Industrial and Domestic Waste Management

Review
Volume 3(2), 2023, 103–114
https://doi.org/10.53623/idwm.v3i2.338

Bioremediation of Pesticide-Contaminated Soils through Composting: Mechanisms, Factors, and Prospects

Wei Lin Wong[1], Monmi Pangging[2], Rubiyatno[3]*

[1]Department of Civil and Construction Engineering, Curtin University, CDT 250, Miri, Malaysia
[2]College of Medicine, National Cheng Kung University Tainan, 701, Taiwan (R.O.C).
[3]University of Yamanashi, Yamanashi 400-8511, Japan.

*Correspondence: yrubi@yamanashi.ac.jp

SUBMITTED: 24 October 2023; REVISED: 27 November 2023; ACCEPTED: 30 November 2023

ABSTRACT: Pesticide contamination of soils poses a significant environmental and agricultural challenge on a global scale, with escalating pesticide consumption in various regions. Composting has emerged as a cost-effective and sustainable bioremediation method for pesticide-contaminated soils. This review article delves into the mechanisms, factors influencing efficiency, and the pros and cons of composting as a strategy to address pesticide pollution in soils. Pesticides enter soil environments through both point sources, such as spillage from storage or disposal areas, and non-point sources, including intensive agricultural use and household applications. The physical and chemical characteristics of pesticides, coupled with soil factors like permeability and particle size, influence their fate and behavior in soils. Composting, as a bioremediation method, offers several advantages, including complete destruction of pesticide compounds through microbial degradation, transforming them into less hazardous products. Key factors affecting composting efficiency include nutrient availability, particle size, temperature, pH, oxygen, and moisture content, all crucial for microorganism growth and pesticide degradation. This article underscores the importance of maintaining optimal conditions for these factors to ensure the high performance and efficiency of pesticide degradation during composting. It also discusses the potential drawbacks of this method. Composting proves to be a promising and eco-friendly approach for remediating pesticide-contaminated soils, addressing both environmental concerns and the need for sustainable agricultural practices.

KEYWORDS: Composting; bioremediation; pesticide; contaminated soil

1. Introduction

It is estimated that the global consumption of pesticide is around 4.19 million metric tonnes in year 2019, where China consumes the most pesticides accounting for 1.76 million metric tons [1]. The pesticides consumption in Southeast Asian countries also has escalated as reported by WHO. The function of pesticides is to control and manage pest and the diseases for protection of agricultural crops. The use of pesticide in the agricultural sector is significant to ensure high yield and production of agricultural crops in meeting the growing food demand due to booming populations. The classification of pesticides can be based on the target species which are herbicides, fungicides and insecticides. Another classification method of the pesticides is on the basis of chemical composition including organochlorine, organophosphate, pyrethroids and carbamates [1]. The widespread application of pesticides in the agricultural sector has caused severe agricultural soil contamination and the persistence of the pesticides in the environment especially the soil environment has raised great concerns due to the toxicity induced by the pesticides. Exposure to pesticides can pose significant health risk to humans such as damage of liver and kidney, problems with nervous systema and diarrhea [2]. Therefore, bioremediation has been proposed as remediation method for soils contaminated by pesticides as this method is more sustainable involving the biodegradation of pesticides in the soil by the microorganisms and can achieve destruction of the organic pollutants through transforming into less hazardous product [3]. Composting is one of the bioremediation methods of the pesticide-contaminated soils due to its cost-effectiveness and sustainability. The mechanism of composting in degrading the pesticides in the contaminated soils and the factors affecting the efficiency of the composting process as well as the pros and cons of composting were discussed in this study.

2. Occurrence of Pesticides

The source of pesticides in the soil environment includes point sources and non-point sources. The point source of the pesticides can be the spillage of pesticides from the storage area or disposal area of pesticides. The intensive use of pesticides in the agricultural activities by the farmers for protection of agricultural crops and enhancing the production and yield of agricultural crops. Apart from agricultural use, pesticides are also applied at the households to control and manage the pest in the gardening at home [4]. Figure 1 showed the classification of the pesticides on the basis of chemical composition. The occurrence of pesticides in the agricultural soils has been reported in several studies as discussed below [5–7]. Based on the study by Pan et al. [6], there is detection of 15 OCPs in the agricultural soils sampled from Yantze River Delta, which is dominated by DDTs with highest mean concentration of 56.2 ng/g and DDT concentration in some of the soil samples exceed the standards limits of 100 ng/g under Environmental Quality Standard for Soil. HCH concentration in the sampled soil is well below the standard limits of 50 ng/g, High concentrations of OCPs discovered in the soil samples from Taicang, Jiangsu can be attributed to the pesticides factories located in the vicinity of the sampling site. The dominance of DDTs and HCHs is also demonstrated by Tang et al. [7] in investigating OCPs in the soils of Ningbo, with average concentration of 55.6 ± 94.8 ng/g and 4.6 ± 2.9ng/g. Organochlorine pesticides are detected in the agricultural soils in Shanghai with dominance of DDTs, HCBs, heptachlor epoxide, and HCHs as reported by Jiang et al. 2009, and intensive agricultural activities with increased use of the pesticides leads to higher concentration of DDTs and HCHs in the south region of Shanghai. There is low level pollution of OCPs in the soil samples based on the China environmental quality standards for soils in the study by previous study [7]. Similar to these studies, Huang et al. 2014 also showed that DDTs is predominant with average concentration of 12.52 ng/g in the topsoil from arid region in China. The pharmaceutical and petrochemical factories nearby the sampling site contribute to high concentration of DDTs in the soils. Higher concentration of HCBs and endosulfan is observed in urban areas compared to rural areas due to the chemical industries present at the area. Sruthi et al. reported the occurrence of 16 OCPs in the paddy soils collected from Kuttanad agroecosystem in India and the concentration of the detected OCPs falls below the permissible limit set by USEPA [8]. Degrendele et al. has discovered 9 types of current use pesticides which is dominated by chlorpyrifos, carbaryl and tebuconazole in the agricultural soils in South Africa [5].

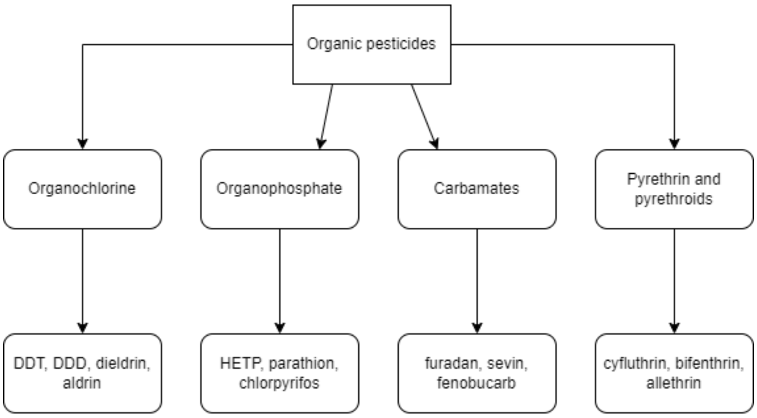

Figure 1. Classification of pesticides.

The occurrence of pesticides in the soil is also reported in the studies in Malaysia and most of the studies investigated the occurrence of pesticides in surface water in Malaysia [9–12]. Farina et al. [10] have investigated the residual concentration of organochlorine pesticides, organophosphorus pesticides and pyrethroids pesticides in the agricultural soils in Cameron Highlands. Elfikrie et al. [9] reported the presence of 11 type of pesticides in the surface water of Tengi River Basin in Selangor, with detection of propiconazole and pymetrozine where the respective concentration is 4493.1 ng/l and 1.3 ng/l. Organophosphorus pesticides including quinalphos, diazinon and chlorpyrifos is discovered in the surface water of Linggi River in Negeri Sembilan with average concentration of 0.0362 µg/l, 0.0328 µg/l, and 0.0275 µg/lwhich are sourced from the application of the pesticides at the agricultural farm, palm oil plantation as well as residential area. Wee et al. also detected organophosphorus pesticides including chlorpyrifos, quinalphos and diazinon in Langat River Basin with average concentration of 0.0202 µg/l, 0.0178 µg/l and 0.0094 ug/l [11]. Table 1 summarizes the studies on the occurrence of pesticide compounds in the agricultural soils and surface water in different regions.

Table 1. Occurrence of pesticides in different regions.

Location	Environment	Dominant pesticide compounds	Average concentration (ng/g; ng/l)	References
Yangtze River Delta, China	Agricultural soils	DDT	56.2	[6]
Ningbo, China	Agricultural soils	DDT	55.6 ± 94.8	[7]
		HCH	4.6 ± 2.9	
Three Gorges Dam, China	Agricultural soils	DDT	1.8	[13]
		HCH	1.27	
Shanghai, China	Agricultural soils	DDT	21.41	[14]
		HCH	2.41	
		HCB	0.64	
Northwest China	Agricultural soils	DDT	12.52	[15]
Kuttanad agroecosystem, India	Agricultural soils	BHC	0.01–9.55	[8]
South Africa	Agricultural soils	Chlorpyrifos	<63.6	[5]
Tengi River Basin, Malaysia	Surface water	Propiconazole	4493.1	[9]
Linggi River, Malaysia	Surface water	Quinalphos	36.2	[12]
Langat River Basin, malaysia	Surface water	Chlorpyrifos	20.2	[11]

3. Fate of Pesticides

The physical and chemical characteristics of the pesticides as well as the soil factors can influence the fate and behaviour of pesticides in the soils. The diffusion rate of pesticides in the soils is slower when the permeability of the soil is lower and the soil particles size is finer with a high surface to volume ratio, hence facilitating the sorption of pesticides to the soil particles. The adsorption of pesticides to the soil particles is enhanced through the cyclic process of wetting and drying under influence of climate conditions [16]. The applied pesticides on the plants or agricultural crops can be absorbed by the plants or remained on the soils without the uptake by the plants. There are three processes governing the fate and contamination of pesticides in the soil environment which are transport, transfer and transformation. The migration of the pesticides from the original sources to other points in the soils is known as the transport process of pesticides. The pesticides are normally sprayed on the plants or crops and the evaporation of the pesticides from the surface of soils or plants can occur. The pesticides in the soil either undergoes sorption to the soil particles or undergoes leaching from the soil matrix to the groundwater below. The transfer of pesticides occurs in different forms and phases. The rainwater infiltration causes the percolation and leaching of the pesticides that are soluble through the soils and to the groundwater below during the rainfall and precipitation events. The pesticides present on the soil layers can be transported to the nearby surface water bodies through erosion and surface runoff. The volatilization of the pesticides into the atmosphere can also occur and the volatilized pesticides can return to the soil environment through precipitation. Another fate of the pesticides in the soil environment is the transformation of the pesticides including chemical degradation, photochemical degradation and microbial degradation. Chemical degradation involves the hydrolysis and redox reaction of pesticides while photochemical degradation of pesticides refers to the degradation of pesticides under exposure to ultraviolet radiation. The pesticides can be degraded into carbon dioxide and water during mineralization, and other compounds during co-metabolism [4, 16]. Figure 2 showed the fate of pesticides in the environment.

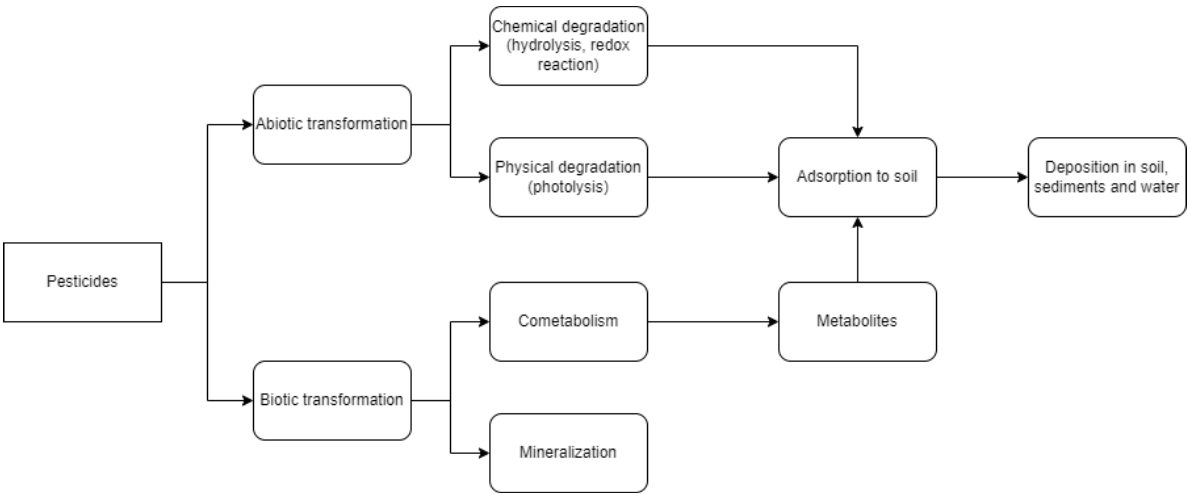

Figure 2. Fate of pesticides.

4. Mechanism of composting

Composting is one of the bioremediation methods of the soil contaminated by organic pollutants including pesticide. The optimum temperature for the composting process is between

54 to 65°C which is under thermotropic conditions to achieve high degradation efficiency of the organic pollutants [17]. The process of composting can be classified into four consecutive stages namely mesophilic, thermophilic, cooling and maturation as shown in Figure 3. The organic matter is utilized as carbon and nutrient source by the microorganisms and the increase of temperature exceeding the ambient temperature is observed during mesophilic stage with temperature increases to 55°C. The high temperature when mesophilic phase ended, and thermophilic stage started indicating high activity of microbes which are mainly thermophilic microbes. The biodegradation of the cellulose commences during the thermophilic stage. The decline of temperature occurs when progressing to the cooling and maturation stage as there is less nutrient source which results in reduction of the microbial activity. The cooling phase is also dominated by mesophilic microbes, with the detection of macrofungi where the complex organic compounds is utilized as sources of nutrients. The stability and maturity of the compost is demonstrated in the maturation stage [18].

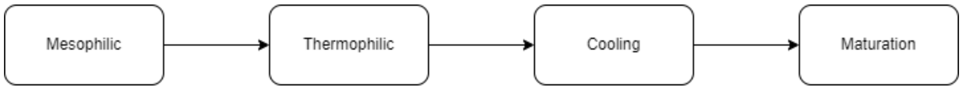

Figure 3. Four stages of composting process.

The mechanism of composting in remediating the pesticides in soil include organic matter adsorption and microbial degradation of pesticides. There are two strategies for the degradation of pesticides using composting method which are direct composting of the pesticides-contaminated soils and the addition of compost [19]. Composting is one of the ex-situ bioremediation methods of pesticides where organic amendment such as straw, leaves, biochar, manure, wood chips and other agricultural wastes is added and mixed with the soils contaminated by pesticides. The addition of organic amendment can facilitate the population growth of microbes including bacteria and fungi by providing additional carbon source for the microbes, resulting in enhanced degradation of the pesticide compounds present in the contaminated soils Biochar is commonly used as organic amendments in composting process to facilitate the degradation of pesticides as biochar can provide a bigger adsorption surface area for pesticides due to the porous structure, and also act as carbon source for the growth of the microbes [20]. Aziz et al. [21] investigated the chlorpyrifos degradation can be enhanced through addition of compost and biochar in the soils as organic amendments with higher activities of enzymes demonstrated. Rubio-Bellido et al. reported increased mineralization of diuron through the addition of urban solid residues compost and sewage sludge compost [22]. Sadiq et al. [23] investigated the bioremediation of soils contaminated by hexachlorocyclohexane (HCH) by applying spent mushroom compost constituted by *Pleurotus ostreatus* and demonstrated the decrease of the HCH isomers from degradation by the lignolytic enzymes. Previous study also adopted the spent mushroom waste of *Pleurotus ostreatus* to degrade DDT 1,1,1-trichloro-2,2-bis (4-chlorophenyl) ethane [24].

The pathway of microbial degradation of organic pollutants including pesticides are metabolism and mineralization, co-metabolism and no-specific oxidation. The metabolism of organic contaminants occurs within the cell. The organic contaminants are utilized as carbon and energy source by microorganisms hence degrading the contaminants which produces carbon dioxide and water as final products of degradation, at the same time promoting the growth of the microbes. Under the co-metabolism process, there is simultaneous degradation and metabolism of the organic contaminants by enzymes and other carbon compounds, leading to the production and accumulation of metabolites. There is no growth of microbes since the organic contaminants is not utilized as carbon and energy source by the microbes. The oxidation and degradation of the organic contaminants which happens outside the cell refers to non-specific oxidation [25].

The bioremediation of the pesticides presents in the soils using composting involves the degradation of pesticides compounds into metabolites and products that are less toxic or the mineralization of pesticides into carbon dioxide and water by microorganisms including bacteria and fungi. The microbes utilize the pesticides compounds as carbon and energy source to carry out metabolic activities during the degradation process of pesticides which is catalyzed by the enzymes produced by the microbes such as oxygenase, peroxidase and hydrolase. There are three stages of the pesticide degradation under microbial action where the first stage is the pesticides are oxidized, reduced or hydrolysed into products which are less hazardous and more soluble in water. These products are further transformed into sugar and amino acids which are eventually converted into secondary compounds with lower toxicity. During the oxidation of pesticides, the electrons are transferred to oxygen acting as final electron acceptor under the catalysis by oxygenase or laccase. The reduction of the pesticides is catalyzed by nitroreductase. The pesticides compounds are breakdown into smaller compounds through the addition of hydrogen for bond cleavage under the catalysis by esterase, lipase and cellulase [20, 26].

The microbes responsible for degrading pesticides play a crucial role in breaking down these substances in soil during the composting process. Generally, the involved microorganisms include actinomycetes, non-actinomycetes bacteria (NAB), and fungi. Bacteria, particularly *Bacillus aryabhattai*, exhibi high tolerance and resistance to the environmental extremes, showcasing significant capabilities in the degradation of pesticides. Pailan et al. identified *Bacillus aryabhattai* sourced from agricultural soil in India as capable of degrading chlorpyrifos and parathion [27]. Chlorpyrifos was degraded by *Pseudomonas* sp. including *Pseudomonas* sp. and *Enterobacter sp*. [28, 29]. Chlorpyrifos can also be degraded by *Streptomyces* sp. which are *Streptomyces olivochomogenes* and *Streptomyces chattanoogensis* from the contaminated soil in Chile in the study by [30]. *Streptomyces* sp. is also used to degrade lindane as reported by Fuentes et al. [31]. Endosulfan can be degraded and detoxified by which utilizes endosulfan as source of carbon, energy and sulfur according to the study [32]. The degradation of the pesticides can be achieved using fungi with the extracellular ligninolytic enzymes produced by fungi such as laccase, lignin peroxidase and manganese peroxidase. Xiao et al. [33] had investigated the degradation of DDTs utilizing white rot fungi which are *Phlebia lindtneri* and *Phlebia brevispora*. Palmer-Brown et al. 2018 demonstrated the biodegradation of cyhalothrin by Cunninghamella elegans and the degradation of 3-phenoxybenzoic acid is performed by the fungus *Aspergillus oryzae* [34].

4.1. Factors and parameters affecting the composting process.

Figure 4 showed the factors affecting the efficiency of the composting process. One of the main parameters affecting the composting process is the nutrients including macronutrients and micronutrients available in the composting materials. The substrate of the microorganisms is the nutrient sources where microbes utilize carbon and nitrogen for energy and growth of the cell respectively. The important indicator for the proportion of nutrients in the compost is C/N ratio. The C/N ratio of the mixture of composting materials can be increased through the addition of bulking agents such as straws, leaves, manure, wood chips and agricultural waste which provides additional source of carbon and minimizes the loss of ammonia through volatilization. On the other hand, the reduction of C/N ratio is enabled through addition of ammonium fertilizers. In terms of particle size of the composting substances, particles with smaller size can offer a larger surface area for degradation by microbes as well as enhancing the homogeneousness of composting materials mixing, hence improving the efficiency of degradation [18].

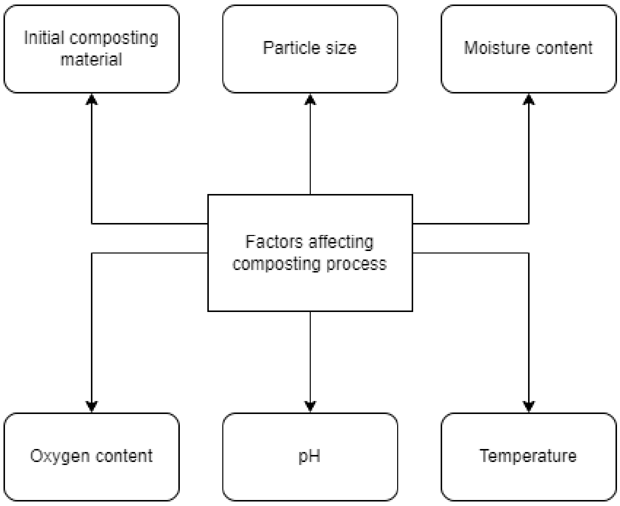

Figure 4. Factors affecting the composting process.

Adequate oxygen supply is crucial for the composting degradation of pesticides, especially in aerobic conditions where microbial metabolic activities rely on oxygen. Aeration, in addition to turning the compost, plays a key role in providing the necessary oxygen to the compost system. Inadequate aeration can lead to anaerobic conditions, while excessive aeration may result in the drying of compost. Maintaining sufficient moisture content is essential to enhance microbial access to nutrients in the composting system. Both low and high levels of moisture content can lead to issues, causing compost drying and inducing anaerobic conditions, respectively. Maintaining an optimal pH range between 5.5 and 8.0 is crucial for effective composting. Bacteria favor a neutral pH, whereas fungi thrive in acidic conditions. Temperature is also a critical factor; elevated temperatures can lead to compost drying and reduced microbial diversity, impeding the composting process. However, thermophiles remain unaffected by high temperatures [18].

4.2. Advantages and disadvantages of composting.

There are several advantages of composting in biodegrading the organic contaminants including pesticides. The main advantages of adopting composting for remediation of pesticide-contaminated soils is complete destruction of the pesticides compounds where pesticides are transformed into less hazardous products under the action of microorganism, instead of being transferred and removed from one place to another through physical and chemical remediation methods. In addition, composting method also enable remediation and treatment of high amount of soils contaminated by pesticides [35]. The diversity of microorganisms present in the composting system enables complete metabolism and mineralization of the organic pollutants hence improving the degradation efficiency of the pesticides [18]. Another advantage of composting method is the sustainability with the utilization of organic waste as compost. Other benefits of composting include improvement of the structure of the soils, the aeration level and retention capacity of water within the soils [36].

The main limitation of the composting method is that the degradation efficiency of pesticides can be affected by several factors including temperature, pH and oxygen as these factors are essential to promote the population growth of the microbes as well as the metabolic activities of the microbes The remediation of pesticides is also relatively slower using bioremediation compared to other remediation methods. The metabolites produced from the degradation of pesticides may induce a higher toxicity in comparison with the pesticides compound. Another concern of the composting method is the potential disruption to the existing environment of the site [37]. Moreover, the operational cost of composting can be higher compared to other in-situ bioremediation method with the contaminate soils being excavated and transported to other places for treatment [35].

There are several beneficial impacts of composting towards the environment and society. The remediation of the soils contaminated by pesticides, heavy metals or other organic contaminants through adding compost to the contaminated soils can promote the degradation of the contaminants. The use of organic waste as compost can achieve sustainable management of organic waste through reducing the waste to be disposed, as well as saving cost from the utilization of organic waste. The application of compost on the agricultural soils can lead to enhancement of the fertility of the soil hence consequently increasing the production and yield of agricultural crops. Erosion control also can be achieved through compost application where the compost added can cause alteration of the structure of the soils and increased stability of the soil aggregates, and the control of erosion can improve the fertility of the soil through reducing loss of nutrients such as nitrogen and phosphorus. Other beneficial impact of composting is plant disease control [38].

5. Conclusion

It can be concluded that composting method which is classified as bioremediation has high potential in remediation and treatment of pesticides compound in the contaminated soils. The remediation of pesticides during composting involves microbial degradation of pesticides where the microbes utilize the pesticide compounds as carbon and energy source and degrade the contaminant at the same time. The factors affecting the efficiency of composting process include available nutrients in the composting material, particle size, temperature, pH, oxygen and moisture content, and some of these factors is associated with the growth and survival of microbes hence it is significant to maintain the optimum condition of these factor to ensure high degradation performance and efficiency of pesticides. The advantages and disadvantages of the composting method is also discussed in this study. Most of the current studies on adoption of composting to biodegrade the pesticides in the contaminated soils are performed in lab scale. Hence future studies on the implementation of composting methods on field scale is required to determine the actual effectiveness of composting in degrading the pesticide compounds present in the contaminated soil. The microorganisms involved in the thermophilic stage and other phase of the composting process is still not known much. Another issue is the fate and associated risks of nonextractable bound residue of pesticides during composting process. Future research on the compost stability as well as microorganism type and activities during every composting phase should be conducted to ensure higher remediation efficiency of pesticides in the contaminated soils adopting composting method. It is also significant to investigate the bioavailability of the pesticides in the contaminated soils to determine the pesticides available to be consumed and degraded by the microbes.

Acknowledgments

The authors thank Curtin University Malaysia for facilitating this study. Collaboration from National Cheng Kung University Taiwan and University of Yamanashi Japan are highly appreciated.

Competing Interest

All authors declare no competing interest.

References

[1] Pathak, V.M.; Verma, V.K.; Rawat, B.S.; Kaur, B.; Babu, N.; Sharma, A.; Dewali, S.; Yadav, M.; Kumari, R.; Singh, S.; Mohapatra, A.; Pandey, V.; Rana, N.; Cunill, J.M. (2022). Current status of pesticide effects on environment, human health and it's eco-friendly management as bioremediation: A comprehensive review. *Frontiers in Microbiology, 13,* 962619. https://doi.org/10.3389/fmicb.2022.962619.

[2] Odukkathil, G.; Vasudevan, N. (2013). Toxicity and bioremediation of pesticides in agricultural soil. *Reviews in Environmental Science and Bio/Technology, 12*, 421–444. https://doi.org/10.1007/s11157-013-9320-4.

[3] Raffa, C.M.; Chiampo, F. (2021). Bioremediation of Agricultural Soils Polluted with Pesticides: A Review. *Bioengineering, 8,* 92. https://doi.org/10.3390/bioengineering8070092.

[4] Syafrudin, M.; Kristanti, R.A.; Yuniarto, A.; Hadibarata, T.; Rhee, J.; Al-Onazi, W.A.; Algarni, T. S.; Almarri, A.H.; Al-Mohaimeed, A.M. (2021). Pesticides in Drinking Water-A Review. *International Journal of Environmental Research and Public Health*, *18*, 468. https://doi.org/10.3390/ijerph18020468.

[5] Degrendele, C.; Klánová, J.; Prokeš, R.; Příbylová, P.; Šenk, P.; Šudoma, M.; Röösli, M.; Dalvie, M. A.; Fuhrimann, S. (2022). Current use pesticides in soil and air from two agricultural sites in South Africa: Implications for environmental fate and human exposure. *Science of The Total Environment, 807,* 150455. https://doi.org/10.1016/j.scitotenv.2021.150455.

[6] Pan, L.; Sun, J.; Li, Z.; Zhan, Y.; Xu, S.; Zhu, L. (2018). Organophosphate pesticide in agricultural soils from the Yangtze River Delta of China: concentration, distribution, and risk assessment. *Environmental Science and Pollution Research, 25*, 4–11. https://doi.org/10.1007/s11356-016-7664-3.

[7] Tang, J.; Feng, J.; Li, G.; Liang, M.; Wang, R.; Cai, C. (2018). Occurrence and possible sources of organochlorine pesticides in soils of Ningbo, East China. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 109*, 495–500. https://doi.org/10.1017/S1755691018000506.

[8] Sruthi, S.N.; Shyleshchandran, M.S.; Sunil; Mathew, P.; Ramasamy, E.V. (2017). Contamination from organochlorine pesticides (OCPs) in agricultural soils of Kuttanad agroecosystem in India and related potential health risk. *Environmental Science Pollution Research, 24*, 969–978 . https://doi.org/10.1007/s11356-016-7834-3

[9] Elfikrie, N.; Ho, Y. bin; Zaidon, S.Z.; Juahir, H.; Tan, E.S.S. (2020). Occurrence of pesticides in surface water, pesticides removal efficiency in drinking water treatment plant and potential health risk to consumers in Tengi River Basin, Malaysia. *Science of The Total Environment*, *712*, 136540.

https://doi.org/10.1016/j.scitotenv.2020.136540.
[10] Farina, Y. (2016). Pesticides Residues In Agricultural Soils And Its Health Assessment For Humans In Cameron Highlands, Malaysia. *Malaysian Journal of Analytical Science*, *20*, 1346–1358. https://doi.org/10.17576/mjas-2016-2006-13.
[11] Wee, S.Y.; Omar, T.F.T.; Aris, A.Z.; Lee, Y. (2016). Surface Water Organophosphorus Pesticides Concentration and Distribution in the Langat River, Selangor, Malaysia. *Exposure and Health, 8,* 497–511. https://doi.org/10.1007/s12403-016-0214-x.
[12] Zainuddin, A.H.; Wee, S.Y.; Aris, A.Z. (2020). Occurrence and potential risk of organophosphorus pesticides in urbanised Linggi River, Negeri Sembilan, Malaysia. *Environmental Geochemistry and Health, 42*, 3703–3715. https://doi.org/10.1007/s10653-020-00604-4.
[13] Liu, M.; Yang, Y.; Yun, X.; Zhang, M.; Wang, J. (2015). Occurrence and assessment of organochlorine pesticides in the agricultural topsoil of Three Gorges Dam region, China. *Environmental Earth Science, 74,* 5001–5008, https://doi.org/10.1007/s12665-015-4512-6.
[14] Jiang, Y.F.; Wang, X.T.; Jia, Y.; Wang, F.; Wu, M.H.; Sheng, G.Y.; Fu, J.M. (2009). Occurrence, distribution and possible sources of organochlorine pesticides in agricultural soil of Shanghai, China. *Journal of Hazardous Materials, 170*, 989–997. https://doi.org/10.1016/j.jhazmat.2009.05.082.
[15] Huang, T.; Guo, Q.; Tian, H.; Mao, X.; Ding, Z.; Zhang, G.; Li, J.; Ma, J.; Gao, H. (2014). Assessing spatial distribution, sources, and human health risk of organochlorine pesticide residues in the soils of arid and semiarid areas of northwest China. *Environmental Science and Pollution Research, 21*, 6124–6135 https://doi.org/10.1007/s11356-014-2505-8.
[16] Eevers, N.; White, J. C.; Vangronsveld, J.; Weyens, N. (2017). Bio- and Phytoremediation of Pesticide-Contaminated Environments. Advances in Botanical Research, 83, 277–318. https://doi.org/10.1016/bs.abr.2017.01.001.
[17] Karimi, H.; Mahdavi, S.; Asgari Lajayer, B.; Moghiseh, E.; Rajput, V.D.; Minkina, T.; Astatkie, T. (2022). Insights on the bioremediation technologies for pesticide-contaminated soils. *Environmental Geochemistry and Health, 44*, 1329–1354. https://doi.org/10.1007/s10653-021-01081-z.
[18] Lin, C.; Cheruiyot, N.K.; Bui, X.T.; Ngo, H.H. (2022). Composting and its application in bioremediation of organic contaminants. *Bioengineered, 13*, 1073–1089. https://doi.org/10.1080/21655979.2021.2017624.
[19] Chen, M.; Xu, P.; Zeng, G.; Yang, C.; Huang, D.; Zhang, J. (2015). Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: Applications, microbes and future research needs. *Biotechnology Advances, 33*, 745–755. https://doi.org/10.1016/j.biotechadv.2015.05.003.
[20] Raffa, C. M.; Chiampo, F. (2021). Bioremediation of Agricultural Soils Polluted with Pesticides: A Review. *Bioengineering, 8,* 92. https://doi.org/10.3390/bioengineering8070092.
[21] Aziz, H.; Wang, X.; Murtaza, G.; Ashar, A.; Hussain, S.; Abid, M.; Murtaza, B.; Saleem, M.H.; Fiaz, S.; Ali, S. (2021). Evaluation of Compost and Biochar to Mitigate Chlorpyrifos Pollution in Soil and Their Effect on Soil Enzyme Dynamics. *Sustainability, 13,* 9695. https://doi.org/10.3390/su13179695.
[22] Rubio-Bellido, M.; Madrid, F.; Morillo, E.; Villaverde, J. (2015). Assisted attenuation of a soil contaminated by diuron using hydroxypropyl-β-cyclodextrin and organic amendments. *Science of The Total Environment, 502,* 699–705. https://doi.org/10.1016/j.scitotenv.2014.09.052.
[23] Sadiq, S.; Mahmood-ul-Hassan, M.; Ahad, K.; Nazir, S. (2018). Bioremediation of hexachlorocyclohexane (HCH) in soil using spent mushroom compost of *Pleurotus ostreatus*. *Bioremediation Journal, 22,* 126–135. https://doi.org/10.1080/10889868.2018.1516615.
[24] Purnomo, A. S.; Mori, T.; Kamei, I.; Nishii, T.; Kondo, R. (2010). Application of mushroom waste medium from *Pleurotus ostreatus* for bioremediation of DDT-contaminated soil. *International*

Biodeterioration & Biodegradation, *64*, 397–402. https://doi.org/10.1016/j.ibiod.2010.04.007.

[25] Lhotský, O.; Covino, S.; Cajthaml, T. (2020). Composting Practices for the Remediation of Matrices Contaminated by Recalcitrant Organic Pollutants. In Advanced Nano-Bio Technologies for Water and Soil Treatment. Applied Environmental Science and Engineering for a Sustainable Future; Filip, J., Cajthaml, T., Najmanová, P., Černík, M., Zbořil, R., Eds.; Springer: Cham, Swithzerland. https://doi.org/10.1007/978-3-030-29840-1_23.

[26] Odukkathil, G.; Vasudevan, N. (2013). Toxicity and bioremediation of pesticides in agricultural soil. *Reviews in Environmental Science and Bio/Technology*, *12*, 421–444. https://doi.org/10.1007/s11157-013-9320-4.

[27] Pailan, S.; Gupta, D.; Apte, S.; Krishnamurthi, S.; Saha, P. (2015). Degradation of organophosphate insecticide by a novel Bacillus aryabhattai strain SanPS1, isolated from soil of agricultural field in Burdwan, West Bengal, India. *International Biodeterioration & Biodegradation*, *103*, 191–195. https://doi.org/10.1016/j.ibiod.2015.05.006.

[28] Awad, N.S.; Sabit, H.H.; Abo-Aba, S.E.M.; Bayoumi, R.A. (2011). Isolation, characterization and fingerprinting of some chlorpyrifos- degrading bacterial strains isolated from Egyptian pesticides-polluted soils. *African Journal of Microbiology Research*, *5*, 2855-2862. https://doi.org/10.5897/ajmr11.044.

[29] Bhagobaty, R.K.; Malik, A. (2008). Utilization of Chlorpyrifos as a Sole Source of Carbon by Bacteria Isolated from Wastewater Irrigated Agricultural Soils in an Industrial Area of Western Uttar Pradesh, India. *Research Journal of Microbiology*, *3*, 293-307.

[30] Briceño, G.; Fuentes, M.S.; Palma, G.; Jorquera, M.A.; Amoroso, M.J.; Diez, M.C. (2012). Chlorpyrifos biodegradation and 3,5,6-trichloro-2-pyridinol production by actinobacteria isolated from soil. *International Biodeterioration & Biodegradation*, *73*, 1–7. https://doi.org/10.1016/J.IBIOD.2012.06.002.

[31] Fuentes, M.S.; Benimeli, C.S.; Cuozzo, S.A.; Amoroso, M.J. (2010). Isolation of pesticide-degrading actinomycetes from a contaminated site: Bacterial growth, removal and dechlorination of organochlorine pesticides. *International Biodeterioration & Biodegradation*, *64*, 434–441. https://doi.org/10.1016/j.ibiod.2010.05.001.

[32] Li, W.; Dai, Y.; Xue, B.; Li, Y.; Peng, X.; Zhang, J.; Yan, Y. (2009). Biodegradation and detoxification of endosulfan in aqueous medium and soil by Achromobacter xylosoxidans strain CS5. *Journal of Hazardous Materials*, *167*, 209–216. https://doi.org/10.1016/j.jhazmat.2008.12.111.

[33] Xiao, P.; Mori, T.; Kamei, I.; Kondo, R. (2011). A novel metabolic pathway for biodegradation of DDT by the white rot fungi, Phlebia lindtneri and Phlebia brevispora. *Biodegradation*, *22*, 859–867. https://doi.org/10.1007/s10532-010-9443-z.

[34] Zhu, Y.; Li, J.; Yao, K.; Zhao, N.; Kang Zhou, &; Hu, X.; Zou, L.; Han, X.; Liu, A.; Liu, S. (2016). Degradation of 3-phenoxybenzoic acid by a filamentous fungus Aspergillus oryzae M-4 strain with self-protection transformation. *Applied Microbiology and Biotechnology*, *100*, 9773–9786. https://doi.org/10.1007/s00253-016-7847-3.

[35] Shekher Giri, B.; Geed, S.; Vikrant, K.; Lee, S.S.; Kim, K.H.; Kumar Kailasa, S.; Vithanage, M.; Chaturvedi, P.; Nath Rai, B.; Sharan Singh, R. (2020). Progress in bioremediation of pesticide residues in the environment. *Environmental Engineering Research*, *26*, 200446–0. https://doi.org/10.4491/eer.2020.446.

[36] Megharaj, M.; Ramakrishnan, B.; Venkateswarlu, K.; Sethunathan, N.; Naidu, R. (2011). Bioremediation approaches for organic pollutants: A critical perspective. *Environment International*, *37*, 1362–1375. https://doi.org/10.1016/j.envint.2011.06.003.

[37] Singh, D.K. (2008). Biodegradation and bioremediation of pesticide in soil: concept, method and recent developments. *Indian Journal of Microbiology*, *48*, 35–40. https://doi.org/10.1007%2Fs12088-008-0004-7.

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