and Proposed Mitigation Measures for Reducing Carbon Footprint. *Gases*, *4*, 18–40. https://doi.org/10.3390/gases4010002.

[42] Clavier, C.; Meftah, M.; Sarkissian, A.; Romand, F.; Hembise Fanton d'Andon, O.; Mangin, A.; Bekki, S.; Dahoo, P.-R.; Galopeau, P.; Lefèvre, F.; et al. (2024). Assessing Greenhouse Gas Monitoring Capabilities Using SolAtmos End-to-End Simulator: Application to the Uvsq-Sat NG Mission. *Remote Sensing*, *16*, 1442. https://doi.org/10.3390/rs16081442.