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Review

Biobeds, a Microbial-Based Remediation System for the Effective Treatment of Pesticide Residues in Agriculture

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Abstract: Pesticides are chemical molecules employed to protect crops from pests in agriculture. The use of pesticides significantly enhances crop yields and helps to guarantee the quality of farm products; due to this, each year, millions of tons of pesticides are employed in crop fields worldwide. However, the extensive use of pesticides has been related to environmental pollution, mainly in soils and water bodies. The presence of pesticides in the environment constitutes a menace to biodiversity, soil fertility, food supply, and human health. Activities related to pesticide use in crops, such as the handling and pesticide dissolution before application, the filling and cleaning of aspersion equipment and machinery, accidental spills in crop fields, and the inadequate disposal of pesticide residues have been identified as important punctual pesticide pollution sources. Therefore, avoiding releasing pesticide residues into the soil and water is crucial to mitigating the environmental pollution associated with agricultural practices. Biobeds are biological systems that have been proposed as feasible, low-cost, and efficient alternatives for punctual pesticide pollution mitigation. Biobeds were first described as trenches packed with a mixture of 50% wheat straw, 25% soil, and 25% peat, covered with a grass layer; this composition is known as a "biomixture". In biobeds, the biomixture absorbs the pesticide residues and supports the development of different microorganisms, such as bacteria and fungi, needed for pesticide degradation in the system. The effectiveness of a biobed systems lies in the high pesticide retention in the biomixture and the degradation potential of the microorganisms growing in the system. In this review, 24 studies published in the last five years (2018–2022) related to pesticide biodegradation in biobed systems are analyzed, emphasizing alternative biomixture composition usage, microbiological strategies, and the key physicochemical parameters for efficient pesticide degradation in the biobed systems. The availability of robust scientific evidence about the simple applicability, low cost, and effectiveness of biobeds for pesticide residue treatment is crucial to increasing the use of biobeds by farmers in different agricultural regions around the world.

Keywords: biobeds; bioremediation; biodegradation; fungicides; herbicides; insecticides; microorganisms; pesticide residues

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1. Introduction

The acceleration of human population growth imposes tremendous pressure on natural resources and on the agricultural systems necessary to supply raw materials and foodstuffs [1–4]. Modern agriculture employs several chemical compounds to increase productivity and avoid the crop losses caused by pests. Among these agrochemicals, pesticides have a primary role [5,6]. Pesticides are chemical substances widely employed for

the control of different crop pests in agricultural areas, to avoid decreases in the quality and yield of farm products during food storage, transportation, and commercialization processes. Pesticides also have important applications in the control of vectors for different diseases in livestock and humans [7,8]. Hence, pesticide usage greatly benefits human societies worldwide [9]. However, the intensive application of pesticides is related to adverse effects on the environment [10], biodiversity [11], soil health and fertility [12], food supply, and human health [13,14]. Thus, almost all processes involving pesticides represent a risk to environmental health [8].

Pesticide residues have been identified in all environmental compartments, soil, water, and air [15]. It is estimated that only a small proportion of the total pesticides employed in agricultural areas reaches the targets in crops, with the remaining percentage dispersed through the environment. Pollution caused by pesticides is an important concern in several regions around the world [16,17]. Moreover, in various less developed countries, many obsolete, unused, or expired pesticides are stored, constituting an environmental risk that endangers environmental and human health [18–21]. The release of pesticides into the environment generates different adverse effects such as reducing the overall soil, water, and air quality, threats to wildlife and biodiversity, and the contamination of food destined for livestock and humans, with acute and chronic toxic effects on humans, among the most relevant [17,22–26].

Pesticides can reach soils and water bodies because of their production and extensive scale application in agricultural systems. Spills, leaks, wastewater, and inappropriate waste disposal in the pesticide manufacturing industry have been identified as an environmental pollution sources [27,28]). However, operations related to pesticide dissolution before application, the filling and cleaning of aspersion equipment and machinery, and accidental spills in crop fields have also been identified as important punctual pesticide pollution sources [29]. The pesticides and their degraded metabolites released from producing factories reach the soil and both surface water and groundwater bodies, threatening aquatic environments and human health [30] through the presence of pesticides in food and drinking water [31]. The adverse impacts of pesticide pollution on the environment and human health make it necessary to implement adequate strategies for the treatment of pesticide residues and the remediation of polluted sites [32,33].

Microbial-mediated bioremediation has been proposed as a cost-competitive, efficient, adaptable, and safe strategy for the treatment of different pollutants [34], including pesticides [35–37]. Biobeds are one of the microbial-mediated bioremediation approaches proposed for the treatment of pesticide wastes. These systems were developed in Sweden for the control and treatment of pesticide pollution caused by the environmental release of effluents derived from the washing of equipment and machinery employed for pesticide application in crop fields, as well as the inadequate disposal of pesticide residues, accidental spills in the handling and application of pesticides, and the residual water from different pesticide formulation plants and agro-industries [38–42]. This technology has been adopted in many countries and successfully applied for the biodegradation of different pesticide residues [41–46]. In this review, we evaluate the key parameters for efficient pesticide degradation in biobed systems, recent studies, the approaches to pesticide biodegradation in biobed systems, and the current challenges and future perspectives for biobeds' implementation and effectiveness.

2. Release of Pesticide Residues into the Environment

Both small and high-scale agricultural activity involve the use and disposal of pesticides and represent significant pollution sources. Pesticide punctual pollution events are generated because of the activities related to the use of different pesticides in crop fields. The release and dispersion of pesticide residues into the environment represent a high risk for ecosystems and human health on a global scale [47,48].

Three critical points can generate contamination by pesticides during agricultural activity. The first occurs when the pesticide application devices are filled; here, highly

concentrated pesticide solutions can be spilled. The second point is when the pesticides are spread in the crop field; after application, pesticides can reach the surrounding environment. The third point is during the handling and washing of the application devices when a high amount of residual water with low-concentration pesticide remnants is generated. Improper handling of these residues causes soil and water pollution by direct disposal, leaching, or runoff processes [31,49–51]. Avoiding pesticide release into the soil and water is a crucial issue in mitigating the environmental pollution associated with agricultural practices, and biobeds have been proposed as a feasible alternative for punctual pesticide pollution mitigation.

3. What Are Biobeds?

Biobeds are biological systems used to treat pesticide residues derived from the operations related to the application of pesticides in crop fields. Their use helps minimize pesticide delivery into the environment, as well as protecting soil and water from pesticide pollution [52,53]. Biobed technology was developed in Sweden in the 1990s by Torstenson and Castillo (1997) [54], as a low-cost and efficient alternative to mitigate pesticide pollution from specific punctual sources. In the original proposal, biobeds had a simple design. The system was a trench packed with a mixture of 50% wheat straw, 25% soil, and 25% peat (biomixture), covered with a grass lid. The biomixture has the function of absorbing pesticide residues and serving as a support for the development of different microorganisms, mainly bacteria and fungi, needed for pesticide degradation in the system (Figure 1).

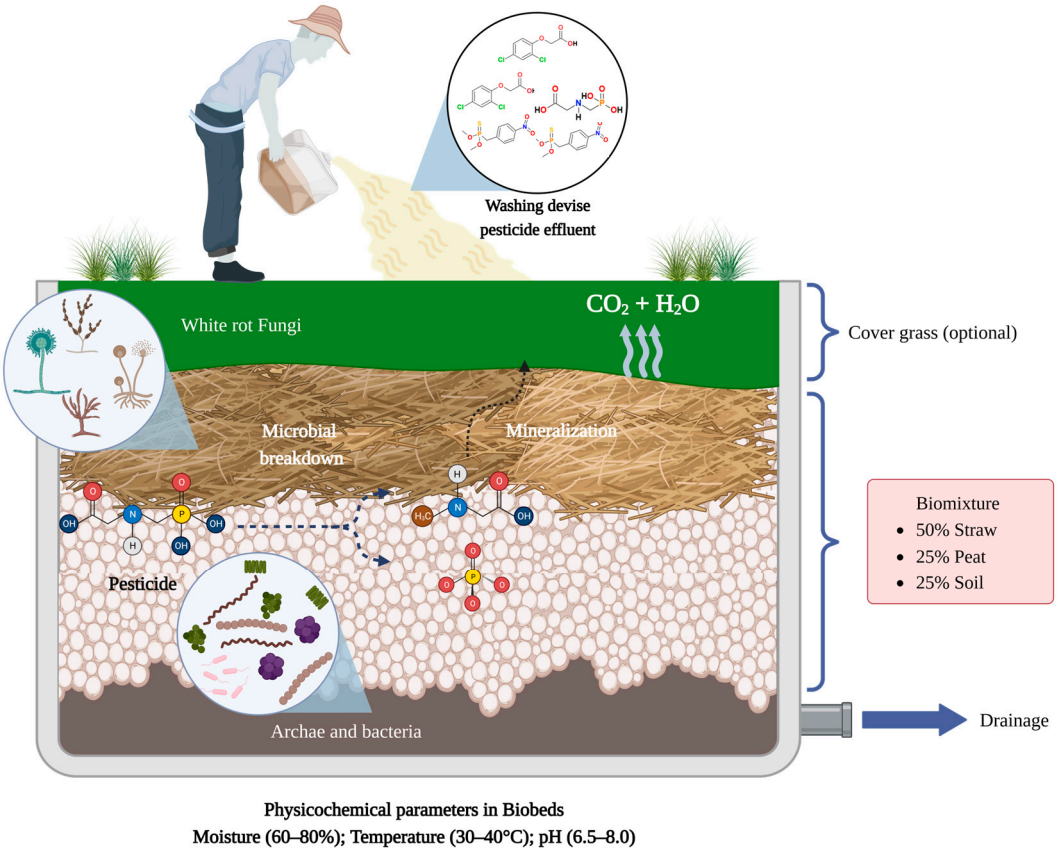


Figure 1. Biobed system design and main characteristics.

Biobeds were fast adopted in Swedish agriculture to treat effluents with different pesticide residues [55]. After that, biobed systems were integrated into several countries of the European Union, and subsequently, experimental devices were established in several countries around the world [56]. In 2016, the number of installed biobed systems in the European Union was around 9000, located mainly in France (4500), Sweden (750), and

the United Kingdom (450), while in the context of Latin America, 1500 biobed systems were installed in Guatemala, and additional experimental scale biobeds are located in Africa, Asia, and North America [57]. The biobed design has been modified according to the climatic characteristics of the regions in which it is located and the availability of the materials for the biomixture, including different lignocellulosic materials instead of wheat straw, or compost instead of peat, as some examples (Figure 2).

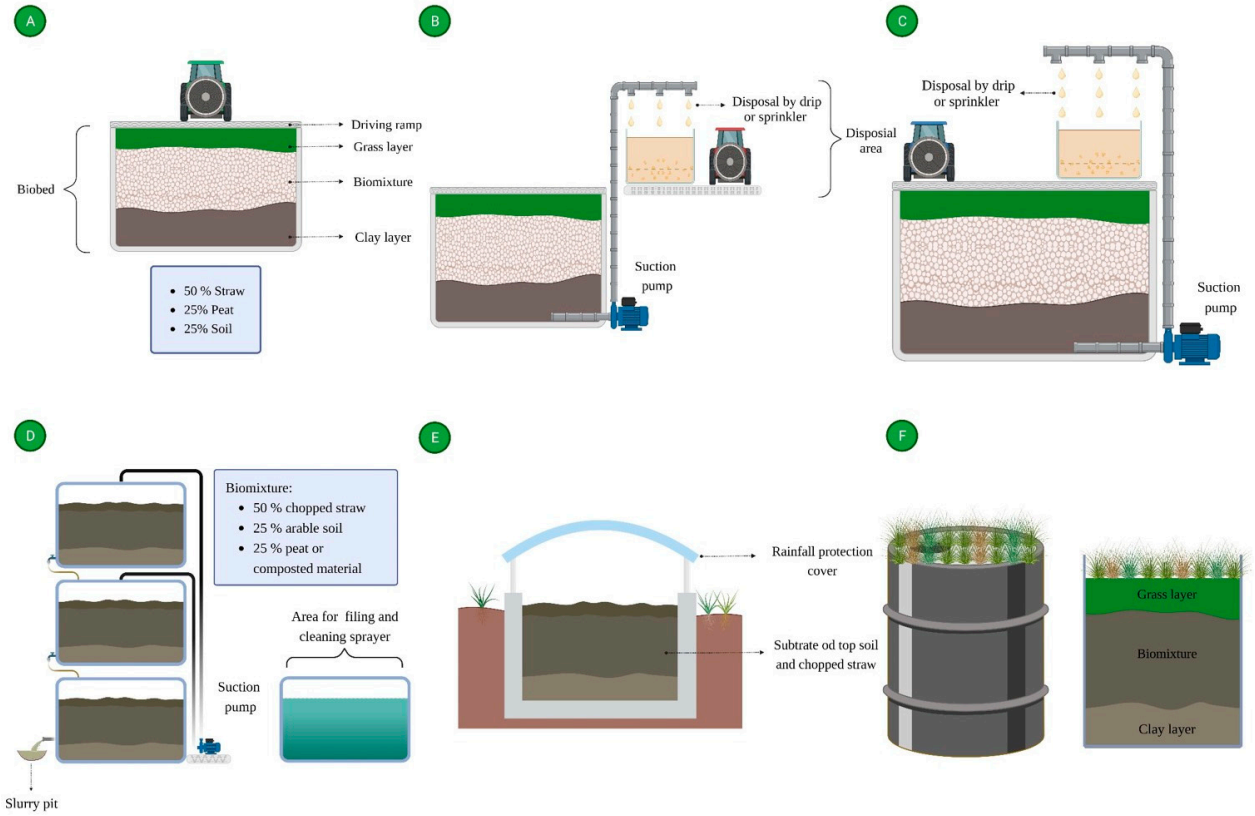


Figure 2. Biobed systems designs in different countries. (**A**) Conventional design (Sweden), (**B**) indirect system design (United Kingdom), (**C**) direct system (United Kingdom), (**D**) three-cell biofilter (Belgium), (**E**) phytobac design (France), and (**F**) barrel small design (Guatemala).

The biobeds' pesticide treatment capacity is related to the design, surface, scale, and biomixture composition. The water-holding capacity of the biomixture is related to the components that integrate it. For example, Henriksen et al. (2003) [58] determined an absorption between 1.6 and 5.2 L·kg^{-1} of biomixture (wheat straw, soil, and peat; 2:1:1) for the herbicides isoproturon and mecoprop. Foog et al. (2004) [59] determined the maximum water-holding in the system for efficient pesticide dissipation was 1121 L/m^2 for a biobed (1.5 m deep) packed with a biomixture composed of wheat straw, soil, compost (2:1:1). Recently, Lescano et al. (2022) [41] treated 200 L of wastewater with the presence of different pesticides in a pilot biobed system (1000 L capacity) packed with a biomixture of soil and millet stubble (1:1).

On the other hand, the climatic conditions of each region can affect the efficiency of pesticide dissipation in these systems. The most important climatic factors that modify the effectiveness of pesticide dissipation in a biobed are the environmental temperature and precipitation/moisture. At low environmental temperatures, the degradation efficiency is reduced; in some regions, low temperatures can freeze the system [60]. On the other hand, high levels of precipitation can generate an imbalance in the water content of the system so that the efficiency and speed of dissipation of pesticides are reduced and can generate pesticide leaching events [60]. Finally, climatic conditions affect the integrity of the biomixture; in temperate climates, the biomixture should be replaced every five to eight

years [55], but in areas with tropical climates, the biomixture should be replaced in six months to two years [52,61]. These facts must be taken in count for the biobeds systems' implementation and adequate pesticide residues treatment.

4. Key Factors in Biobeds' Effectiveness

4.1. Biomixture

The composition of the biomixture is a key factor for the efficiency of pesticide degradation in biobed systems; so, each component (wheat straw, soil, and peat) plays an important role [62]. For example, wheat straw is a lignocellulosic substrate that acts as an adsorbent for pesticides in the system, serves as physical support for the development of microbial communities, provides essential nutrients for the growth of fungi and bacteria, and stimulates the production of ligninolytic enzymes, such as laccases and peroxidases, reported to be highly efficient in the degradation of different pesticides. The soil supplies microorganisms to the system and stimulates the microbial activity that mediates the degradation of the pesticides, while peat is a porous material that increases pesticide retention in the biobed system, regulates the moisture, and reduces the pH, factors that favor pesticide dissipation [63–66].

In the biomixture, wheat straw can be replaced by other lignocellulosic substrates, depending on the availability of these materials in a particular country where biobed systems are applied. For example, Karanasios et al. (2010) [67] reported the use of different low-cost lignocellulosic materials, such as sunflower crop residues, olive leaves, grape stalks, orange peels, corn cobs, and spent mushroom substrate for the degradation of mixtures of pesticides in biobed systems. In this study, the alternative substrates favored the retention of pesticides in the system, and comparable pesticide half-life values, concerning those observed in the biobeds with the presence of wheat straw, were documented.

In another study, Diez et al. (2013) [68] complemented the biomixture composition with the addition of lignocellulosic materials, such as pine sawdust (25%) and barley husk (25%), for the degradation of the pesticides carbendazim, isoproturon, and chlorpyrifos. The systems that contained wheat straw/barley husk (25%/25%) showed higher degradation percentages for carbendazim and chlorpyrifos after 90 days compared to the systems with only wheat straw (50%) and wheat straw/pine sawdust (25%/25%).

In a similar study, Urrutia et al. (2013) [66] evaluated the addition of lignocellulosic materials such as barley husk, oat husk, and sawdust to biobed biomixtures for the treatment of the pesticides atrazine, chlorpyrifos, and isoproturon. Among the three lignocellulosic materials, oat husk was the best substitute for wheat straw, with similar pesticide degradation rates compared to the biomixture that included just wheat straw. In contrast, barley husk and sawdust can be added to the biomixtures in combination with wheat straw but not as the sole lignocellulosic material in the biomixture composition.

Gongora-Echeverría et al. (2017) [69] evaluated the suitability of wheat straw substitution in biobed systems, employing different materials of high availability in southeastern Mexico such as compost, sisal fibers, corn stoves, and seaweed in combination with soil for the treatment of a pesticide mixture composed of 2,4-dichloro phenoxy acetic acid (2,4-D, 1.08 mg/cm^3 of mixture), atrazine (2.5 mg/cm^3 of mixture), carbofuran (0.23 mg/cm^3 of mixture), diazinon (0.34 mg/cm^3 of mixture), and glyphosate (0.36 mg/cm^3 of mixture), mimicking the composition of pesticide effluents generated by farmers in Yucatan, Mexico. In all evaluated biomixtures, the five pesticides' dissipation was over 99% after 41 days.

Peat is an important component in biobed biomixtures; however, in some regions, this material has low availability or high cost. So, in biomixtures, peat has been substituted by alternative material or just eliminated from the biomixture composition [70,71]. Among the alternative materials to peat for biobed mixtures, compost [72–76] or vermicompost [43,77–79] are notable for being the most reported.

Various agro-industrial wastes have been employed in the biomixture composition in biobed systems to treat fungicides, herbicides, and insecticides from different chemical families. They include spent coffee grounds [80], coir [80], cotton crop residues [81,82],

garden wastes [83,84], livestock manure [80,85], olive leaves [68,86,87], pine bark [80], and sewage sludge [88]. Spent mushroom substrates and biochar have also been incorporated into the biomixture composition as complementary materials in pesticide dissipation [38,39,42,70,89–91].

4.2. Microorganisms

In the biobed systems, the microbiota colonizing the biomixture are responsible for the pesticide degradation. Microorganisms such as bacteria and fungi may use pesticide molecules such as carbon, nitrogen, phosphorous, and energy sources for their growth. The efficient pesticide degradation by microorganisms is related to their great genetic plasticity, the production of diverse pesticide-degrading enzymes, fast growth, and adaptability to living in polluted environments [89].

The materials that integrate the biomixture retain the pesticide molecules in the biobeds and serve as a habitat for the development of different soil autochthonous microorganisms [92]. In biobeds, the presence of lignocellulosic materials reduces the pH in the system generating an environment that favors the growth and development of lignin-degrading fungi, such as different species of white-rot fungi [45]. White-rot fungi are organisms broadly reported in the biodegradation of several organic pollutants, including pesticides from different chemical families [93–98]. Fungi can produce extracellular enzymes, such as peroxidases, laccases, and the cytochrome P450 complex, implicated in pesticide degradation [99–101]. On the other hand, the presence of peat in the biomixture also favors the development of white-rot fungi in biobeds; however, in biomixtures without peat, the pesticide degradation is mediated mainly by the bacterial community [45]. Bacteria may act in synergy with fungi to enhance the pesticide and derived metabolites degradation; so, they can also produce different pesticide-degrading enzymes, such as dehalogenases, hydrolases, oxidoreductases, oxygenases, and esterases [102–106].

In biobed systems, the biomixture supports the development of broad microbial diversity, and recent studies have evaluated such microbial complexity. For example, through a metagenomics approach, Bergsveinson et al. (2018) [107] assessed the bacterial and fungal diversity in four biobed systems employed for treating pesticide rinsates with differential composition and pesticide concentrations. As a result of the study, around 440 bacterial genera and an average of 285 fungal genera were identified in each biobed system. In a similar study, Góngora-Echeverría et al. (2018) [108] identified several archaea (23), bacteria (598), and fungi (64) species in lab-scale biobed systems with the presence of a mixture of commercial pesticide formulates (2,4-D, atrazine, carbofuran, diazinon, and glyphosate). In addition, Russell et al. (2021) [109] evaluated the bacterial diversity in a two-cell biobed system. After the treatment of pesticide residues, in cell one, 81 bacterial species from 58 genera were identified, while in cell two, 36 bacterial species from 33 genera were identified. The most representative bacterial genera in both biobed cells were *Afipia*, *Sphingopyxis*, and *Pseudomonas*.

The development of a great diversity of microorganisms in the biobed systems is crucial for the efficient treatment of pesticide residues. However, the metabolic activities of the indigenous microbiota do not always guarantee total pesticide degradation. Due to this, bioaugmentation strategies have been employed to enhance pesticide biodegradation efficiency in biobed systems. This strategy is based on the addition of selected endogenous or exogenous microorganisms, such as specific fungi and bacterial strains, or the use of characterized or non-characterized microbial consortia [45,52]. The key characteristics for selecting microorganisms for a bioaugmentation strategy include pesticide resistance, high pesticide degradation efficiency, fast growth, and simple culture in lab conditions [110,111]. Examples of microorganisms used in biobed bioaugmentation strategies include uncharacterized microbial consortia, archaea species, bacteria of different phyla such as *Actinobacteria* (*Streptomyces* spp.), *Bacteroidetes*, *Firmicutes*, and mainly Proteobacteria (*Achromobacter* ssp., *Bordetella* ssp., *Pseudomonas* ssp., and *Variovorax* ssp.), and white-rot fungi from different classes (*Aphelidiomycetes* and *Pezizomycetes*) and species (*Trametes versicolor* and *Stereum hirsutum*).

4.3. Physicochemical Parameters

Pesticide dissipation effectiveness in biobed systems is strongly related to the biomixture composition and the metabolic activity of the different microorganisms; however, other key parameters include the pre-incubation time, moisture, temperature, and pesticide concentration in the system. Fernández-Alberti et al. (2012) [112] evaluated the effect of the biomixture pre-incubation time and moisture on chlorpyrifos (insecticide) degradation. In the study, the biomixture was composed of wheat straw, peat, and soil (2:1:1), pre-incubation took place (25 ± 1 °C) over 0, 15, and 30 days, and three water-holding-capacity percentages (WHC 40%, 60%, and 80%) were evaluated. The best condition for chlorpyrifos degradation (>70%) was 15 days pre-incubation and 60% WHC. Pre-incubation favors the microbial community proliferation in the biomixture, while at a high moisture (60% WHC), the ligninolytic enzyme activity in the biomixture increases.

In a similar study, Tortella et al. (2012) [113] evaluated the effect of the biomixture maturity and concentration on the chlorpyrifos degradation; the biomixture (wheat straw, peat and soil, 2:1:1) was pre-incubated over 0, 15, and 30 days; after that time, three chlorpyrifos concentrations (200, 320, and 480 $mg \cdot kg^{-1}$) were added to the biomixture. The biomixture's maturity did not affect the chlorpyrifos degradation; all the biomixtures showed degradation percentages above 50%. However, increasing the chlorpyrifos concentration reduced the degradation efficiency and the hydrolytic and phenoloxidase activities in the systems. More recently, Kumari et al. (2019) [114] evaluated the effect of pre-incubation, pesticide concentration, and moisture on the degradation process of azoxystrobin (fungicide) and imidacloprid (insecticide) in biobed systems, employing biomixtures that included rice straw/corn cobs, peat, and compost (2:1:1). Ten days of biomixture pre-incubation before pesticide application reduced by 5–9 times the degradation rate of the insecticide imidacloprid, while the increase in the WHC from 60% to 80% had a positive effect on the degradation rates of both pesticides, reducing their half-life time. However, increases in the concentration of the pesticides from 30 to 100 $mg \cdot kg^{-1}$ reduced the degradation rates of both pesticides.

Cordova-Méndez et al. (2021) [46] evaluated the effect of moisture and temperature on the dissipation of five pesticides, two insecticides: carbofuran and diazinon, and three herbicides: atrazine, 2,4-D, and glyphosate; five temperatures (5, 15, 25, 35, and 45 °C) and five water holding capacity percentages (20%, 40%, 60%, 80%, and 100%) were evaluated. The increasing temperature positively affected the dissipation of the five pesticides evaluated; the highest dissipation percentages were observed at temperatures of 35 and 45 °C. However, the increase in the water-holding percentages did not show a significant improvement in pesticide dissipation. The observed increase in pesticide dissipation was related to higher microbial activity at higher temperatures. According to the reviewed studies, for efficient pesticide treatment in biobed systems, physicochemical parameters, such as the preincubation time, moisture, temperature, and pesticide concentration in the system, must be optimized.

4.4. Analysis of the Biobeds' Treated Effluents

According to the biobed design, the systems are isolated from the soil through an impermeable layer, and it has been proposed that treated effluents ending from biobed systems could be reused for crop irrigation [115]. However, leachate analysis in biobed systems is essential to guarantee the efficiency of the treatment process and avoid releasing pesticides into the environment, causing soil and water pollution. In this sense, Henriksen et al. (2003) [58] evaluated the dissipation of the herbicides mecoprop and isoproturon in a biobed system. To determine the pesticide dissipation, the concentration of both herbicides in the leachate was assessed after a year, the concentrations of isoproturon and mecoprop were of 1.4% and 13%, respectively, of the initial dose (8 g), and the presence of a higher concentration of mecoprop in the biobed leachate was associated with its lower retention in the biobed biomixture.

The excessive effluent load in the biobed systems could be a limiting factor for pesticide retention and dissipation efficiency, causing the release of leachates with pesticide concentration above the limits established in the regulations. Foog et al. (2004) [59] evaluated the effect of reducing the effluent loads in a biobed system (1.5 m deep) over the concentration of pesticides in leachates. They observed that a reduction from 1175 to 688 L/m^2 of biomixture decreased the pesticide concentration in leachate from <0.32% to <0.006%, while a decrease to 202 L/m^2 reduced the pesticide concentration to <0.0001%; according to their results, the maximum water holding in the system for efficient pesticide dissipation was 1121 L/m^2. In another study, Spliid et al. (2006) [116] evaluated the presence of pesticides in leachates from a biobed system. The concentrations of 21 pesticides (5 g each in the mixture) were assessed through LC-MS/MS; after 593 days of treatment, only the herbicide bentazone showed a significant presence in leachates (14% of the original dose), ten pesticides were not detected in leachates, and the ten remaining pesticides showed reductions below 2% of the initial dose. The authors concluded that the biobeds were effective in retaining and degrading pesticides, generating effluents with lower pesticide concentrations.

More recently, Karas et al. (2015) [38] evaluated the risk associated with the environmental release of the biobed-depurated wastewater, the leachates containing fungicides from pilot biobed systems. The leachates included traces of fungicides (diphenylamine, imazalil, ortho-phenylphenol, and thiabendazole); acute effects were evaluated in aquatic organisms, such as the crustacean *Daphnia magna* and the fish *Oncorhynchus mykiss*, while chronic effects were assessed in the fish *Oncorhynchus mykiss*, the algae *Pseudokirchneriella subcapitata*, and sediment-dwelling invertebrates such as *Chironomus* sp. The biobed-depurated effluents with diphenylamine, imazalil, and ortho-phenylphenol did not show either an acute or chronic exposure risk in any bioindicator organism; only the effluents with thiabendazole showed an acute exposure risk for *Daphnia magna* and a chronic exposure risk for *Oncorhynchus mykiss*. In the same study, the treatment of fungicides using bioaugmentation with fungicide-degrader bacteria generated effluents that showed no acute or chronic exposure risk for the organisms evaluated. The authors conclude that biobed-treated effluents do not represent an environmental risk and can be safely disposed.

5. Recent Studies of Pesticide Biodegradation in Biobed Systems

5.1. Fungicides

Table 1 shows the key information related to recent studies on the treatment of fungicides in biobed systems. Eleven studies published over the last five years were identified. These studies assessed the dissipation of ten fungicide compounds from eight different chemical families. Among the most studied fungicides were metalaxyl (54.5%) and carbendazim (27.3%). In the biobed systems, 11 different biomixture compositions were evaluated, just one with the conventional composition: wheat straw, peat, and soil (50:25:25). Alternative biomixture compositions included the use of diverse components, such as coconut fiber (18.2%), corn cobs (18.2%), rice straw (18.2%), vine shoots/branches (18.2%), and millet stubble (9.1%), which act as lignocellulosic materials substituted for wheat straw, and compost (45.5%), vermicompost (9.1%), and spent mushroom substrate (9.1%), which acted as a peat substitute.

In most of the reviewed studies (81.8%), the microbial community in charge of the fungicide dissipation was supplemented by the soil included in the biomixture composition (the soil's indigenous microbial community). Only one study characterized the microbial community at the group level, including Proteobacteria, Firmicutes, Actinobacteria, and Acidobacteria as the most representative phyla [79]. In the study carried out by Castro-Gutiérrez et al. (2019) [117], a bioaugmentation strategy with the white rot fungus *Trametes versicolor* was used for the dissipation of the fungicides metalaxyl and carbendazim.

Table 1. Degradation of fungicide residues in biobed systems.

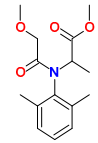
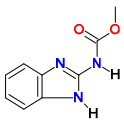
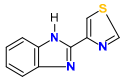
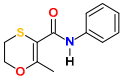
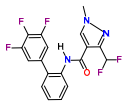
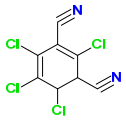
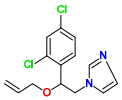
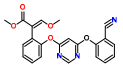
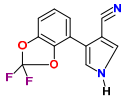
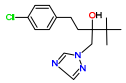
Chemical Family	Fungicide	Biomixture (%)	Microorganisms	Concentration ($mg \cdot kg^{-1}$)	Degradation (%)	Degradation Time (Days)	Analytical Determination	Reference
Acylalanine	 Metalaxyl	Wheat straw, spent mushroom substrate, and soil (25:50:25)	Soil's indigenous microbial community	9.5 †	50	3	HPLC-DAD	[42]
		Vine branches, garden compost, and soil (40:40:20)	Soil's indigenous microbial community	131.6	47	150	HPLC-UV	[74]
		Wheat straw, spent mushroom substrate, and soil (25:50:25)	Soil's indigenous microbial community	28	80	100	HPLC	[39]
		Coconut fiber, garden compost, and soil (45:13:42)	*Trametes versicolor*	30	97	16	UHPLC-MS/MS	[117]
		Vine shoots, vermicompost, and soil (25:50:25)	Soil's indigenous microbial community	50	48	15	HPLC-DAD	[74]
		Coconut fiber, garden compost, soil (50:25:25), and antibiotic oxytetracycline (10 $mg \cdot kg^{-1}$)	Proteobacteria, Firmicutes, Actinobacteria, and Acidobacteria	30	100	16	UHPLC-MS/MS	[79]
Benzimidazoles	 Carbendazim	Millet stubble and soil (50:50)	Soil's indigenous microbial community	1.14	99	60	HPLC-MS	[41]
		Coconut fiber, garden compost, and soil (45:13:42)	*Trametes versicolor*	40	97	16	UHPLC-MS/MS	[117]
		Coconut fiber, garden compost, soil (50:25:25), and antibiotic oxytetracycline (10 $mg \cdot kg^{-1}$)	Proteobacteria, Firmicutes, Actinobacteria, and Acidobacteria	40	100	16	UHPLC-MS/MS	[79]
	 Thiabendazole	Wheat straw, spent mushroom substrate, and soil (25:50:25)	Soil's indigenous microbial community	2.3 †	50	45	HPLC-DAD	[42]
Carboxamides	 Carboxin	Wheat straw, spent mushroom substrate, and soil (25:50:25)	Soil's indigenous microbial community	5.14 †	50	3.7	HPLC-DAD	[42]
				52	100	20	HPLC	[39]
	 Fluxapyroxad	Wheat straw, spent mushroom substrate, and soil (25:50:25)	Soil's indigenous microbial community	8.7 †	50	143	HPLC-DAD	[42]
				34	30	100	HPLC	[39]

Table 1. *Cont.*

Chemical Family	Fungicide	Biomixture (%)	Microorganisms	Concentration (mg·kg^{-1})	Degradation (%)	Degradation Time (Days)	Analytical Determination	Reference
Chloronitriles	 Chlorothalonil	Wheat straw, spent mushroom substrate, and soil (25:50:25)	Soil's indigenous microbial community	8.1 †	50	3	HPLC-DAD	[42]
Imidazoles	 Imazalil	Wheat straw, spent mushroom substrate, and soil (25:50:25)	Soil's indigenous microbial community	75 †	50	29	HPLC-DAD	[42]
Methoxt-acrylates	 Azoxystrobin	Rice straw, compost, and soil (40:20:20)	Soil's indigenous microbial community	100 †	82	45	HPLC-MS	[75]
		Corn cobs, compost, and soil (40:20:20)			69			
		Rice straw, compost, and soil (40:20:20)	Soil's indigenous microbial community	30 †	94.8	28	HPLC	[114]
		Rice straw, peat, and soil (40:40:20)			98.5			
		Corn cobs, compost, and soil (40:20:20)			98.4			
		Corn cobs, peat, and soil (40:20:20)			95.3			
Phenylpyrroles	 Fludioxonil	Wheat straw, spent mushroom substrate, and soil (25:50:25)	Soil's indigenous microbial community	3.2 †	50	79	HPLC-DAD	[42]
		Wheat straw, spent mushroom substrate, and soil (25:50:25)	Uncharacterized bacterial consortium	10	50	42.4	HPLC	[39]
				20				
				150				
Triazoles	 Tebuconazole	Wheat straw, peat, and soil (50:25:25)	Soil's indigenous microbial community	0.0945	100	168	UHPLC-MS/MS	[118]
		Vine shoots, vermicompost, and soil (25:50:25)	Soil's indigenous microbial community	50	13	15	HPLC-DAD	[43]

† = Dose (mg·L^{-1}). HPLC/UHPLC = high-performance liquid chromatography/ultra high-performance liquid chromatography. DAD = diode array detector. UV = ultraviolet-visible detector. MS = mass spectrometry. MS/MS = tandem mass spectrometry.

According to the identified studies, the fungicide dissipation efficiency in the biobed systems ranged from 13% to 100%. Tebuconazole (50 mg·kg^{-1}) showed the lowest degradation rate, with only 13% after 15 days in a biobed system employing a biomixture composed of vine shoots, vermicompost, and soil (25:50:25) [43]. While the dissipation of the fungicides metalaxyl (30 mg·kg^{-1}) [79], carbendazim (40 mg·kg^{-1}) [79] and carboxin (52 mg·kg^{-1}) [39] reached 100% in 16–20 days. For 54.5% of the reviewed studies, the observed fungicide dissipation was over 90%.

5.2. Herbicides

Table 2 shows information related to the recent studies on treating herbicides in biobed systems. Twelve studies published in the period between 2018 and 2022 were identified. In these studies, the dissipation of five herbicide compounds belonging to four chemical families was studied; atrazine (58.3%), glyphosate (50%), and 2,4-D (25%) were the most represented herbicides. The studies reported the use of 16 different biomixture compositions. In addition to the conventional wheat straw/stubble (25%), the reported biomixtures included in their composition alternative lignocellulosic materials, such as corn husk/stover (25%), rice straw (18.8%), alfalfa straw (12.5%), millet stubble (6.3%), seaweed (6.3), sisal (*Agave sisalana* fibers) (6.3%), and coconut fiber (6.3%). In seven (43.5%) of the biomixtures reported, peat or any alternative peat substitute was included in the composition, while in the remaining biomixtures, compost (38%), river waste (12.5%), rice husk ashes (6.3%), and wheat straw biochar (6.3%) were included in the biomixture composition as alternative materials to peat.

In five (41.7%) of the twelve reviewed studies, the soil indigenous microbial community carried out herbicide dissipation in the biobed systems. In four studies (33.3%), the main microbial (archaea, bacteria, and fungi) groups present in the biobeds were identified, and in three studies, a microbial bioaugmentation strategy was employed. Córdova-Mendez et al. (2021) [46] identified the presence of white-rot fungi growing on the biomixtures (corn husk and soil; 50:50) used for the treatment of the herbicides atrazine, glyphosate, and 2,4-D. Concerning the bioaugmentation strategies, Castro-Gutiérrez et al. (2019) [117] evaluated the use of the white-rot fungi *Trametes versicolor* as an inoculant in the biomixture (coconut fiber, garden compost, and soil; 45:13:42) for the treatment of herbicide atrazine (40 mg·kg^{-1}), observing a dissipation of 68.4% in 16 days. In addition, Kumari et al. (2022) [76] evaluated the use of a bacterial consortium previously characterized as efficient in atrazine degradation as an inoculant for the biobed system in the dissipation of a mixture of atrazine and fipronil (50 mg·L^{-1}). Employing three biomixture compositions, the atrazine dissipation ranged between 94 and 98% after 60 days.

According to the identified studies, the fungicide dissipation efficiency in the biobed systems ranged from 68% to 100%. The herbicide atrazine (40 mg·kg^{-1}) showed the lowest dissipation, 68% in 16 days, in a biobed system with a biomixture composed of coconut fiber, garden compost, and soil (45:13:42) [79], while the highest dissipation ranges were observed for glyphosate [108,119,120].

Table 2. Degradation of herbicide residues in biobed systems.

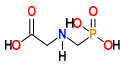
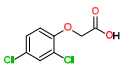
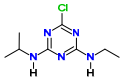
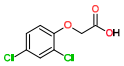
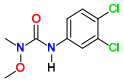
Chemical Family	Herbicide	Biomixture (%)	Microorganisms	Concentration ($mg \cdot kg^{-1}$)	Degradation (%)	Degradation Time (Days)	Analytical Determination	Reference
Organophosphates (glycines)	 Glyphosate	Millet stubble and soil (50:50)	Soil's indigenous microbial community	9.6	99	60	HPLC-MS	[38]
		Corn husk and soil (50:50)	White-rot fungi	0.8	99	20	GC-ECD-NPD	[46]
		Alfalfa straw and soil (50:50) + *Eisenia fetida*	Soil's indigenous microbial community	1000	90	90	HPLC-UV	[121]
		Alfalfa straw, river waste, and soil (50:25:25) + *Eisenia fetida*						
		Wheat stubble and soil (50:50) + *Eisenia fetida*			100			
		Wheat straw and soil (50:50)	A total of 21 species of bacteria, *Pseudomonas nitroreducens*, Rhodospirillales order, and *Pseudomonas* sp.	50 †	90	15	GC-ECD-NPD	[119]
		Alfalfa straw and soil (50:50)	Soil's indigenous microbial community	1000	85	63	HPLC-UV	[120]
		Alfalfa straw, river waste, and soil (50:25:25)			100			
		Wheat stubble and soil (50:50)						
		Wheat stubble, river waste, and soil (50:25:25)						
		Corn stover and soil (50:50)	A total of 23 species of archaea, 598 species of bacteria, and 64 species of fungi	1800 †	100	41	GC-ECD	[108]
		Seaweed, compost, and soil (25:25:50)						
		Corn stover, compost, and soil (25:25:50)						
		Corn stover, sisal, and soil (25:25:50)						
Phenoxy-carboxylates	 2,4-Dichlorophenoxyacetic acid (2,4-D)	Wheat stubble and soil (50:50)	Soil's indigenous microbial community	1200	100	30	HPLC-UV	[122]
		Corn husk and soil (50:50)	White-rot fungi	22,250	99	20	GC-ECD	[46]
		Corn stover and soil (50:50)	A total of 23 species of archaea, 598 species of bacteria, and 64 species of fungi	5400 †	88	41	GC-ECD	[108]
		Seaweed, compost, and soil (25:25:50)						
		Corn stover, compost, and soil (25:25:50)						
		Corn stover, sisal, and soil (25:25:50)						

Table 2. *Cont.*

Chemical Family	Herbicide	Biomixture (%)	Microorganisms	Concentration (mg·kg^{-1})	Degradation (%)	Degradation Time (Days)	Analytical Determination	Reference
Triazines	 Atrazine	Millet stubble and soil (50:50)	Soil's indigenous microbial community	0.68	99	20	HPLC-MS	[41]
		Rice straw, compost, and soil (25:25:50)	Atrazine degrading microbial consortium *Bacillus megaterium*	50 †	98	60	HPLC-MS/MS	[76]
		Rice straw, compost + rice husk ash, and soil (50:25:25)			94			
		Rice straw, compost + straw biochar, and soil (50:25:25)			98			
		Corn husk and soil (50:50)	White-rot fungi	1116	99	20	GC-ECD-NPD	[46]
		Coconut fiber, garden compost, and soil (45:13:42)	*Trametes versicolor*	40	68.4	16	UHPLC-MS/MS	[117]
		Corn stover and soil (50:50)	A total of 23 species of archaea, 598 species of bacteria, and 64 species of fungi	12,500	91	41	GC-ECD	[108]
		Seaweed, compost, and soil (25:25:50)						
		Corn stover, compost, and soil (25:25:50)						
		Corn stover, sisal, and soil (25:25:50)						
		Coconut fiber, garden compost, and soil (bioaugmented) (45:13:42)	Proteobacteria, Firmicutes, and Actinobacteria	40	70	16	UHPLC-MS/MS	[79]
		Coconut fiber, garden compost, soil, and antibiotic oxytetracycline (45:13:42)						
		Coconut fiber, garden compost, and soil (bioaugmented + oxytetracycline) (45:13:42)			72			
		Coconut fiber, garden compost, and soil (45:13:42)			68			
		Wheat straw, peat, and andisol topsoil (50:25:25)	Actinobacteria, bacteria and fungi	50	93	30	HPLC	[123]
	 Prometryn	Millet stubble and soil (50:50)	Soil's indigenous microbial community	4.1	99	60	HPLC	[41]
Ureas	 Linuron	Coconut fiber, compost, and soil (50:25:25)	Soil's indigenous microbial community	64	100	14	HPLC-MS	[73]

† = Dose (mg·L^{-1}). HPLC/UHPLC = high-performance liquid chromatography/ultra high-performance liquid chromatography. GC = gas chromatography. ECD = electron-capture detector. NPD = nitrogen phosphorus detector. UV = ultraviolet-visible detection. MS = mass spectrometry. MS/MS = tandem mass spectrometry.

5.3. Insecticides

Regarding the dissipation of insecticide compounds in biobed systems, 15 studies were identified from 2018 to 2022 (Table 3). These studies describe the dissipation of seven insecticide compounds belonging to five chemical families in biobed systems. The most evaluated insecticides were carbofuran, imidacloprid, and chlorpyrifos, with four studies each. In these studies, 25 biomixture compositions were evaluated, highlighting the use of alternative materials substituted for the conventional components of biomixture (wheat straw and peat). Lignocellulosic materials, such as corn husk/stover/straw (28%), coconut fiber (20%), rice straw (16%), corn cobs (8%), vine shoots/branches (8%), cereal brand (4%), millet stubble (4%), and seaweed (4%), were employed instead of wheat straw, while materials such as compost/vermicompost (60%) were the main substitutes for peat.

The soil indigenous microbial community carried out the dissipation of the insecticide compounds in the biobed systems (46.7%). In three studies (20%), the microbial community was characterized, and in five studies (33.3%), a bioaugmentation strategy was employed to enhance the insecticide dissipation in biobeds. All the insecticides evaluated reached high dissipation percentages in biobed systems, including carbofuran (98–100%), imidacloprid (22–100%), chlorpyrifos (6–100%), diazinon (98–100%), phosmet (91–99%), fipronil (80–86%), and cypermethrin (95–97%). A lower dissipation was observed for chlorpyrifos (50 $mg \cdot L^{-1}$), 6% after 28 days in a biomixture composed of wheat straw, peat, and soil (50:25:25) inoculated with *Streptomyces* spp. [124] in comparison to the study of Diez et al. (2018) [123], in which the dissipation of chlorpyrifos (50 $mg \cdot kg^{-1}$) reached 100% after 30 days in a biomixture with the same composition but with the presence of a microbial community of actinobacteria, bacteria, and fungi.

Overall, carbofuran (carbamates) and diazinon (organophosphates) showed higher dissipation ranges in the studies included in Table 3. Carbofuran (20 $mg \cdot kg^{-1}$) was dissipated at 100% after 16 days in biomixtures composed of coconut fiber, garden compost, and soil (45:13:42) bioaugmented with *Pseudomonas* sp. and *Sphingobium* sp. and the presence of the antibiotic oxytetracycline [117], while diazinon (50 $mg \cdot L^{-1}$) was dissipated at 100% after 240 days in a biomixture composed of wheat straw, peat, and soil (50:25:25), inoculated with *Streptomyces* spp. [124]. However, the same insecticide at a higher dose (1718 $mg \cdot L^{-1}$) reached dissipation ranges of 98–99% after just 41 days in a biomixture including materials such as corn stover/seaweed/sisal, compost, and soil (25:25:50) [108].

Table 3. Degradation of insecticide residues in biobed systems.

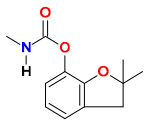
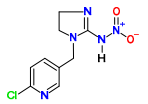
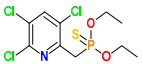
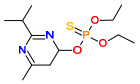
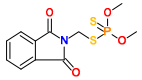
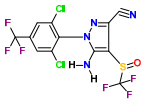
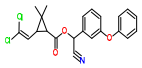
Chemical Family	Insecticide	Biomixture (%)	Microorganisms	Concentration ($mg \cdot kg^{-1}$)	Degradation (%)	Degradation Time (Days)	Analytical Determination	Reference
Carbamates	 Carbofuran	Corn husk and soil (50:50)	White-rot fungi	511	99	41	GC-MS	[46]
		Coconut fiber, garden compost, and soil (45:13:42)	*Trametes versicolor*	30	99	16	UHPLC-MS/MS	[117]
		Coconut fiber, garden compost, and soil + oxytetracycline (45:13:42)						
		Coconut fiber, garden compost, and soil + bacterial bioaugmentation (45:13:42)						
		Coconut fiber, garden compost, and soil + oxytetracycline and bacterial bioaugmentation (45:13:42)						
		Coconut fiber, garden compost, and soil (45:13:42)	Proteobacteria, firmicutes, actinobacteria, and acidobacteria	30	100	16	UHPLC	[79]
		Coconut fiber, garden compost, and soil + oxytetracycline (45:13:42)						
		Coconut fiber, garden compost, and soil bioaugmentation (45:13:42)	Proteobacteria (pseudomonas and sphingobium)					
		Coconut fiber, garden compost, and soil + oxytetracycline and bacterial bioaugmentation (45:13:42)						
		Corn stover and soil (50:50)	A total of 23 species of archaea, 598 species of bacteria, and 64 species of fungi	1145	98	20	GC-ECD-NPD	[108]
		Seaweed, compost, and soil (25:25:50)						
		Corn stover, compost and soil (25:25:50)						
		Corn stover, sisal and soil (25:25:50)						
Neonicotinoids	 Imidacloprid	Millet stubble and soil (50:50)	Soil's indigenous microbial community	9	40	60	HPLC-MS	[41]
		Rice straw, compost, and soil (40:40:20)	Soil's indigenous microbial community	100 †	100	45	HPLC-MS/MS	[76]
		Corn cob, compost, and soil (40:40:20)						
		Rice straw, compost and soil (40:40:20)	Soil's indigenous microbial community	20	70	28	HPLC	[114]
		Rice straw, peat, and soil (40:40:20)			74			
		Corn cobs, peat, and soil (40:40:20)			84			
		Corn cobs, compost, and soil (40:40:20)			90			
		Vine shoots, vermicompost, and soil (25:50:25)	Soil's indigenous microbial community	50	22	15	HPLC-DAD	[43]

Table 3. *Cont.*

Chemical Family	Insecticide	Biomixture (%)	Microorganisms	Concentration (mg·kg^{-1})	Degradation (%)	Degradation Time (Days)	Analytical Determination	Reference
Organophosphates	 Chlorpyrifos	Cereal bran, peat, and soil (50:25:25 MB1)	*Abortiporus biennis*	60	92	50	GC-ECD	[125]
		Cereal bran, peat, and soil (50:25:25 MB2)			64	21	GC-MS	
		Vine branches, compost, and soil (40:40:20)	Soil's indigenous microbial community	26.3	32	126	HPLC-UV	[74]
		Wheat straw, peat, and soil (50:25:25)	*Streptomyces* spp.	50 †	6	28	HPLC	[124]
		Wheat straw, peat, and soil (50:25:25)	Actinobacteria, bacteria, and fungi	50	100	30	HPLC	[123]
	 Diazinon	Corn husk and soil (50:50)	White-rot fungi	766	99	35	GC-MS	[46]
		Wheat straw, peat, and soil (50:25:25)	*Streptomyces* spp.	50 †	100	240	HPLC	[124]
		Corn stover and soil (50:50)	A total of 23 species of archaea, 598 species of bacteria, and 64 species of fungi	1718 †	99	41	GC-ECD-NPD	[108]
		Seaweed, compost, and soil (25:25:50)			99			
		Corn stover, compost, and soil (25:25:50)			99			
		Corn stover, sisal, and soil (25:25:50)			98			
	 Phosmet	Corn straw, peat, and soil (50:25:25 SB)	Soil's indigenous microbial community	35	91	90	UHPLC-MS/MS	[79]
		Corn straw, pine litter, and soil (50:25:25 PB)			96			
		Corn straw, vermicompost, and soil (50:25:25 VB)			99			
	Organophosphate mixture	Coconut fiber, compost, and farm soil (50:25:25)	Soil's indigenous microbial community	125	68.5	128	UHPL-MS	[72]
Phenylpyrazole	 Fipronil	Rice straw, compost + rice husk ash, and soil (50:25:25)	Soil's indigenous microbial community	50 †	80	60	HPLC-MS/MS	[76]
		Rice straw, compost + wheat straw biochar, and soil (50:25:25)			84			
		Compost, wheat straw biochar, and soil (50:25:25)			86			
Pyrethroid	 Cypermethrin	Clay and *Acacia concinna* 10% (90:10)	*Bordetella petrii* I GV 34, *Bordetella petrii* II GV 36, and *Achromobacter xyloxidans* GV 47	50 †	95	32	GC-MS	[126]
		Clay and sawdust 5% (95:5)			97			

† = Dose (mg·L^{-1}). HPLC/UHPLC = high-performance liquid chromatography/ultra high-performance liquid chromatography. GC = gas chromatography. ECD = electron-capture detector. NPD = nitrogen phosphorus detector. UV = ultraviolet-visible detection. MS = mass spectrometry. MS/MS = tandem mass spectrometry.

5.4. Characteristics and Risk Profiles of the Pesticides Treated in Biobeds

In the present review, the studies reported the treatment of 22 pesticide molecules through biobed systems. The identified pesticides included ten fungicides, five herbicides, and seven insecticides. The characteristics and risk profiles of these pesticides are shown in Table 4. According to their solubility in water, most of the pesticides have low (59.1%) or moderate (22.7%) solubility; only the fungicide metalaxyl, the herbicides 2,4-D and glyphosate, and the insecticide imidacloprid presented high solubility in water. Regarding their persistence in soils, most of the pesticides did not show great persistence (77.3%); only the fungicides fludioxonil and fluxapyroxad and the insecticides imidacloprid and fipronil were persistent, while the fungicide thiabendazole and the insecticide chlorpyrifos were very persistent. The leachability of pesticides is a significant environmental concern. The pesticides included in the present review had low or moderate leachability (86.3%); only the pesticides, Azoxystrobin (fungicide), 2,4-D (herbicide), and imidacloprid (insecticide) had high leachability capacity and therefore a greater risk for the contamination of underground water bodies. Likewise, most pesticides presented a low bioaccumulation potential (72.7%) or at the threshold for concern (27.3%).

According to their acute, oral, and dermal toxicity in rats, the WHO classifies pesticides into five groups. Most pesticides in the present review are classified as slightly or moderately hazardous (77.3%), and only one, carbofuran, is a highly hazardous pesticide. However, despite not presenting high levels of acute danger in mammals, these pesticides have other characteristics that threaten the environment and human health. All the identified pesticides have different degrees of toxicity in model organisms such as birds (50%), fish (90.9%), crustaceans, such as Daphnia magna (59.1%), pollinators, such as bees (45.5%), and earthworms (36.4%), grouping them as xenobiotics with a high ecotoxicological risk. On the other hand, the acute and chronic effects in mammals (40.9%) of these pesticides, which can be moderate or high, also have proven or possible reproductive/development effects (72.7%), endocrine disruptor profiles (54.5%), and confirmed or possible carcinogenic effects (22.7%). In the case of pesticides such as chlorpyrifos, diazinon, and phosmet, they are inhibitors of the acetylcholinesterase enzyme, while the herbicide 2,4-D and the insecticides chlorpyrifos, diazinon, fipronil, and phosmet generate neurotoxic effects in mammals; these are the reason why these pesticides are a threat to human health. All these compounds have characteristics that make them a risk for environmental and human health. Preventing their release to the environment (soil and water) from agricultural practices is crucial.

Table 4. Characteristics and risk profiles of the pesticides included in the review.

	Characteristics				**Risk Profile**		
Pesticide	**Water Solubility** [1]	**Persistence in Soil** [2]	**Leachability** [3]	**Bioaccumulative Potential** [4]	**Acute Toxicity** [5]	**Ecotoxicity** [6]	**Human Health** [7]
Fungicides							
Metalaxyl	High	Moderately persistent	Moderate	Low	Moderately hazardous	Moderate acute toxicity in birds, fish, and *Daphnia magna* Moderate chronic toxicity in *Daphnia magna* and earthworms	Moderate acute toxicity in mammals Moderate chronic toxicity in mammals
Carboxin	Moderate	Not persistent	Moderate	Low	Slightly hazardous	Moderate acute and chronic toxicity in birds, fish, *Daphnia magna*, and earthworms	Moderate chronic toxicity in mammals and possible reproduction/development effects
Imazalil	Moderate	Moderately persistent	Low	Low	Moderately hazardous	High chronic toxicity in fish	Endocrine disrupter and reproduction/development effects
Azoxystrobin	Low	Moderately persistent	High	Low	Unlikely to present acute hazard	Moderate acute toxicity in fish, *Daphnia magna*, bees, and earthworms Moderate chronic toxicity in fish, *Daphnia magna*, and earthworms	Moderate chronic toxicity in mammals and possible reproduction/development effects
Carbendazim	Low	Moderately persistent	Moderate	Low	Unlikely to present acute hazard	High chronic toxicity in fish, *Daphnia magna*, and earthworms	Endocrine disrupter and reproduction/development effects
Chlorothalonil	Low	Not persistent	Low	Threshold for concern	Unlikely to present acute hazard	High acute and chronic toxicity in fish and *Daphnia magna*	Carcinogen, endocrine disrupter, and reproduction/development effect
Fludioxonil	Low	Persistent	Low	Threshold for concern	Unlikely to present acute hazard	High acute and chronic toxicity in fish and *Daphnia magna*	Possible carcinogen and possible reproduction/development effects
Fluxapyroxad	Low	Persistent	Moderate	Low	Slightly hazardous	High chronic toxicity in fish	Possible carcinogen and possible reproduction/development effects
Tebuconazole	Low	Moderately persistent	Moderate	Low	Moderately hazardous	High chronic toxicity in birds and fish	Endocrine disrupter and reproduction/development effects
Thiabendazole	Low	Very persistent	Moderate	Low	Slightly hazardous	High chronic toxicity in fish	Moderate chronic toxicity in mammals, possible carcinogen, and possible reproduction/development effects
Herbicides							
2,4 D	High	Not persistent	High	Low	Moderately hazardous	Moderate acute toxicity in birds, fish, bees, and earthworms Moderate chronic toxicity in birds, fish, and earthworms	Endocrine disrupter, reproduction/development effects, and neurotoxicant.
Glyphosate	High	Not persistent	Low	Low	Slightly hazardous	Moderate chronic toxicity in birds, fish, and earthworms	Possible carcinogen, possible endocrine disrupter, and possible reproduction/development effects
Linuron	Moderate	Moderately persistent	Moderate	Low	Slightly hazardous	Moderate acute toxicity in birds, fishes, *Daphnia magna*, bees, and earthworms Moderatechronic toxicity in birds, fish, *Daphnia magna*, and earthworms	High chronic toxicity in mammals and high reproduction/development effects

Table 4. *Cont.*

	Characteristics				Risk Profile		
Pesticide	**Water Solubility** [1]	**Persistence in Soil** [2]	**Leachability** [3]	**Bioaccumulative Potential** [4]	**Acute Toxicity** [5]	**Ecotoxicity** [6]	**Human Health** [7]
Atrazine	Low	Moderately persistent	Moderate	Low	Slightly hazardous	Moderate acute toxicity in fish, *Daphnia magna*, and earthworms Moderate chronic toxicity in fish and *Daphnia magna*	Endocrine disrupter
Prometryn	Low	Moderately persistent	Low	Low	Slightly hazardous	High chronic toxicity in fish	Endocrine disrupter
Insecticides							
Imidacloprid	High	Persistent	High	Low	Slightly hazardous	High acute toxicity in birds and bees High chronic toxicity in birds	Reproduction/development effects
Carbofuran	Moderate	Not persistent	Moderate	Low	Highly hazardous	High acute toxicity in birds, *Daphnia magna*, and bees High chronic toxicity in fish and *Daphnia magna*	High acute toxicity in mammals, endocrine disrupter, and reproduction/development effects
Diazinon	Moderate	Not persistent	Low	Threshold for concern	Slightly hazardous	High acute toxicity in birds, *Daphnia magna*, and bees High chronic toxicity in *Daphnia magna*	Endocrine disrupter, acetyl cholinesterase inhibitor, and neurotoxicant
Chlorpyrifos	Low	Very persistent	Low	Threshold for concern	Slightly hazardous	High acute toxicity in birds, fish, *Daphnia magna*, and bees High chronic toxicity in birds, fish, *Daphnia magna*, and earthworms	High acute and chronic toxicity in mammals, endocrine disrupter, reproduction/development effects, acetyl cholinesterase inhibitor, and neurotoxicant
Cypermethrin	Low	Not persistent	Low	Threshold for concern	Slightly hazardous	High acute toxicity in fish, *Daphnia magna*, and bees High chronic toxicity in *Daphnia magna*	High acute toxicity in mammals and endocrine disrupter
Fipronil	Low	Persistent	Moderate	Threshold for concern	Slightly hazardous	High acute toxicity in birds and bees High chronic toxicity in birds and fish	High acute and chronic toxicity in mammals and neurotoxicant
Phosmet	Low	Not persistent	Low	Low	Slightly hazardous	High acute toxicity in *Daphnia magna* and bees High chronic toxicity in fish and *Daphnia magna*	Reproduction/development effects, acetyl cholinesterase inhibitor, and neurotoxicant

[1] Water solubility (20 °C; $mg \cdot L^{-1}$): low ($\leq$50), moderate (50–500), and high (>500). [2] Persistence in soil: soil aerobic degradation in days: not persistent (<30), moderately persistent (30–100), persistent (100–365), and very persistent (>365). [3] Leachability: Groundwater Ubiquity Score (GUS Index) [127]): low (<1.8), moderate (1.8–2.8), and high (>2.8). [4] Bioaccumulative potential: bio-concentration factor (kg^{-1}): low (<100), threshold for concern (100–5000), and high (>5000). [5] Acute toxicity: risk associated with acute exposure according to the WHO Recommended Classification of Pesticides by Hazard (WHO, 2020 [128]), LD_{50} ($mg \cdot kg^{-1}$ body weigh) in rats: unlikely to present acute hazard (U) (oral and dermal 5000 of higher); slightly hazardous (III), oral and dermal > 2000; moderately hazardous (II), oral 50–2000 and dermal 200–2000; highly hazardous (Ib), oral 5–200 and dermal 50–200; extremely hazardous (Ia), oral < 5 and dermal < 50. [6] Ecotoxicity: acute and chronic toxicity doses are specific to each model organism; information was taken from the Pesticide Properties Database (PPDB, Hertfordshire University, UK) [129], available at http://sitem.herts.ac.uk/aeru/ppdb/en/ (accessed on 15 June 2023). [7] Human health: acute oral effects on mammals (dose $mg \cdot kg^{-1}$): low (>2000), moderate (100–2000), and high (<100); chronic effects on mammals (dose $mg \cdot kg^{-1}d^{-1}$): low (>200), moderate (10–200), and high (<10).

6. Conclusions

Biobed systems have been proposed as an alternative for reducing pesticide pollution in crop fields. These treatment systems have become relevant worldwide due to their effectiveness, simplicity, and adaptability, thus generating alternative designs and including diverse materials in biomixture composition. Most studies in the field have evaluated alternative materials in order to substitute wheat straw and peat in the biobed biomixture. Lignocellulosic materials such as coconut fiber, corn husk/stover/straw, corn cobs, and rice straw were the most reported materials substituted for wheat straw. At the same time, compost was the most common substitute for peat. Moreover, for efficient pesticide treatment in biobed systems, physicochemical parameters, such as the preincubation time, moisture, temperature, and pesticide concentration in the system, must be considered to optimize the degradation process.

Among the reviewed studies, pesticide dissipation was mainly carried out by the soil's indigenous microbial community, which was included in the biomixture composition. However, in recent studies, metagenomic approaches have been included in characterizing the microbial community in biobed systems, identifying complex mixtures of different archaea, bacteria, and fungi species. Recently, to enhance pesticide dissipation in biobed systems, bioaugmentation with selected fungi and bacteria has been carried out with promising results. The dissipation of ten fungicide compounds, five herbicides, and seven insecticides in biobed systems was found among the reviewed studies. Overall, biobed systems lead to a high level of pesticide dissipation, above 90%, including the dissipation of pesticides of emerging concern such as glyphosate, highly hazardous pesticides such as carbofuran, and highly persistent pesticides such as atrazine. However, only some studies evaluated the dissipation of the mixtures of multiple pesticide compounds. Future research in pesticide dissipation through biobed systems must include bioaugmentation strategies with effective pesticide-degrader microorganisms to assess the dissipation of complex pesticide mixtures.

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References

1. Pawlak, K.; Kołodziejczak, M. The role of agriculture in ensuring food security in developing countries: Considerations in the context of the problem of sustainable food production. *Sustainability* **2020**, *12*, 5488. [CrossRef]
2. Pereira, P.; Barceló, D.; Panagos, P. Soil and water threats in a changing environment. *Environ. Res.* **2020**, *186*, 109501. [CrossRef] [PubMed]
3. Maja, M.M.; Ayano, S.F. The impact of population growth on natural resources and farmers' capacity to adapt to climate change in low-income countries. *Earth Syst. Environ.* **2021**, *5*, 271–283. [CrossRef]
4. Molajou, A.; Afshar, A.; Khosravi, M.; Soleimanian, E.; Vahabzadeh, M.; Variani, H.A. A new paradigm of water, food, and energy nexus. *Environ. Sci. Pollut. Res.* **2021**. [CrossRef]
5. Gomes, H.D.O.; Menezes, J.M.C.; da Costa, J.G.M.; Coutinho, H.D.M.; Teixeira, R.N.P.; do Nascimento, R.F. A socio-environmental perspective on pesticide use and food production. *Ecotoxicol. Environ. Saf.* **2020**, *197*, 110627. [CrossRef]
6. Mandal, A.; Sarkar, B.; Mandal, S.; Vithanage, M.; Patra, A.K.; Manna, M.C. Impact of agrochemicals on soil health. In *Agrochemicals Detection, Treatment and Remediation, Pesticides and Chemical Fertilizers*; Prasad, M.N.V., Ed.; Butterworth-Heinemann: Oxford, UK, 2020; pp. 161–187. [CrossRef]

7. Abubakar, Y.; Tijjani, H.; Egbuna, C.; Adetunji, C.O.; Kala, S.; Kryeziu, T.L.; Ifemeje, J.C.; Patrick-Iwuanyanwu, K.C. Pesticides, history, and classification. In *Natural Remedies for Pest, Disease and Weed Control*; Chukwuebuka Egbuna, C., Sawicka, B., Eds.; Academic Press: Oxford, UK, 2020; pp. 29–42. [CrossRef]
8. Rani, L.; Thapa, K.; Kanojia, N.; Sharma, N.; Singh, S.; Grewal, A.S.; Srivastav, A.L.; Kaushal, J. An extensive review on the consequences of chemical pesticides on human health and environment. *J. Clean. Prod.* **2020**, *283*, 124657. [CrossRef]
9. Maksymiv, I. Pesticides: Benefits and hazards. *J. Vasyl Stefanyk Precarpath. Nat. Univ.* **2015**, *2*, 70–76. [CrossRef]
10. Castrejón-Godínez, M.L.; Rodríguez, A.; Sánchez-Salinas, E.; Mussali-Galante, P.; Tovar-Sánchez, E.; Ortiz-Hernández, M.L. Soils Contaminated with Persistent Organic Pollutants (POPs): Current Situations, Management, and Bioremediation Techniques: A Mexican Case Study. In *Pesticides Bioremediation*; Siddiqui, S., Meghvansi, M.K., Chaudhary, K.K., Eds.; Springer: Cham, Switzerland, 2022; pp. 413–453. [CrossRef]
11. Brühl, C.A.; Zaller, J.G. Biodiversity decline as a consequence of an inappropriate environmental risk assessment of pesticides. *Front. Environ. Sci.* **2019**, *7*, 177. [CrossRef]
12. Tripathi, S.; Srivastava, P.; Devi, R.S.; Bhadouria, R. Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. In *Agrochemicals Detection, Treatment and Remediation, Pesticides and Chemical Fertilizers*; Agrochemicals detection, treatment and remediation; Prasad, M.N.V., Ed.; Butterworth-Heinemann: Oxford, UK, 2020; pp. 25–54. [CrossRef]
13. Sharma, A.; Kumar, V.; Shahzad, B.; Tanveer, M.; Sidhu, G.P.S.; Handa, N.; Kohli, S.K.; Yadav, P.; Bali, A.S.; Parihar, R.D.; et al. Worldwide pesticide usage and its impacts on ecosystem. *SN Appl. Sci.* **2019**, *1*, 1446. [CrossRef]
14. Dhananjayan, V.; Jayanthi, P.; Jayakumar, S.; Ravichandran, B. Agrochemicals Impact on Ecosystem and Bio-monitoring. In *Resources Use Efficiency in Agriculture*; Kumar, S., Meena, R.S., Jhariya, M.K., Eds.; Springer: Singapore, 2020; pp. 349–388. [CrossRef]
15. Phat, C.; Ty, B.; Kuok, F.; Andrews, E.M.; Kurniawan, W.; Hinode, H. Residual Pesticides. In *Water and Life in Tonle Sap Lake*; Yoshimura, C., Khanal, R., Sovannara, U., Eds.; Springer: Singapore, 2022; pp. 387–397. [CrossRef]
16. Shalaby, S.; Abdou, G. The influence of soil microorganisms and bio-or-organic fertilizers on dissipation of some pesticides in soil and potato tubers. *J. Plant Prot. Res.* **2010**, *50*, 86–92. [CrossRef]
17. Tudi, M.; Ruan, H.D.; Wang, L.; Lyu, J.; Sadler, R.; Connell, D.; Chu, C.; Phung, D.T. Agriculture development, pesticide application and its impact on the environment. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1112. [CrossRef] [PubMed]
18. Dollimore, L.; Schimpf, W. Obsolete pesticide stocks–the past 25 years, lessons learned and observations for the future. *Outlooks Pest Manag.* **2013**, *24*, 251–256. [CrossRef]
19. Vijgen, J.; Weber, R.; Lichtensteiger, W.; Schlumpf, M. The legacy of pesticides and POPs stockpiles—A threat to health and the environment. *Environ. Sci. Pollut. Res.* **2018**, *25*, 31793–31798. [CrossRef]
20. Alshemmari, H. Inventories and assessment of POPs in the State of Kuwait as a basis for Stockholm Convention implementation. *Emerg. Contam.* **2021**, *7*, 88–98. [CrossRef]
21. Mit, N.; Cherednichenko, O.; Mussayeva, A.; Khamdiyeva, O.; Amirgalieva, A.; Begmanova, M.; Tolebaeva, A.; Koishekenova, G.; Zaypanova, S.; Pilyugina, A.; et al. Ecological risk assessment and long-term environmental pollution caused by obsolete undisposed organochlorine pesticides. *J. Environ. Sci. Health B* **2021**, *56*, 490–502. [CrossRef] [PubMed]
22. Chitara, M.K.; Singh, R.P.; Gupta, P.K.; Mishra, D.; Jatav, S.S.; Sharma, S.; Jatav, H.S. The risk associated with crop ecosystem management and pesticides pollution. In *Ecosystem Services: Types, Management and Benefits*; Jatav, H.S., Rajput, V.D., Eds.; Nova Science Publishers, Inc.: New York, NY, USA, 2022; pp. 151–163.
23. Bhandari, G.; Atreya, K.; Scheepers, P.T.; Geissen, V. Concentration and distribution of pesticide residues in soil: Non-dietary human health risk assessment. *Chemosphere* **2020**, *253*, 126594. [CrossRef]
24. Singh, S.P.; Singh, M.K. Soil pollution and human health. In *Plant Responses to Soil Pollution*; Singh, P., Singh, S.K., Prasad, S.M., Eds.; Springer: Singapore, 2020; pp. 205–220. [CrossRef]
25. Morin-Crini, N.; Lichtfouse, E.; Liu, G.; Balaram, V.; Ribeiro, A.R.L.; Lu, Z.; Stock, F.; Carmona, E.; Teixeira, M.R.; Picos-Corrales, L.A.; et al. Worldwide cases of water pollution by emerging contaminants: A review. *Environ. Chem. Lett.* **2022**, *20*, 2311–2338. [CrossRef]
26. Narayanan, M.; Kandasamy, S.; He, Z.; Kumarasamy, S. Ecological impacts of pesticides on soil and water ecosystems and its natural degradation process. In *Pesticides in the Natural Environment*; Singh, P., Singh, S., Sillanpää, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 23–49. [CrossRef]
27. Sarker, S.; Akbor, M.A.; Nahar, A.; Hasan, M.; Islam, A.R.M.T.; Siddique, M.A.B. Level of pesticides contamination in the major river systems: A review on South Asian countries perspective. *Heliyon* **2021**, *7*, e07270. [CrossRef]
28. Tao, Y.; Liu, J.; Xu, Y.; Liu, H.; Yang, G.; He, Y.; Xu, J.; Lu, Z. Suspecting screening "known unknown" pesticides and transformation products in soil at pesticide manufacturing sites. *Sci. Total Environ.* **2022**, *808*, 152074. [CrossRef]
29. Bagheri, A.; Emami, N.; Damalas, C.A. Farmers' behavior towards safe pesticide handling: An analysis with the theory of planned behavior. *Sci. Total Environ.* **2021**, *751*, 141709. [CrossRef]
30. Islam, M.A.; Amin, S.N.; Rahman, M.A.; Juraimi, A.S.; Uddin, M.K.; Brown, C.L.; Arshad, A. Chronic effects of organic pesticides on the aquatic environment and human health: A review. *Environ. Nanotechnol. Monit. Manag.* **2022**, *18*, 100740. [CrossRef]
31. Syafrudin, M.; Kristanti, R.A.; Yuniarto, A.; Hadibarata, T.; Rhee, J.; Al-Onazi, W.A.; Algarmi, T.S.; Almarri, A.H.; Al-Mohaimeed, A.M. Pesticides in drinking water—A review. *Int. J. Environ. Res. Public Health* **2021**, *18*, 468. [CrossRef] [PubMed]

32. Boudh, S.; Singh, J.S. Pesticide contamination: Environmental problems and remediation strategies. In *Emerging and Eco-Friendly Approaches for Waste Management*; Bharagava, R., Chowdhary, P., Eds.; Springer: Singapore, 2019; pp. 245–269. [CrossRef]
33. Kalyabina, V.P.; Esimbekova, E.N.; Kopylova, K.V.; Kratasyuk, V.A. Pesticides: Formulants, distribution pathways and effects on human health–a review. *Toxicol. Rep.* **2021**, *8*, 1179–1192. [CrossRef] [PubMed]
34. Wang, X.; Sial, M.U.; Bashir, M.A.; Bilal, M.; Raza, Q.U.A.; Ali Raza, H.M.; Rehim, A.; Geng, Y. Pesticides xenobiotics in soil ecosystem and their remediation approaches. *Sustainability* **2022**, *14*, 3353. [CrossRef]
35. Rajmohan, K.S.; Chandrasekaran, R.; Varjani, S. A review on occurrence of pesticides in environment and current technologies for their remediation and management. *Indian J. Microbiol.* **2020**, *60*, 125–138. [CrossRef] [PubMed]
36. Raffa, C.M.; Chiampo, F. Bioremediation of agricultural soils polluted with pesticides: A review. *Bioengineering* **2021**, *8*, 92. [CrossRef]
37. Karimi, H.; Mahdavi, S.; Asgari Lajayer, B.; Moghiseh, E.; Rajput, V.D.; Minkina, T.; Astatkie, T. Insights on the bioremediation technologies for pesticide-contaminated soils. *Environ. Geochem. Health* **2022**, *44*, 1329–1354. [CrossRef]
38. Karas, P.; Metsoviti, A.; Zisis, V.; Ehaliotis, C.; Omirou, M.; Papadopoulou, E.S.; Menkissoglou-Spiroudi, U.; Manta, S.; Komiotis, D.; Karpouzas, D.G. Dissipation, metabolism and sorption of pesticides used in fruit-packaging plants: Towards an optimized depuration of their pesticide-contaminated agro-industrial effluents. *Sci. Total Environ.* **2015**, *530*, 129–139. [CrossRef]
39. Papazlatani, C.V.; Karas, P.A.; Tucat, G.; Karpouzas, D.G. Expanding the use of biobeds: Degradation and adsorption of pesticides contained in effluents from seed-coating, bulb disinfestation and fruit-packaging activities. *J. Environ. Manag.* **2019**, *248*, 109221. [CrossRef]
40. Rezende, S.; Cesio, M.V.; Archondo, L.; Russi, C.; Martínez, P.; Rivero, A.; Besil, N. Pilot study of biobeds application for the remediation of citrus agro-industrial wastewaters. *Int. J. Environ. Anal. Chem.* **2021**, 1–17. [CrossRef]
41. Lescano, M.; Fussoni, N.; Vidal, E.; Zalazar, C. Biodegradation of pesticide-contaminated wastewaters from a formulation plant employing a pilot scale biobed. *Sci. Total Environ.* **2022**, *807*, 150758. [CrossRef] [PubMed]
42. Papazlatani, C.V.; Karas, P.A.; Lampronikou, E.; Karpouzas, D.G. Using biobeds for the treatment of fungicide-contaminated effluents from various agro-food processing industries: Microbiome responses and mobile genetic element dynamics. *Sci. Total Environ.* **2022**, *823*, 153744. [CrossRef]
43. Romero, E.; Delgado-Moreno, L.; Nogales, R. Pesticide dissipation and enzyme activities in ungrassed and grassed biomixtures, composed of winery wastes, used in biobed bioremediation systems. *Water Air Soil Pollut.* **2019**, *230*, 33. [CrossRef]
44. Carniel, L.S.C.; Niemeyer, J.C.; de Oliveira Filho, L.C.I.; Alexandre, D.; Gebler, L.; Klauberg-Filho, O. Are there any risks of the disposal of pesticide effluents in soils? Biobed system meets ecotoxicology ensuring safety to soil fauna. *Ecotoxicology* **2020**, *29*, 1409–1421. [CrossRef]
45. Pinto, A.P.; Lopes, M.E.; Dordio, A.; Castanheiro, J.E.F. Bioaugmentation an effective strategy to improve the performance of biobeds: A review. In *Agrochemicals Detection, Treatment and Remediation*; Prassad, M.N.V., Ed.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 207–240. [CrossRef]
46. Córdova-Méndez, E.A.; Góngora-Echeverría, V.R.; González-Sánchez, A.; Quintal-Franco, C.; Giácoman-Vallejos, G.; Ponce-Caballero, C. Pesticide treatment in biobed systems at microcosms level under critical moisture and temperature range using an Orthic Solonchaks soil from southeastern Mexico amended with corn husk as support. *Sci. Total Environ.* **2021**, *772*, 145038. [CrossRef] [PubMed]
47. Özkara, A.; Akyıl, D.; Konuk, M. Pesticides, environmental pollution, and health. In *Environmental Health Risk-Hazardous Factors to Living Species*; Larramendy, M.L., Soloneski, S., Eds.; Intech Open: London, UK, 2016; pp. 3–27. [CrossRef]
48. Tang, F.H.; Lenzen, M.; McBratney, A.; Maggi, F. Risk of pesticide pollution at the global scale. *Nat. Geosci.* **2021**, *14*, 206–210. [CrossRef]
49. Dhananjayan, V.; Jayakumar, S.; Ravichandran, B. Conventional methods of pesticide application in agricultural field and fate of the pesticides in the environment and human health. In *Controlled Release of Pesticides for Sustainable Agriculture*; Rakhimol, K.R., Sabu, T., Tatiana, V., Jayachandran, K., Eds.; Springer: Cham, Switzerland, 2020; pp. 1–37. [CrossRef]
50. Le Cor, F.; Slaby, S.; Dufour, V.; Iuretig, A.; Feidt, C.; Dauchy, X.; Banas, D. Occurrence of pesticides and their transformation products in headwater streams: Contamination status and effect of ponds on contaminant concentrations. *Sci. Total Environ.* **2021**, *788*, 147715. [CrossRef] [PubMed]
51. Brhich, A.; Ait Sidi Brahim, M.; Merzouki, H.; Chatoui, R.; Merzouki, M. Fate and impact of pesticides: Environmental and human health issues. In *Nutrition and Human Health*; Chatoui, H., Merzouki, M., Moummou, H., Tilaoui, M., Saadaoui, N., Brhich, A., Eds.; Springer: Cham, Switzerland, 2022; pp. 41–53. [CrossRef]
52. Dias, L.D.A.; Gebler, L.; Niemeyer, J.C.; Itako, A.T. Destination of pesticide residues on biobeds: State of the art and future perspectives in Latin America. *Chemosphere* **2020**, *248*, 126038. [CrossRef]
53. Delgado-Moreno, L.; Bazhari, S.; Nogales, R.; Romero, E. Innovative application of biobed bioremediation systems to remove emerging contaminants: Adsorption, degradation and bioaccesibility. *Sci. Total Environ.* **2019**, *651*, 990–997. [CrossRef]
54. Torstensson, L.; Castillo, M. Use of biobeds in Sweden to minimize environmental spillages from agricultural spraying equipment. *Pestic. Outlook* **1997**, *8*, 24–27.
55. Torstensson, L. Experiences of biobeds in practical use in Sweden. *Pestic. Outlook* **2000**, *11*, 206–211. [CrossRef]
56. Castillo, M.D.P.; Torstensson, L.; Stenström, J. Biobeds for environmental protection from pesticide use—A review. *J. Agric. Food Chem.* **2008**, *56*, 6206–6219. [CrossRef]

57. Biobeds.org. The International Biobed Site. 2022. Available online: https://bricksite.com/biobed (accessed on 1 February 2023).
58. Henriksen, V.V.; Helweg, A.; Spliid, N.H.; Felding, G.; Stenvang, L. Capacity of model biobeds to retain and degrade mecoprop and isoproturon. *Pest Manag. Sci.* **2003**, *59*, 1076–1082. [CrossRef] [PubMed]
59. Fogg, P.; Boxall, A.B.; Walker, A.; Jukes, A. Leaching of pesticides from biobeds: Effect of biobed depth and water loading. *J. Agric. Food Chem.* **2004**, *52*, 6217–6227. [CrossRef] [PubMed]
60. Castillo, M.D.P.; Torstensson, L. Biobeds-Biotechnology for environmental protection from pesticide pollution. In *Methods and Techniques for Cleaning-Up Contaminated Sites*; Annable, M.D., Teodorescu, M., Hlavinek, P., Diels, L., Eds.; Springer: Cham, Switzerland, 2008; pp. 145–151.
61. Cooper, R.J.; Fitt, P.; Hiscock, K.M.; Lovett, A.A.; Gumm, L.; Dugdale, S.J.; Rambohul, J.; Williamson, A.; Noble, L.; Beamish, J.; et al. Assessing the effectiveness of a three-stage on-farm biobed in treating pesticide contaminated wastewater. *J. Environ. Manag.* **2016**, *181*, 874–882. [CrossRef] [PubMed]
62. Saez, J.M.; Bigliardo, A.L.; Raimondo, E.E.; Briceño, G.E.; Polti, M.A.; Benimeli, C.S. Lindane dissipation in a biomixture: Effect of soil properties and bioaugmentation. *Ecotoxicol. Environ. Saf.* **2018**, *156*, 97–105. [CrossRef]
63. Castillo, M.D.P.; Torstensson, L. Effect of biobed composition, moisture, and temperature on the degradation of pesticides. *J. Agric. Food Chem.* **2007**, *55*, 5725–5733. [CrossRef]
64. De Wilde, T.; Spanoghe, P.; Debaer, C.; Ryckeboer, J.; Springael, D.; Jaeken, P. Overview of on-farm bioremediation systems to reduce the occurrence of point source contamination. *Pest Manag. Sci.* **2007**, *63*, 111–128. [CrossRef]
65. Karanasios, E.; Karpouzas, D.G.; Tsiropoulos, N.G. Key parameters and practices controlling pesticide degradation efficiency of biobed substrates. *J. Environ. Sci. Health B* **2012**, *47*, 589–598. [CrossRef]
66. Urrutia, C.; Rubilar, O.; Tortella, G.R.; Diez, M.C. Degradation of pesticide mixture on modified matrix of a biopurification system with alternatives lignocellulosic wastes. *Chemosphere* **2013**, *92*, 1361–1366. [CrossRef]
67. Karanasios, E.; Tsiropoulos, N.G.; Karpouzas, D.G.; Menkissoglu-Spiroudi, U. Novel biomixtures based on local Mediterranean lignocellulosic materials: Evaluation for use in biobed systems. *Chemosphere* **2010**, *80*, 914–921. [CrossRef] [PubMed]
68. Diez, M.C.; Tortella, G.R.; Briceño, G.; Castillo, M.D.P.; Díaz, J.; Palma, G.; Altamirano, C.; Calderón, C.; Rubilar, O. Influence of novel lignocellulosic residues in a biobed biopurification system on the degradation of pesticides applied in repeatedly high doses. *Electron. J. Biotechnol.* **2013**, *16*, 1–11. [CrossRef]
69. Góngora-Echeverría, V.R.; Martin-Laurent, F.; Quintal-Franco, C.; Giácoman-Vallejos, G.; Ponce-Caballero, C. Agricultural effluent treatment in biobed systems using novel substrates from southeastern Mexico: The relationship with physicochemical parameters of biomixtures. *Environ. Sci. Pollut. Res.* **2017**, *24*, 9741–9753. [CrossRef] [PubMed]
70. Gao, W.; Liang, J.; Pizzul, L.; Feng, X.M.; Zhang, K.; del Pilar Castillo, M. Evaluation of spent mushroom substrate as substitute of peat in chinese biobeds. *Int. Biodeterior. Biodegrad.* **2015**, *98*, 107–112. [CrossRef]
71. Yarpuz-Bozdogan, N.; Bozdogan, A.M.; Daglioglu, N.; Sagliker, H. Determination of the effect of agricultural wastes alternative to peat in biobed. *Fresenius Environ. Bull.* **2020**, *29*, 9906–9913.
72. Masís-Mora, M.; Lizano-Fallas, V.; Tortella, G.; Beita-Sandí, W.; Rodríguez-Rodríguez, C.E. Removal of triazines, triazoles and organophophates in biomixtures and application of a biopurification system for the treatment of laboratory wastewaters. *Chemosphere* **2019**, *233*, 733–743. [CrossRef] [PubMed]
73. Acosta-Sánchez, A.; Soto-Garita, C.; Masís-Mora, M.; Cambronero-Heinrichs, J.C.; Rodríguez-Rodríguez, C.E. Impaired pesticide removal and detoxification by biomixtures during the simulated pesticide application cycle of a tropical agricultural system. *Ecotoxicol. Environ. Saf.* **2020**, *195*, 110460. [CrossRef]
74. Vischetti, C.; Monaci, E.; Casucci, C.; De Bernardi, A.; Cardinali, A. Adsorption and degradation of three pesticides in a vineyard soil and in an organic biomix. *Environments* **2020**, *7*, 113. [CrossRef]
75. Kumari, A.; Kumari, U.; Gupta, S.; Singh, N. Azoxystrobin and imidacloprid degradation in biobed setup under laboratory conditions. *J. Environ. Anal. Chem.* **2021**, *103*, 2292–2299. [CrossRef]
76. Kumari, U.; Banerjee, T.; Narayanan, N.; Yadav, S.; Singh, N. Ash and biochar mixed biomixtures to degrade co-applied atrazine and fipronil in bio-augmented biobeds. *J. Environ. Anal. Chem.* **2022**. [CrossRef]
77. Delgado-Moreno, L.; Nogales, R.; Romero, E. Biodegradation of high doses of commercial pesticide products in pilot-scale biobeds using olive-oil agroindustry wastes. *J. Environ. Manag.* **2017**, *204*, 160–169. [CrossRef] [PubMed]
78. Delgado-Moreno, L.; Nogales, R.; Romero, E. Wastes from the olive oil production in sustainable bioremediation systems to prevent pesticides water contamination. *Int. J. Environ. Sci. Technol.* **2017**, *14*, 2471–2484. [CrossRef]
79. Dias, L.D.A.; Itako, A.T.; Gebler, L.; Tolentino Júnior, J.B.; Pizzutti, I.R.; Fontana, M.E.; Janish, B.D.; Niemeyer, J.C. Pine litter and vermicompost as alternative substrates for biobeds: Efficiency in pesticide degradation. *Water Air Soil Pollut.* **2021**, *232*, 283. [CrossRef]
80. Fenoll, J.; Garrido, I.; Hellín, P.; Flores, P.; Vela, N.; Navarro, S. Use of different organic wastes as strategy to mitigate the leaching potential of phenylurea herbicides through the soil. *Environ. Sci. Pollut. Res.* **2015**, *22*, 4336–4349. [CrossRef] [PubMed]
81. Kravvariti, K.; Tsiropoulos, N.G.; Karpouzas, D.G. Degradation and adsorption of terbuthylazine and chlorpyrifos in biobed biomixtures from composted cotton crop residues. *Pest Manag. Sci.* **2010**, *66*, 1122–1128. [CrossRef]
82. Lemerhyeratte, A.; Zougagh, M.; El Mouden, O.I.; Salghi, R.; Bazzi, L.; Hormatallah, A.; Zine, S. Biobed system to reduce four pesticide organophosphorus point contamination at farm level. *Orient. J. Chem.* **2010**, *26*, 15–22.

83. Ruiz-Hidalgo, K.; Chin-Pampillo, J.S.; Masís-Mora, M.; Carazo-Rojas, E.; Rodríguez-Rodríguez, C.E. Optimization of a fungally bioaugmented biomixture for carbofuran removal in on-farm biopurification systems. *Water Air Soil Pollut.* **2016**, *227*, 3. [CrossRef]
84. Castro-Gutiérrez, V.; Masís-Mora, M.; Carazo-Rojas, E.; Mora-López, M.; Rodríguez-Rodríguez, C.E. Impact of oxytetracycline and bacterial bioaugmentation on the efficiency and microbial community structure of a pesticide-degrading biomixture. *Environ. Sci. Pollut. Res.* **2018**, *25*, 11787–11799. [CrossRef]
85. Cessna, A.J.; Knight, J.D.; Ngombe, D.; Wolf, T.M. Effect of temperature on the dissipation of seven herbicides in a biobed matrix. *Can. J. Soil Sci.* **2017**, *97*, 717–731. [CrossRef]
86. El Bakouri, H.; Morillo, J.; Usero, J.; Vanderlinden, E.; Vidal, H. Effectiveness of acid-treated agricultural stones used in biopurification systems to avoid pesticide contamination of water resources caused by direct losses: Part I. Equilibrium experiments and kinetics. *Bioresour. Technol.* **2010**, *101*, 5084–5091. [CrossRef]
87. Karanasios, E.; Tsiropoulos, N.G.; Karpouzas, D.G.; Ehaliotis, C. Degradation and adsorption of pesticides in compost-based biomixtures as potential substrates for biobeds in Southern Europe. *J. Agric. Food Chem.* **2010**, *58*, 9147–9156. [CrossRef]
88. Rojas, R.; Morillo, J.; Usero, J.; Vanderlinden, E.; El Bakouri, H. Adsorption study of low-cost and locally available organic substances and a soil to remove pesticides from aqueous solutions. *J. Hydrol.* **2015**, *520*, 461–472. [CrossRef]
89. Briceño, G.; Tortella, G.; Rubilar, O.; Palma, G.; Diez, M.C. Advances in Chile for the treatment of pesticide residues: Biobeds technology. In *Bioremediation in Latin America: Current Research and Perspectives*; Alvarez, A., Polti, M., Eds.; Springer: Cham, Switzerland, 2014; pp. 53–68. [CrossRef]
90. Kumari, U.; Banerjee, T.; Singh, N. Evaluating ash and biochar mixed biomixtures for atrazine and fipronil degradation. *Environ. Technol. Innov.* **2021**, *23*, 101745. [CrossRef]
91. Karas, P.A.; Makri, S.; Papadopoulou, E.S.; Ehaliotis, C.; Menkissoglu-Spiroudi, U.; Karpouzas, D.G. The potential of organic substrates based on mushroom substrate and straw to dissipate fungicides contained in effluents from the fruit-packaging industry–Is there a role for *Pleurotus ostreatus*? *Ecotoxicol. Environ. Saf.* **2016**, *124*, 447–454. [CrossRef] [PubMed]
92. Adak, T.; Mahapatra, B.; Swain, H.; Patil, N.B.; Gowda, G.B.; Annamalai, M.; Pokhare, S.S.; Meena, K.S.; Rath, P.C.; Jena, M. Indigenous biobed to limit point source pollution of imidacloprid in tropical countries. *J. Environ. Manag.* **2020**, *272*, 111084. [CrossRef] [PubMed]
93. Mohapatra, D.; Rath, S.K.; Mohapatra, P.K. Bioremediation of insecticides by white-rot fungi and its environmental relevance. In *Mycoremediation and Environmental Sustainability*; Prasad, R., Ed.; Springer: Cham, Switzerland, 2018; pp. 181–212. [CrossRef]
94. Chandra, P.; Enespa. Fungal Enzymes for Bioremediation of Contaminated Soil. In *Recent Advancement in White Biotechnology through Fungi*; Yadav, A., Singh, S., Mishra, S., Gupta, A., Eds.; Springer: Cham, Switzerland, 2019; pp. 189–215. [CrossRef]
95. Singh, R.K.; Tripathi, R.; Ranjan, A.; Srivastava, A.K. Fungi as potential candidates for bioremediation. In *Abatement of Environmental Pollutants*; Singh, P., Kumar, A., Borthakur, A., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 177–191. [CrossRef]
96. Kathiravan, A.; Gnanadoss, J.J. White-rot fungi-mediated bioremediation as a sustainable method for xenobiotic degradation. *Environ. Exp. Biol.* **2021**, *19*, 103–119. [CrossRef]
97. Tomer, A.; Singh, R.; Singh, S.K.; Dwivedi, S.A.; Reddy, C.U.; Keloth, M.R.A.; Rachel, R. Role of fungi in bioremediation and environmental sustainability. In *Mycoremediation and Environmental Sustainability*; Prasad, R., Nayak, S.C., Kharwar, R.N., Dubey, N.K., Eds.; Springer: Cham, Switzerland, 2021; pp. 187–200. [CrossRef]
98. Vaksmaa, A.; Guerrero-Cruz, S.; Ghosh, P.; Zeghal, E.; Hernando-Morales, V.; Niemann, H. Role of fungi in bioremediation of emerging pollutants. *Front. Mar. Sci.* **2023**, *10*, 1070905. [CrossRef]
99. Singh, N.; Kumar, A.; Sharma, B. Role of fungal enzymes for bioremediation of hazardous chemicals. In *Recent Advancement in White Biotechnology through Fungi*; Yadav, A., Singh, S., Mishra, S., Gupta, A., Eds.; Springer: Cham, Switzerland, 2019; pp. 237–256. [CrossRef]
100. Zhuo, R.; Fan, F. A comprehensive insight into the application of white rot fungi and their lignocellulolytic enzymes in the removal of organic pollutants. *Sci. Total Environ.* **2021**, *778*, 146132. [CrossRef] [PubMed]
101. Lin, S.; Wei, J.; Yang, B.; Zhang, M.; Zhuo, R. Bioremediation of organic pollutants by white rot fungal cytochrome P450: The role and mechanism of CYP450 in biodegradation. *Chemosphere* **2022**, *301*, 134776. [CrossRef]
102. Ortiz-Hernández, M.L.; Sánchez-Salinas, E.; Dantán-González, E.; Castrejón-Godínez, M.L. Pesticide biodegradation: Mechanisms, genetics and strategies to enhance the process. In *Biodegradation-Life of Science*; Chamy, R., Rosenkranz, F., Eds.; IntechOpen: London, UK, 2013; pp. 251–287. [CrossRef]
103. Kumar, S.; Kaushik, G.; Dar, M.A.; Nimesh, S.; López-Chuken, U.J.; Villarreal-Chiu, J.F. Microbial degradation of organophosphate pesticides: A review. *Pedosphere* **2018**, *28*, 190–208. [CrossRef]
104. Kumar, S.S.; Ghosh, P.; Malyan, S.K.; Sharma, J.; Kumar, V. A comprehensive review on enzymatic degradation of the organophosphate pesticide malathion in the environment. *J. Environ. Sci. Health C* **2019**, *37*, 288–329. [CrossRef] [PubMed]
105. Dave, S.; Das, J. Role of microbial enzymes for biodegradation and bioremediation of environmental pollutants: Challenges and future prospects. In *Bioremediation for Environmental Sustainability*; Saxena, G., Kumar, V., Shah, M.P., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 325–346. [CrossRef]
106. Saravanan, A.; Kumar, P.S.; Vo, D.V.N.; Jeevanantham, S.; Karishma, S.; Yaashikaa, P.R. A review on catalytic-enzyme degradation of toxic environmental pollutants: Microbial enzymes. *J. Hazard. Mater.* **2021**, *419*, 126451. [CrossRef]

107. Bergsveinson, J.; Perry, B.J.; Sheedy, C.; Braul, L.; Reedyk, S.; Gossen, B.D.; Yost, C.K. Identifying the core bacterial and fungal communities within four agricultural biobeds used for the treatment of pesticide rinsates. *J. Appl. Microbiol.* **2018**, *125*, 1333–1342. [CrossRef] [PubMed]
108. Góngora-Echeverría, V.R.; Quintal-Franco, C.; Arena-Ortiz, M.L.; Giácoman-Vallejos, G.; Ponce-Caballero, C. Identification of microbial species present in a pesticide dissipation process in biobed systems using typical substrates from southeastern Mexico as a biomixture at a laboratory scale. *Sci. Total Environ.* **2018**, *628*, 528–538. [CrossRef]
109. Russell, J.N.; Perry, B.J.; Bergsveinson, J.; Freeman, C.N.; Sheedy, C.; Nilsson, D.; Braul, L.; Yost, C.K. Metagenomic and metatranscriptomic analysis reveals enrichment for xenobiotic-degrading bacterial specialists and xenobiotic-degrading genes in a Canadian prairie two-cell biobed system. *Environ. Microbiol. Rep.* **2021**, *13*, 720–727. [CrossRef] [PubMed]
110. Cycoń, M.; Mrozik, A.; Piotrowska-Seget, Z. Bioaugmentation as a strategy for the remediation of pesticide-polluted soil: A review. *Chemosphere* **2017**, *172*, 52–71. [CrossRef]
111. Magan, N.; Gouma, S.; Fragoeiro, S.; Shuaib, M.E.; Bastos, A.C. Bacterial and fungal bioremediation strategies. In *Microbial Biodegradation and Bioremediation*; Das, S., Dash, H.R., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 193–212. [CrossRef]
112. Fernández-Alberti, S.; Rubilar, O.; Tortella, G.R.; Diez, M.C. Chlorpyrifos degradation in a biomix: Effect of pre-incubation and water holding capacity. *J. Soil Sci. Plant Nutr.* **2012**, *12*, 785–799. [CrossRef]
113. Tortella, G.R.; Rubilar, O.; Castillo, M.; Cea, M.; Mella-Herrera, R.; Diez, M.C. Chlorpyrifos degradation in a biomixture of biobed at different maturity stages. *Chemosphere* **2012**, *88*, 224–228. [CrossRef]
114. Kumari, A.; Singh, N.; Ramakrishnan, B. Parameters affecting azoxystrobin and imidacloprid degradation in biobed substrates in the North Indian tropical environment. *J. Environ. Sci. Health B* **2019**, *54*, 843–857. [CrossRef]
115. Basford, B. BIOBEDS. *Outlooks Pest Manag.* **2010**, *21*, 78–80. [CrossRef]
116. Spliid, N.H.; Helweg, A.; Heinrichson, K. Leaching and degradation of 21 pesticides in a full-scale model biobed. *Chemosphere* **2006**, *65*, 2223–2232. [CrossRef] [PubMed]
117. Castro-Gutiérrez, V.; Masís-Mora, M.; Carazo-Rojas, E.; Mora-López, M.; Rodríguez-Rodríguez, C.E. Fungal and bacterial co-bioaugmentation of a pesticide-degrading biomixture: Pesticide removal and community structure variations during different treatments. *Water Air Soil Pollut.* **2019**, *230*, 247. [CrossRef]
118. Veiga-Bernardelli, P.; Nagel-Hassemer, M.; Gebler, L. Introduction of advanced oxidative pre-treatment in the biobed reactor system in the final disposal process of pesticide effluents. *Chem. Eng. Trans.* **2021**, *86*, 685–690. [CrossRef]
119. Lescano, M.R.; Masin, C.E.; Rodríguez, A.R.; Godoy, J.L.; Zalazar, C.S. Earthworms to improve glyphosate degradation in biobeds. *Environ. Sci. Pollut. Res.* **2020**, *27*, 27023–27031. [CrossRef] [PubMed]
120. Góngora-Echeverría, V.; García-Escalante, R.; Rojas-Herrera, R.; Giácoman-Vallejos, G.; Ponce-Caballero, C. Pesticide bioremediation in liquid media using a microbial consortium and bacteria-pure strains isolated from a biomixture used in agricultural areas. *Ecotoxicol. Environ. Saf.* **2020**, *200*, 110734. [CrossRef] [PubMed]
121. Lescano, M.R.; Pizzul, L.; Castillo, M.D.P.; Zalazar, C.S. Glyphosate and aminomethylphosphonic acid degradation in biomixtures based on alfalfa straw, wheat stubble and river waste. *J. Environ. Manag.* **2018**, *228*, 451–457. [CrossRef] [PubMed]
122. Fernandez, M.E.; Morel, M.R.; Clebot, A.C.; Zalazar, C.S.; Ballari, M.M. Effectiveness of a simple biomixture for the adsorption and elimination of 2,4-dichlorophenoxyacetic acid (2,4-D) herbicide and its metabolite, 2,4-dichlorophenol (2,4-DCP), for a biobed system. *J. Environ. Chem. Eng.* **2022**, *10*, 106877. [CrossRef]
123. Diez, M.C.; Leiva, B.; Gallardo, F. Novel insights in biopurification system for dissipation of a pesticide mixture in repeated applications. *Environ. Sci. Pollut. Res.* **2018**, *25*, 21440–21450. [CrossRef]
124. Rivero, A.; Gérez, N.; Jesús, F.; Niell, S.; Pia-Cerdeiras, M.; Heinzen, H.; Cesio, M.V. Unambiguous evaluation of chlorpyrifos and TCP bioremediation in laboratory and field experiments. *Int. J. Environ. Anal. Chem.* **2022**, *102*, 6845–6857. [CrossRef]
125. Briceño, G.; Vergara, K.; Schalchli, H.; Palma, G.; Tortella, G.; Fuentes, M.S.; Diez, M.C. Organophosphorus pesticide mixture removal from environmental matrices by a soil S treptomyces mixed culture. *Environ. Sci. Pollut. Res.* **2018**, *25*, 21296–21307. [CrossRef]
126. Odukkathil, G.; Vasudevan, N. Bacteria amended clay biochar composite biobed system to treat agriculture runoff. *J. Environ. Manag.* **2020**, *269*, 110694. [CrossRef] [PubMed]
127. Gustafson, D.I. Groundwater ubiquity score: A simple method for assessing pesticide leachability. *Environ. Toxicol. Chem. Int. J.* **1989**, *8*, 339–357. [CrossRef]
128. Inter-Organization Programme for the Sound Management of Chemicals; World Health Organization. *The WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification 2019*; World Health Organization: Geneva, Switzerland, 2020; 92p. Available online: https://www.who.int/publications/i/item/9789240005662 (accessed on 15 June 2023).
129. Hertfordshire University. *PPDB: Pesticide Properties DataBase*; University of Hertfordshire: Hatfield, UK, 2017; Available online: http://sitem.herts.ac.uk/aeru/ppdb/en/ (accessed on 12 June 2023).