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Exploring the Potential of Composting for Bioremediation of Pesticides in Agricultural Sector

Yu Yan Lau[1], Erika Hernandes[2], Risky Ayu Kristanti[3]*, Yureana Wijayanti[4,5], Mehmet Emre[6]

[1]Faculty of Engineering and Science, Curtin University, CDT250, Miri 98009, Malaysia
[2]Universidad Autónoma Agraria Antonio Narro, Saltillo, 25315, Coahuila, Mexico
[3]Research Center for Oceanography, National Research and Innovation Agency, Jakarta, 14430, Indonesia
[4]Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia, 11480
[5]Environmental Engineering, School of Engineering and Energy, Murdoch University, Western Australia, Australia
[6]Faculty of Science, Dicle University, Diyarbakır, Turkey

*Correspondence: risky.ayu.kristanti@brin.go.id

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ABSTRACT: The rapid expansion of the human population has raised the chemical stress on the environment due to the increased demand of agricultural yields. The use of pesticides is the primary contributor to environmental chemical stress, which is essential for agricultural expansion in order to produce enough food to sustain the burgeoning human population. Pesticide residues in soil have grown to be a subject of rising concern as a result of their high soil retention and potential harm to unintended species. Diverse remediation strategies, such as physical, chemical, and biological, for limiting and getting rid of such contaminants have been put forth to deal with this problem. Bioremediation is one of these techniques, which has been deemed the best for reducing pollution because of its low environmental impact, simplicity of operation and construction. Microorganisms are implemented in this technique to break down and get rid of toxins in the environment or to reduce the toxicity of chemical compounds. This study thoroughly analyses the different composting soil remediation methods, including landfarming, biopiles, and windrows, to reduce and eliminate soil pollution. Although biological treatment is the best option for cleaning up polluted soil, it is still important to evaluate and review the approaches over the long term to determine whether they are effective in the field. It is because the reactivity of the microorganisms is highly dependent on environmental parameters, and the contemporary environment is characterised by unpredictable weather patterns, localised droughts, and temperature fluctuations.

KEYWORDS: Pesticides; sources; fate; impacts; challenges; composting

1. Introduction

Pesticides are chemical compounds used extensively in the agricultural sector and public health safety schemes to combat pests and diseases. They are composed of various chemical molecules designed to target specific pests or disease vectors. In agriculture, pesticides are used to protect crops from pests, weeds, and diseases, ensuring higher yields and safeguarding food production. In public health, pesticides play a crucial role in controlling vectors like mosquitoes, which transmit diseases such as malaria and dengue fever. The typical examples of pesticides are insecticides, fungicides, herbicides, rodenticides, and plant development enhancers or inhibitors. Other uses for these goods include the upkeep and development of non-agriculture regions such as open-air urban green areas and athletic fields. In addition, these chemicals are used in less well-known areas, such as in pet cleansers and construction materials, to get rid of the undesirable species growth [1]. Pesticides evolved into a crucial instrument for crop production enhancement and plant protection with the evolution of agriculture. A wide variety of pesticides must be applied for effective pest management in order to combat pests and boost agricultural output, as the pest infection can cause 45% of the annual food production loss [2]. According to studies, the pesticides consumption has increased approximately 18 folds since 1960, which results at least twice yields of paddy, wheat and cornmeal to cope with the high population demand [3]. An estimated 2 million tonnes of pesticides are utilised per year throughout the world; herbicides represented for 47.5% of this total, then preceded by insecticides (29.5%), fungicides (17.5%), and other pesticides (5.5%). China is the leading contributor in terms of pesticides usage. Although pesticides are crucial to crop productivity and the economy, their extensive usage cause major environmental and health problems [2, 3]. Table 1 has listed the amount of pesticides used in different nations.

Table 1. Quantity of pesticides used in different countries [2].

Country	Pesticides used per year (10^6 kg)
China	1807
India	56
Malaysia	49
Pakistan	28
Thailand	22
Vietnam	192
South Korea	198
Myanmar	6
Nepal	0.45

Inappropriate pesticide usages can pollute the soil and damage creatures that are not the intended targets. Instead of only endangering bacterial and fungal communities, the application of pesticide has the potential to damage earthworm populations and alter soil biomass. Microbial biomass plays a crucial part in the soil nutrient component cycles through the transformation of biological matter into elemental nutrients available for plant essential. It is predicted that in 2050, pesticides consumption would be approximately 3 times more than it was in 2000 due to the more extensive use of pesticides to meet the growing food demand by the increased human population. This predicament has put human health and the environment in a jeopardy condition [4]. The pesticide leftovers and metabolic products can build up in the soil at excessively high degrees, and they can diffuse through the soil, water and air, or linger in the plantations and posing a concern to the human beings. In recent years, government and the general public have increasingly acknowledged the possible negative consequences of pesticides on the ecosystem and public health. Soil remediation is currently preferred in order to protect human health and advance sustainable development. [5].

Composting is the aerobic microbial breakdown of organic matter to produce a stable compound that is suitable for use as green fertilizer. Composting can aid in the bioremediation of pesticides by stabilising and deteriorating them in polluted soils. This technique involves combining and mixing the polluted soil with non-hazardous organic admixtures in order to encourage the growth of bacterial or fungal population, which in turn promotes pesticides to undergo physical-chemical-biological reactions that alter their chemical structure and metabolic stability. Therefore, composting is an appropriate procedure for stabilizing pesticides in soils through microbial community-mediated breakdown, thereby improving soil quality [6]. The process of composting is shown in Figure 1.

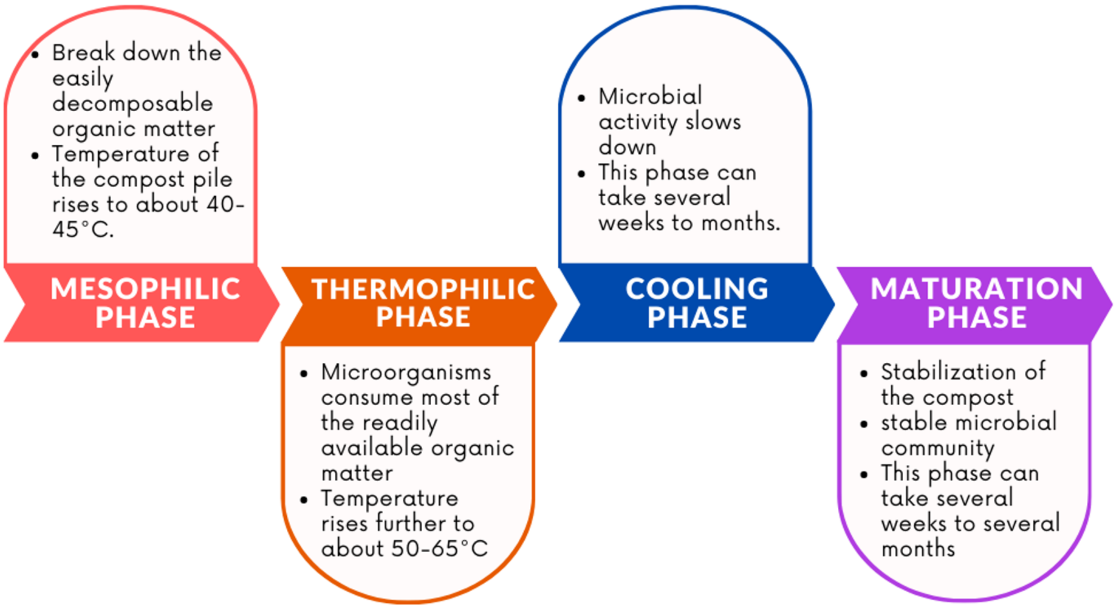

Figure 1. The process of composting.

2. Types of Pesticides

Pesticides are categorized into three main groups based on their target pests: herbicides, insecticides, and fungicides. Herbicides are designed to control and eliminate unwanted plants, commonly known as weeds, that compete with crops for resources. They selectively target plants while minimizing damage to the desired crop species. Insecticides, as the name suggests, are formulated to kill or repel insects that pose a threat to agricultural crops, forests, or human health. They target various life stages of insects, including eggs, larvae, and adult forms. Fungicides, on the other hand, are specifically developed to combat fungal infections that can damage crops, fruits, and vegetables. These pesticides inhibit the growth and spread of fungi, protecting plants from diseases like blight, mildew, and rust. Each category of pesticide plays a vital role in maintaining crop productivity and preventing the loss of agricultural yield caused by pests and diseases [2]. Pesticides can be categorized into distinct groups based on their chemical composition, including organophosphates, carbamates, organochlorides, and pyrethroids. These classifications are determined by the specific chemical structures and properties of the pesticides, which contribute to their effectiveness and potential environmental impacts [7]. Pesticides are present in the nature in varied amounts depending on how they are used. Pesticides are frequently detected in the ecosystem as mixture compounds and have been linked to a variety of unwanted organic and inorganic chemicals. They thus have a negative direct and indirect impact on non-target populations. Pesticides also disrupt competition between preys and predators by causing death on certain organisms and interrupting the food chain, and significantly affect how a community is structured [8].

3. Sources and Transport of Pesticides

Pesticides can enter the aquatic ecology both knowingly or unwittingly due to their wide spectral range. The main pesticide sources are categorised in this section based on their access point into the environment. Pesticides can be either point or non-point, and both forms can pollute the environment by infiltrating the ecosystem [8]. Point sources are defined as the pollution origins that may be determined and discovered, as the pesticides are discharged directly into the waterbodies through a spillway or outlet point. Non-point sources, also known as dispersed sources, are those that originally come from a wide region where it is difficult to pinpoint the cause of pollution [8, 9]. The possible sources of pesticides is shown in Figure 2. The sources that contributed the majority of the pesticides into the environment are being discussed further in the following section.

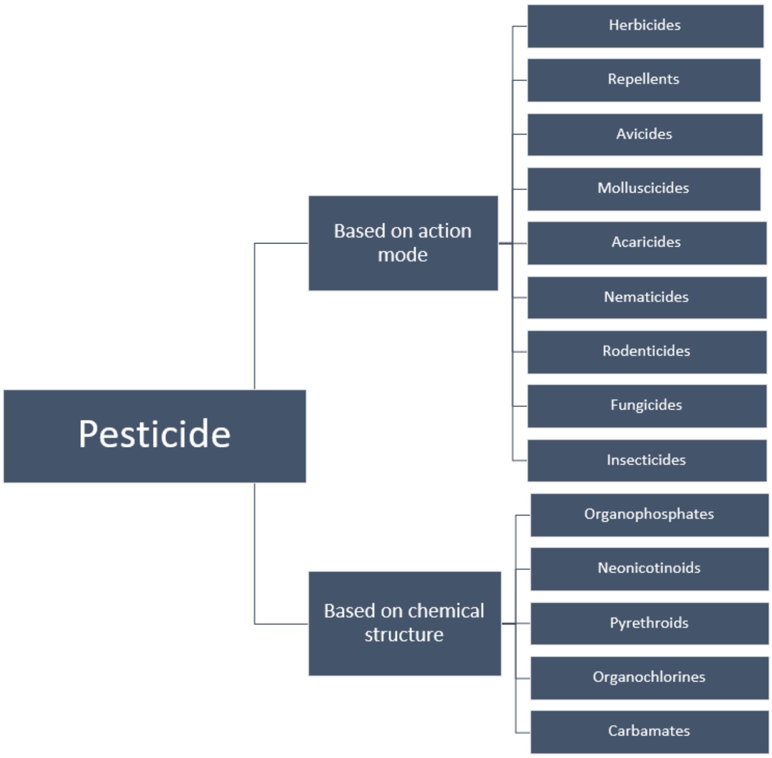

Figure 2. Pesticide classification.

3.1. Point and non-point sources.

The sources of pesticides into the environment is shown in Figure 3. Wastewater treatment facilities and sewage systems are possible point sources in aquatic environment. Fresh fruits and vegetables typically contain higher pesticide residues due to pesticide introduction for pest management to ensure that the plantations are safe from external infection, which frequently releases into the drainage system throughout the wash cycle [10]. Food packing sectors have an impact on pesticide levels in aquatic settings because fruits and vegetables are sprayed or coated with fungicides to reduce damages from fungal invasion. There was approximately 677 millions tonnes of fruits and 880 millions tonnes of vegetation produced in worldwide in 2013, which had added a significant quantity of pesticides to wastewater and ultimately the aquatic ecosystem [11]. Aquaculture is the sector with the quickest growth rates, with production predicted to double by 2030. Aquaculture employs pesticides to improve productivity in order to meet recent population growth and consumer demand. Livestock rearing is a significant additional source of pesticides in the aquatic ecosystem. Animal diseases are controlled by pesticides in livestock production, and these pesticides may enter water courses by wastewater discharge. By 2050, the pesticides consumption for livestock is expected to double due to population growth, which could result in a greater environmental exposure to pesticides [12, 13]. Agriculture is regarded as one of main non-point sources of pesticide. They are being released into the aquatic system through drainage systems or surface spillage during farming techniques. The main causes of the environmental effects of agriculture use are the utilization of greater concentration than standard, inappropriate applications, unauthorised use of prohibited pesticides, and mishandling. As a result, agricultural soils have been found to be a significant source of persistent pesticides and a continual stream of pesticide outflow into the water bodies [14]. Additionally, pesticides are employed in forests to aid in regeneration with the application of herbicides, in addition to eliminating the insects and preventing illnesses from outbreak. Pesticides might be sprayed manually or by air spray based on the approaches adopted to manage the forest. Manually sprayed herbicides could contaminate the local ecosystem by evaporating into the air or leaking into surrounding surface waters [15].

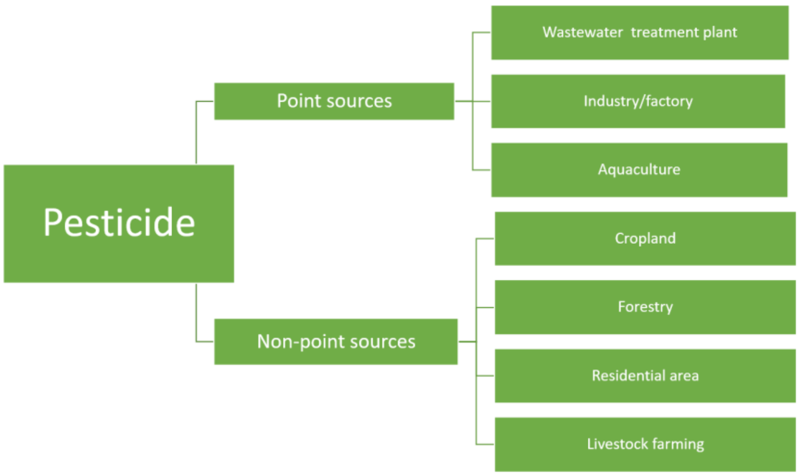

Figure 3. The sources of pesticides into the environment [8, 12].

3.2. Fate and transport.

Pesticides have the ability to infiltrate environment when they are being used on designated plantations or when being discarded, having negative effects on the land system and living organisms. The pesticides are released into the environment, where they may migrate from their origins through air or water and decay [16]. Degradation of pesticides in the ecosystem can form new chemical compounds with various ecotoxicological effects. It is because different chemical compositions reveal variations in their interactions with the environmental components. Pesticides travel from their original application sites to other environmental compartments by means of transport mechanisms such as sorption, leaching, volatilization, and runoff [17]. Figure 4 has depicted the pesticide fate and transfer in the ecological system, and each of the mechanisms is further explained in the section that follows.

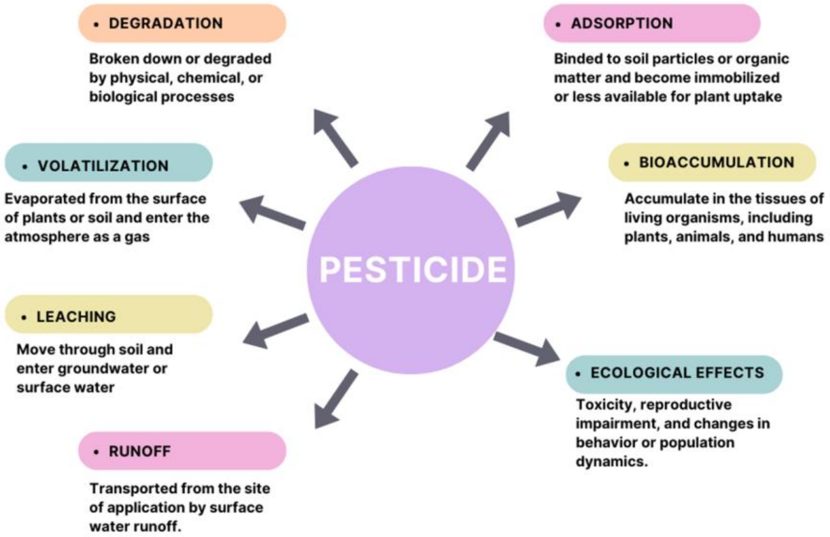

Figure 4. Pesticide behaviour in the natural environment.

3.2.1. Pesticide decomposition.

The presence of microorganisms, chemical interactions, or ultraviolet radiation are the causes of pesticides deterioration. The rate of degradation is influenced by environmental parameters including water availability, soil alkalinity or acidity, and thermal condition, as well as by the chemical pesticide properties such as hydrophobicity or hydrophilicity, solubility and volatility [18]. The process of pesticide breakdown produces several intermediates while dominating the retention of pesticide in soil system. Pesticide disintegration can involve three different forms: microbiological, chemical, and thermal. Pesticides are subjected to microbiological degradation when they are decomposed by fungi and bacteria [19]. The variables that affect the effectiveness of this decomposition process are oxygen level, temperature, soil humidity, soil pH, and soil porosity structure. For instance, pH has a significant impact on the compounds decomposition of benalaxyl, with higher pH soils degrading more rapidly under conditions of increased hydroxide ion concentration [20]. Additionally, pesticides can be disintegrated in the soil through chemical interactions. The reaction mechanism of solar radiation contributes a significant part in the molecular breakdown on top of the soil due to the molecule is being energised and constantly active. Temperature, pH levels, relative humidity, and the soil's ability to bind pesticides all have an impact on the nature and intensity of chemical breakdown [21]. Moreover, the destruction of pesticide structures by sunlight is known as photodegradation. The degree to which a pesticide can be photodegraded depends on the amount of light, how long the exposure is, and the characteristics of the insecticide [22].

3.2.2. Pesticide migration.

3.2.2.1. Sorption.

In actuality, only small portion of the pesticides in use exhibit signs of resistance against plant infections or illnesses. Considerable soil pollution results from high concentration of pesticides that are still present reaching the soil. The sorption mechanism is a process that causes pesticides to adhere to soil particles because of the interaction between chemical compounds and soil particles [23]. The variables that have an impact the soil absorption process are its alkalinity or acidity, organic matter concentration, and the presence of soil supplements.

Comparatively to other coarser soil types like sandy soil, soil that contains more organic matter or clay is far more adsorbent to pesticides. It is because organic or clayey soils have larger particulate surface area, indicating that there are more opportunities for pesticides to attach to the particles. Besides, clay has a higher absorptivity than other soil types because the majority of negatively charged particles on its surface tend to attract the positively charged of pesticides [24]. Moisture has an additional impact on the adsorption of pesticides in soil, with dry soil absorb more pesticides than wet soils do. This condition arises because, in high water content soils, water molecules might contend with the pesticides for the binding sites [25]. Another element that obstructs the sorption efficiency is temperature; as an example, ammonium nitrogen adsorption is increased in the conditions of higher temperature. The majority of pesticides are persistent in the soil, therefore they have higher possibility of being absorbed by plantations throughout their lifecycle. Such pesticides types might harm plantations or leave behind residues, causing further damage to the other organisms [17, 26].

3.2.2.2. Leaching.

As forementioned that only minority of pesticides are actually used to protect the crop yields from the diseases, the remaining pesticides can seep into watercourses, such as surface water and groundwater, and trigger water contamination. Solubility is a key factor in leaching when assessing whether pesticides reach water sources because pesticides that are soluble in water can infiltrate in the soil and reach the undergrounds. The ability for pesticide leaking into the soil increases with soil permeability, which is another important element affecting the fate of pesticide. This circumstance can be indicated that higher soil permeability provides more pathways for pesticides to travel from their application point to other locations [27]. Furthermore, climatic parameters such as rainfall events and temperature, can affect the leaching feature of pesticides. Precipitation provides an assistance for pesticides to migrate downward leaching to groundwater [28]. Temperature affects soil evapotranspiration, which in turn affects how pesticides leach out of the soil since it makes more energy available to transform liquid to vapour. Under the circumstance of elevated temperature, the volatile pesticides are evaporating into the atmosphere and are being transported by the wind. Soil factors such as soil structure and nutrient availability also has the potential to affect the water penetration, causing the pesticides transfer into the groundwater [29].

3.2.2.3. Volatilization.

Volatilization is the process of transforming a compound from solid or a liquid state into a gas. After pesticides are volatilized, they have higher potential to transport much farther from treated surface by air flow than through other media. Vapour pressure, temperature, dampness, wind speed or direction, as well as soil features such as composition, organic matter concentration, and water content are several significant elements that affect the volatilization level of pesticides [30]. The pesticide tends to volatilize in the condition of high vapour pressure. Additionally, volatilization is often made worse by higher climates, low humidity levels, and high air circulation. Pesticides that are firmly adsorb to soil particles are also less susceptible to volatilize [30, 31].

3.2.2.4. Surface runoff.

Pesticides in the water that are transported across an inclined surface are known as runoff. Pesticides may be bonded to soil particulate matter of the eroding soil or may migrate as chemicals that dissolve in water. This is closely related to a number of variables, such as the gradient or slope of an area, the composition and water content of soil, the quantity and duration of rainfall. Runoff happens when water is delivered to a field at a rate that prevents the soil from absorbing it. Pesticide runoff is brought on by excessive surface water accumulation brought on by over-irrigation [32]. The runoff has the potential to pollute torrents, wetlands, reservoirs, and wells with pesticides, which could be detrimental to the environment, wildlife and human beings [33].

4. Challenges Faced by the Pesticides Contamination

The negative impacts of pesticide use outweigh their positive ones. Pesticides severely harm non-target taxa, the biodiversity of flora and fauna, terrestrial and aquatic food chains and ecological systems. The reason for this is that approximately 85% of the pesticides have higher volatility, which causes them to evaporate after several days of application, transferring pesticides far from their origins and expanding the region that is contaminated. As a result, the unexpectedly afflicted creatures might sustain significant harm. Therefore, the appropriate pesticide usage is important in every sectors in order to ensure that the application does not cause hazards for the biodiversity, including terrestrial and aquatic ecosystems due to their toxicity [34].

4.1. Terrestrial organisms.

The majority of terrestrial animals, including vertebrates and invertebrates, are exposed to pesticides via direct precipitation of the sprayed substances on them, which is analogous to transdermal on their epidermis. Spray particulates are typically composed of saturated active compounds in water or oil based carrier solution, together with or without a minor amount of adjuvant content. The external coverage of animals can be damaged and dropped when exposed to higher pesticide dosages [34]. The rapid dermal toxicity that results from the high absorption of the lipophilic insecticides via their skin frequently results in the animal's death [35]. It is impossible for organisms to avoid from pesticides exposure because farming fields and their surrounds are the natural habitat to numerous unintended living creatures. The sprayed pesticides are then can be inhaled by the terrestrial species, as they are normally being transported by the wind action. The inhaled pollutants have the potential to deliver the chemicals through the lungs and enter the blood circulation due to their microscopic size which can cause damage to their internal organs. The third exposure is the ingestion of pesticide-contaminated resources such as plantations or water. This is considered as primary poisoning in this mechanism by direct consumption the contaminated substances, rather than secondary poisoning [34]. Secondary poisoning is the action that the organisms consumed the predators that consisted of pesticide residues in their bodies [36]. When low concentration of highly poisonous pesticides are primarily ingested by organisms, they often cause acute symptoms; if significant amounts are consumed, these effects may be fatal. While in the case of second poisoning, it frequently results in long-term toxicity and unanticipated adverse effects. Nevertheless, if the chemical is extremely toxic or the pollution is significant because of improper handling and usage, secondary poisoning can still be fatal to the predator even when applied at the recommended dose [37].

4.2. Aquatic organisms.

Pesticides frequently come into touch with aquatic animals through their skin, breathing, and ingesting. It is because aquatic organisms come into direct touch with water, pesticides can induce negative effects through skin pores. Besides, aquatic species can also be exposed to pesticides by consuming pesticide-affected prey or by drinking polluted water, as well as directly absorbing pesticides through their gills into their respiratory systems. The aquatic ecosystem make up by diverse groups of creatures, including invertebrates, vertebrates, plants, or microbes. All of the impacts that pesticides have on creatures have the potential to be fatal or sublethal [38]. Pesticide residues are endangered for the long-term sustainability of important ecosystems by disrupting aquatic creatures' ecological interactions and reducing biodiversity. Figure 5 shows the pathways of pesticides into the aquatic creatures [39]. Fish are the aquatic species that are most frequently studied due to their close interaction with the marine ecology chemistry. They are essential components of the aquatic food web since they constitute a significant food resources for the significant proportion of marine mammals [38, 39]. The majority of aquatic life exposed to pesticides may experience immunological diseases, hormone imbalance, and genetic oxidative damage. Recent studies on the biological consequences of pesticides on fish have revealed that the reactive oxygen species production is one of the most frequent outcomes of these consequences, in addition to neurological illnesses, metabolic derangements, and developmental damage. Recently, it was reported that the degree of pesticide pollution in water was directly connected with the overall number of cancer diagnoses in the aquatic population, highlighting the importance of determining pesticide contamination [40].

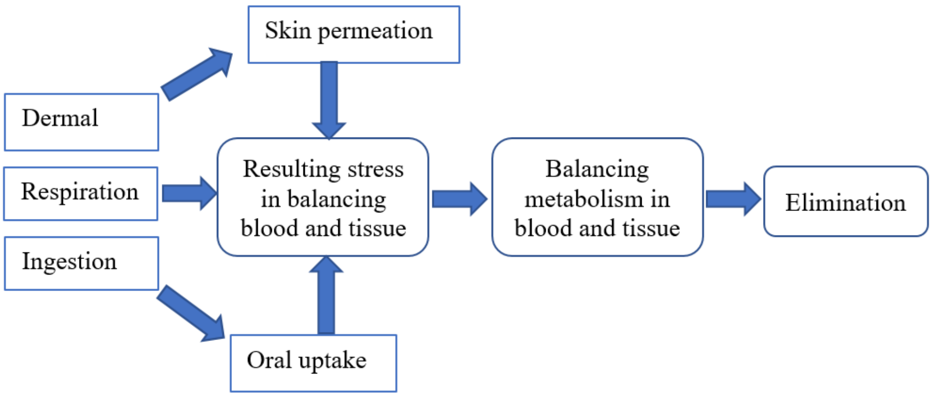

Figure 5. Routes of pesticides entering the aquatic species bodies [39].

4.3. Soil pollution.

Although pesticides are employed to facilitate plant growth and enhance agricultural yields by inhibiting the external pressures like the invasion of foreign organisms, their excessive uses pose potential hazards and detrimental consequences on the soil health [41]. A healthy soil mechanism may support ecological integrity by preserving its environments, and it can also sustain and improve the habitats for living creatures and plantations. The elements that govern the soil integrity are biological (microorganisms behaviour), chemical (soil alkalinity or acidity and organic carbon content), and physical (soil structure and water retention capability), which of them are interrelated and have an impact on one other. It is well known that pesticides can persist and retain in soil for a longer time and transform into substances that have poisonous and detrimental effects. The pesticides also lowered the soil pH, which accelerated the dissolution of mineral-rich soil particulates that are crucial for oil outflow. This resulted in severely compacted soil with poor air ventilation and sewerage movement. The presence of microbes also crucial to the development of healthy soil as they function in maintaining the soil nutrient element cycle. The beneficial microbes may become less abundant in acidic soil, due to their sensitivity to environmental changes [42].

4.4. Surface water and groundwater contamination.

Farming, commercial, and industrial areas are usually found to have higher pesticide concentrations. This is because pesticides applied in croplands are either retained in the soil or broken down into various chemical compounds, rather than being totally absorbed by plants. Pesticides that are solubilized in water will travel with water droplets through the soil profile and subsequently reach the underground water, particularly during rainfall occurrences. While insoluble pesticides will adhere to the surfaces of soil particles, which increases the likelihood that they may wash away with runoff and erosion into surface waterways and pollute river systems and tributaries. The soil surface layer between 2.5 mm and 8.5 mm is where pesticides are most susceptible to discharge, as the top portion of soil is more exposed to the environment [43]. Pesticides that have been volatilized in the atmosphere also have the potential in the contribution of water pollution as they are redeposited during the rainy event and then reach the watercourses. The parameters of pesticide behaviour, soil properties, site circumstances, as well as the pesticide usage and management procedures, all affect how contaminated the water is with pesticides [44].

5. Human Health Impacts

Pesticide exposure can take place directly via the usage in the workplace, farmland, and household, as well as indirectly via nutrition. Pesticides can get into the human body through four typical routes: the dermis, the mouth, the eyes, and the respiratory system. Although pesticides can be transported by the blood circulation, they can be eliminated through sweating, urinating, and exhaling. The degree of exposure as well as the toxicity of the components in pesticides determine how hazardous they are to humans. Besides, several groups, including youngsters, pregnant women, or elders are more vulnerable to the consequences of pesticides than others [45]. Consequently, pesticide exposure can have a variety of health issues depending on an individual occupation, the concentration of their exposure, or other factors. Figure 6 shows the potential health issues that closely related to pesticide exposure and the common ailments are being discussed further in the following section.

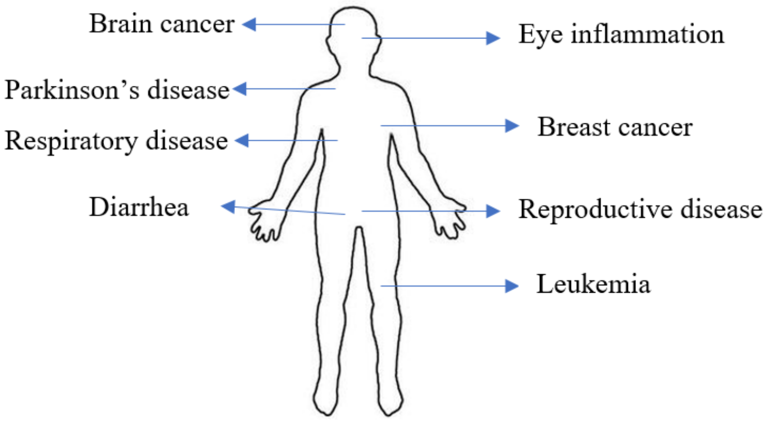

Figure 6. Common human health issues related to pesticides exposure [45, 46].

5.1 Carcinogenic effects.

Cancer is resulted by uncontrollable cell development, unrestricted cell duplication, altered growth of hormones, and treatment tolerance. Pesticides exposure stimulates the development of cancer and chronically low exposure is thought to be one of the primary contributors for the rising cancer prevalence. Breast cancer is the major culprit of cancer-associated mortality among women. There are approximately 80% of pesticides are consisted of endocrine disrupting elements that can interfere with the endocrine system's ability to function [46]. Chlorpyrifos is one of the hormone-disrupting substances in pesticides that triggered redox instability that disrupted the activity of antioxidant enzymes in cancerous cells [47]. According to a study from Brazil, domestic pesticide consumption increases the breast cancer risk, which accounts for the majority of cases of breast cancer that are detected [48]. Leukaemia is another malignancy that primarily affects children and is brought on by a mother infection during pregnancy. The reason is that genetic mutations might result through the transmission of infectious organisms with carcinogenic potential from the mother to the foetus. The infection may cause immunological resistance because the foetal adaptive immune response is underdeveloped. This endurance would enable the prolonged presence and the growth of infected cells, eventually causing leukaemia disease in infants [49].

5.2 Reproductive effects.

Both men and women may be harmed by reproductive risks encountered in the environment or the working area. The main issue brought on by man's pesticide exposures may be due to mutations and variations in the genetic sequence or makeup, as well as other harmful effects on testicular functionality [50]. The majority of pesticides, which contain organophosphorus ingredients, have the potential to decrease the function of male reproductive system through mechanisms like decreased sperm motility, slowed sperm production, sperm DNA damage, and increased aberrant sperm structure. According to studies, there are up to 25% less chances of conception due to sperm morphology interruption [51]. Hormonal disruption is the principal effect of pesticide exposure in women. Oestrogen and progesterone levels are regulated by hormonal balance, which is essential hormone for maintaining female fertility and reproduction. This disturbance may result in menstrual cycle disruption, pregnancy lengthening, miscarriage, and infertility [52].

5.3 Respiratory diseases.

Respiratory issues are caused by pesticides, particularly those that contain compounds that have the ability to reduce the amount of red blood cell cholinesterase and inhibit its development. Exposure to occupational pesticides has been correlated to a multitude of respiratory problems and illnesses, particularly in farm laborers [53]. The pesticides inhaled by individuals can disrupt the airway epithelium through inflammation, immunodeficiency, and increased sensitivity to pathogens or other sensory receptors, resulting in respiratory problems [54]. There have been reports of sneezing, ventilatory inflammation, dry or sore throat, cough, dyspnoea, and difficulty breathing as respiratory symptoms linked to pesticide exposure. A research conducted in the United States between 2000 and 2008 found a 3.3 per million growth in the prevalence rate of non-occupationally related respiratory illnesses brought on by pesticides, with 84% of injury issues happening in the household. The most frequent exposures were to pesticide-contaminated indoor air and direct spray exposures, while pesticides were applied [55].

6. Remediation Technologies

Composting is regarded as one of the techniques to restore and treat contaminated soil by utilising microbes to break down contaminants. According to the definition of composting, it is the aerobic microbial decomposition of organic materials into stable compounds, which then can be utilised as biofertilizers [56]. Composting can contribute to pesticide bioremediation by stabilising or deteriorating them in polluted soils. Organic matter is metabolised and degraded with the compost introduction, as the pesticides are subjected to physical-chemical-biological reactions that alter their chemical compositions and metabolic stability. Thus, composting is an appropriate procedure for restoring pesticides in soils through microbial community-mediated breakdown, thereby improving soil quality [57]. Soil quality is normally determined by abiotic factors, including soil acidity or alkalinity, water content and soil texture. However, biotic factors, microorganism activities, also play significant roles in achieving soil quality because of their responsibilities in biochemical processes and the preservation of soil structure [58]. Composting can be conducted with other techniques using landfarming, biopiles and windrows. The purpose of each composting approach is described in Table 2, along with its benefits and drawbacks. The section below discusses a detailed description of each technology.

6.1 Landfarming.

Landfarming can be conducted as ex-situ and in-situ biological remediation strategies. The key determinant of whether land farming can be done in situ or ex situ is soil depth that the pollutants have reached. In landfarming, the contaminated soils are typically dredged up or tilled, however it appears that the type of bioremediation depends on the treatment site. In-situ landfarming indicates that the treatment of polluted soil is carried out in the polluted area, while ex-situ farming implies that the contaminated soil is transferred to other locations for remedial activities. In-situ land farming is a remediation method typically used when pollutants are found less than 1 metre below the surface of the ground [59]. The working principle of this technique is that the dredged contaminated soils are introduced on predefined layer support above the soil profile to allow aerobic decomposition of contaminants by native microbes. Air ventilation, nutrient inclusion, and water delivery are three ways that the introduction of tillage helps to promote native microbial activity and improve the productivity of land farming [60]. A proper landfarming structure should involve a waterproof lining to lower the possibility of leakage or evaporation of contaminants into the surrounding areas during the bioremediation [61].

The landfarming bioremediation approach is ease to construct and practise, therefore it has a low capital cost because it does not require advanced technologies. Additionally, it is capable of treating a sizable amount of contaminated soil with low negative consequences on the environment and low energy consumption. Even though it is the simplest remediation technique among bioremediation methods, it has several drawbacks. It necessitates a vast operation area due to the size of excavated polluted soil, increasing the pollutants exposed to the environment. Additionally, microbial activity is greatly influenced by environmental conditions, which has an effect on the effectiveness of treatment. This treatment has higher operating cost due to the involvement of excavation, and is less effective at eliminating inorganic pollutants [62].

Table 2. Comparison of different composting technologies.

Technology	Advantages	Disadvantages	References
Landfarming	- Simplicity of implementation - Ability to treat high amount of contaminated soil -Low energy consumption	-Large area requirement -Environment dependent -High operational cost	[62]
Biopiles	-Less area requirement	- Advanced technology involvement - High maintenance cost -High operation cost -High energy consumption	[66, 67]
Windrows	- High hydrocarbon removal rate - Soil type dependent	-Incapable for toxic volatised chemical compounds -Release of greenhouse gases	[69, 70]

6.2 Biopiles.

Biopile-mediated biological treatment requires piling excavated tainted soil at the top part of the ground surface, followed by introducing nutrients to the soil and occasionally aerating it in order to improve the remedial action by boosting microbial activity. The main elements of this method are oxygenation, irrigation, nutrient supplementation, and leachate-collecting mechanism, and a recovery site. It is used more frequently because of its beneficial qualities, such as cost feasibility, which allows for productive biodegradation under the condition that nutrients, temperature and oxygenation are sufficiently managed [63]. Biopiles are ideally constructed on a protective layer to prevent the pollutants from discharging into the atmosphere and surrounding areas caused by severe weather conditions [64]. The implementation of biopiles to contaminated areas has the tendency to prevent light weight or low density of pollutants from vaporising into the atmosphere. Remediation times for the biopiling remediation method can be shortened by introducing heating systems into the design to increase microorganism reactive actions, which in turn increases the biodegradation rate [65].

The main advantage of implementing biopile system is space conservation in comparison to other ex-situ bioremediation methods like land farming. It also consists of some drawbacks, including a comprehensive engineering aspect, high maintenance and operation expenses, and a requirement for an electrical supply that uses an air pump to distribute air uniformly across polluted piles of soil [66]. Furthermore, overheating the air might cause soil undergoing bioremediation to dry up, which will hinder microbial activity and encourage volatilization rather than microbial degradation, decreasing the treatment efficiency [66, 67].

6.3 Windrows.

Windrows work in turning of the polluted soil on a regular basis in order to increase the degrading activities of the native hydrocarbon clastic bacteria in the soil. The parameters affecting the process's effectiveness are the frequency of turning contaminated soil, the addition of water, the dispersal of pollutants, the supply of nutrients, and the reactivity of microbes [68]. Turning is the primary factor responsible for the treatment productivity because it affects other factors including temperature, oxygen saturation, and soil carbon content. For instance, the temperature of the unturned contaminated soil decreased more slowly to the optimal temperature, and consisted of low carbon and oxygen concentration. Therefore, it takes less time for turned windrows to biodegrade than unturned ones since the aforementioned conditions are unfavourable for microbial degradation [68, 69].

It demonstrated a higher hydrocarbon removal rate compared to biopile treatment, although the effectiveness of this method is greatly influenced by the soil type, which was shown to be more likely to crack [70]. However, it might not be the ideal course of action to pursue in remediating soil contaminated with hazardous volatised chemicals. It is because the establishment of an anaerobic zone inside heaped contaminated soil, which often takes place after oxygenation, has been linked to the production of methane gas release. This scenario has increased the concertation of atmospheric greenhouse gas, resulting in climate change or global warming [71].

6. Challenges Faced for Future Studies

Currently, high emphasis has been given to the potential threats that polluted soils pose to human health, terrestrial, and aquatic ecosystem. Numerous strategies have been designed to reduce these hazards, with composting is thought to be the most efficient way in improving waste treatment and management, soil organic carbon and soil quality. Although composting is regarded as the ideal management practise, it has limitations and challenges that need further study. The majority of scientific research that have been accepted for publication are carried out on laboratory scale utilising artificially polluted soils. The present research has identified a dearth of studies investigating naturally pesticide-contaminated soils at field scale settings. Therefore, a considerable amount of effort should go into implementing on-site remediation technologies so that their actual costs and potential operational issues can be fully determined. However, obtaining funding for large-scale studies is problematic without the involvement of organizations. In this situation, these organizations are incentivised to withhold information in order to gain an advantage, and non-disclosure agreements forbid the dissemination of the findings [72]. Besides, the soil pollutant's susceptibility to adsorption, reactivity, and usage impact its availability. Pesticides that have been incorporated into the soil profile can firmly bind to the soil's surface, and the ageing process of pollutants causes changes in their bioavailability over time. This process caused the restoration process more challenging as the bioavailability should be thoroughly evaluated prior to choosing any remediation technique for soil pollution management. Therefore, future research should be carried out to ensure that the fate of pesticides can be fully grasped and determined. Other than that, the ineffectiveness of bioremediation due to the poor adaptability of exotic microbes in contaminated soils should be investigated using the proper procedures [73]. Furthermore, international collaboration is important of conserving the environment and public health from pesticides. Although affluent nations have set up sophisticated procedures for approving pesticides and regulating their sale and application, other nations may not adhere to the same stringent regulations. Therefore, the primary preventive approach is to raise environmental knowledge in order to appropriately apply chemicals in farming practices, thereby minimizing the effects on environments [74].

4. Conclusions

Pesticides are regularly employed in agricultural productivity to avoid or minimise pest-related losses. However, the extensive use of pesticides at different fields has caused soil contamination, endangering human health and having an adverse effect in the environment. Then, remedial measures are suggested to clean up the polluted soil and cease the pollution from getting worse. Numerous benefits come with microbe-mediated treatment of pesticides, including minimal investment and operational costs, simple technology involvement, and cost-effective environmental protection. It is advantageous in reducing the possible damage pesticides bring to the ecosystem while maintaining agricultural productivity and output. Although numerous studies have been carried out in this field, pesticide-related environmental damage and health risks are still major concerns. It might be due to the deficiency of recognised multipurpose microbes that can be utilised to detoxify a wide range of chemical compounds. Therefore, additional research can be conducted to genetically modify the microbes, providing vibrant opportunities in this area. There may also be a large number of unrecognised bacteria that have different pesticide-detoxifying capacities. Therefore, it is crucial that more research be done in order to explore innovative microbes with these qualities in other parts of the world. Hazardous chemical substances can be eliminated from the ground by understanding the traits of various microbe species used to remediate polluted soil, preserving the integrity of the ecosystem and well-being.

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Conflicts of Interest

The authors declare no conflict of interest.

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