Sorption/Desorption, Leaching, and Transport Behavior of Pesticides in Soils: A Review on Recent Advances and Published Scientific Research

Maria C. Vagi and Andreas S. Petsas

Contents

Abstract Pesticides are chemical compounds designed to be used as plant protection products (PPPs). They are applied in the field for the protection of plants against pests, weeds, and several diseases that affect and decrease the quantity and quality of agricultural crop products. After their environmental release, these synthetic substances undergo a variety of abiotic and biotic processes which determine their distribution in the environmental compartments, and consequently their fate and persistence. Sorption, desorption, and leaching are some of the processes that are included among the most important transportation pathways. Due to their extensive

M. C. Vagi (✉)
Laboratory of Environmental Quality and Geo-spatial Applications, Department of Marine Sciences, School of the Environment, University of the Aegean, Mytilene, Lesvos, Greece
e-mail: mbag@env.aegean.gr

A. S. Petsas
Department of Food Science and Nutrition, School of the Environment, University of the Aegean, Myrina, Lemnos, Greece
e-mail: apetsas@env.aegean.gr

application and their potential ecotoxicological effects, the global scientific interest focusing on the research of the environmental fate and behavior of pesticides after their entrance in the environmental matrices is undiminished. The present chapter is a review of the recent scientific literature regarding the recent research on the fate of pesticides in soil regarding the processes of sorption/desorption and leaching. Based on the gathered information derived from the reviewed articles on the subject published in the last 5.5 years (from 01/01/2016 to 30/06/2021), useful conclusions and observations are reported about research trends. Furthermore, knowledge gaps in the current research are highlighted and suggestions for future research on this topic are also discussed.

Keywords Desorption, Environmental fate, Leaching, Organic micropollutants, Persistent organic pollutants, Pesticides, Soil distribution, Sorption, Transportation

1   Introduction

A wide variety of anthropogenic compounds with organic nature that are synthetic compounds produced for multiple purposes or applications are extensively used worldwide, such as personal care products, drugs and medicines, pharmaceuticals, plastics and polymers, dyes, solvents, endocrine-disrupting compounds, and several others. Pesticides, also known as PPPs, are also included among this long list of persistent organic pollutants (POPs) which are characterized as potential toxicants toward nontarget organisms.

More specific, the term pesticide is used for substances designed to be applied as PPPs against various pests, weeds, and diseases that are harmful to cultivated plants, and consequently threat and affect the crop yields. Their molecules are characterized by different physicochemical properties, mobility, bioavailability, and toxicity.

Concentrations of pesticides have been detected and measured in numerous environmental samples such as soil [1], surface water [2, 3], groundwater [4], sediment [2, 3], edible cultured fruits, vegetables, and agricultural products [5, 6]. In a recent study of Zhang et al. [3] investigating the occurrence of five target neonicotinoid insecticides in soil-water-sediment systems of urban and rural areas in South China the concentration levels of reported results were within the range of 0.003–229 ng g^{-1} (dry weight, dw), 7.94–636 ng L^{-1}, and 0.017–31.3 ng g^{-1} (dw) for soil, water, and sediment samples, respectively. According to a different study of Pico et al. [6] the pesticide residues of 15 compounds (mainly insecticides and fungicides) out of a list of 62 substances belonging to a wide variety of chemical classes were detected in fruits from Saudi Arabia, whereas in 20% of the samples the detectable concentrations were above the maximum residue limits (MRLs). The results of a survey conducted by Zambito Marsala et al. [4] revealed the presence of seven pesticides (chlorantraniliprole, dimethomorph, fluopicolide, metalaxyl, penconazole, and tetraconazole) in 30% of the studied wells (situated in the Tidone

Valley, Province of Piacenza, North-West of Italy) at a level higher than 0.1 μg L^{-1} that is the Environmental Quality Standard (EQS) for groundwater.

Based on the relevant published scientific literature, the occurrence, distribution, and persistence of those POPs in the ecosystems is a subject on which the interest of the global scientific community is focused undiminished. Therefore, the aim of the present study is to carry out a review concerning the scientific articles published within the last 5.5 years (from 01/01/2016 to 30/06/2021), regarding the research of the environmental fate of pesticides in natural soil samples and under different environmental conditions.

In more details, the current chapter provides a review of pesticides and selected transportation and distribution processes, which take place into soil environments and therefore determine the bioavailability and persistence of the selected molecules into field systems. The first section provides general data about the topic of discussion, i.e., pesticides classification, pathways of their entry into terrestrial matrices, and interactions between different environmental compartments. Subsequent sections discuss selected migration and mobility mechanisms on which the global scientific research interest has been focused. Particularly, the studies focusing on the phenomena of sorption/desorption and leaching are reviewed, and their main findings are summarized.

2 Pesticides in Soil Samples

An expansive range of synthetic pesticides belonging to different chemical classes, possessing diverse physicochemical properties, and targeting to multiple and dissimilar pests are available in the market. Those compounds are mainly used in agriculture and applied in the cultured fields.

Based on the criteria of their chemical structure pesticides are subdivided into categories of anilides, amides, organophosphates, organothiophosphates, carbamates, benzothiazoles, triazines, neonicotinoids, organochlorines, and many other chemical classes. The classification of pesticides based on their target organisms includes the classes of acaricides, fungicides, herbicides, insecticides, nematicides, and plant growth regulators. According to the World Health Organization (WHO) the classification of pesticides, based on their hazard towards exposed organisms, contains five classes which are: extremely hazardous (Class Ia), highly hazardous (Class Ib), moderately hazardous (Class II), slightly hazardous (Class III), and unlikely to present acute hazard (Class U) [7].

The introduction of pesticides into the environment takes place mainly through agricultural and urban applications of disease vectors control. Once in the soil, pesticides can enter aquatic environmental bodies through alternative pathways. The main phenomena that are responsible for the mitigation of pesticides are diffuse processes, surface runoff, leaching, erosion, spray-drift, and atmospheric deposition after their volatilization [8, 9].
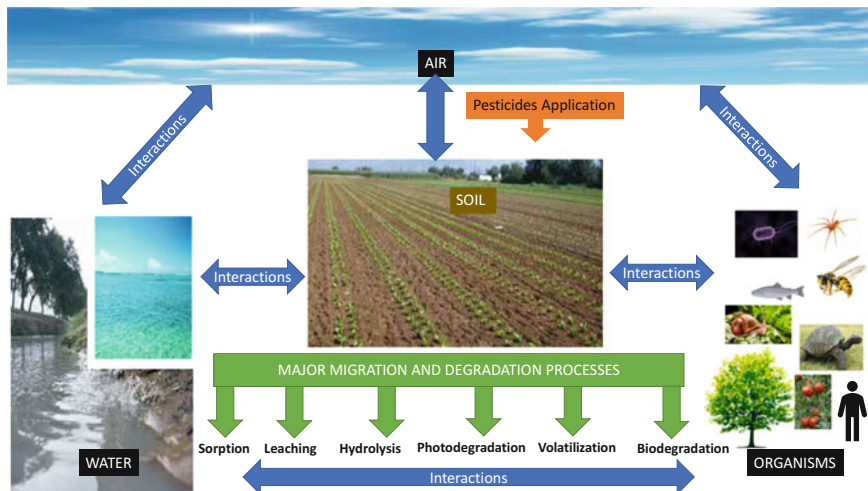
Fig. 1 Major migration and degradation processes to which pesticides substances are subjected to after their application in the field and interactions between other environmental compartments

As shown in Fig. 1, possible transfer and distribution of pesticide compounds between soil, water, air, and biota matrices occur while the extent of each interaction and exchanging phase phenomenon is affected by several parameters, which in turn are simultaneously dependent on: (1) the molecule and its physicochemical properties, (2) the characteristics of the environmental substrate that contains the pesticide, (3) the application practice in terms of method, pesticide load, frequency, time season, and other factors, (4) the environmental conditions such as temperature, wind, etc., and finally (5) the geological and climatic characteristics of the site of the application [10, 11].

After entering the environmental matrices, they go under chemical, (direct/indirect) photochemical, or biological degradation processes that are possible to take place concurrently with other physical phenomena that determine their removal and distribution into different environmental substrates, such as adsorption, evaporation, and surface movement [9].

Data concerning the major factors affecting the environmental fate and persistence of a pesticide are detailed in Fig. 2. Consequently, due to their unquestionable occurrence in residual quantities contained in various natural matrices and the potential ecotoxicological impacts increased scientific concerns have been raised.

In the subsequent sections, some of the main distribution and degradation pathways that determine the fate of pesticides in soil-water systems are discussed and the most important results of reviewed bibliography are summarized and presented.
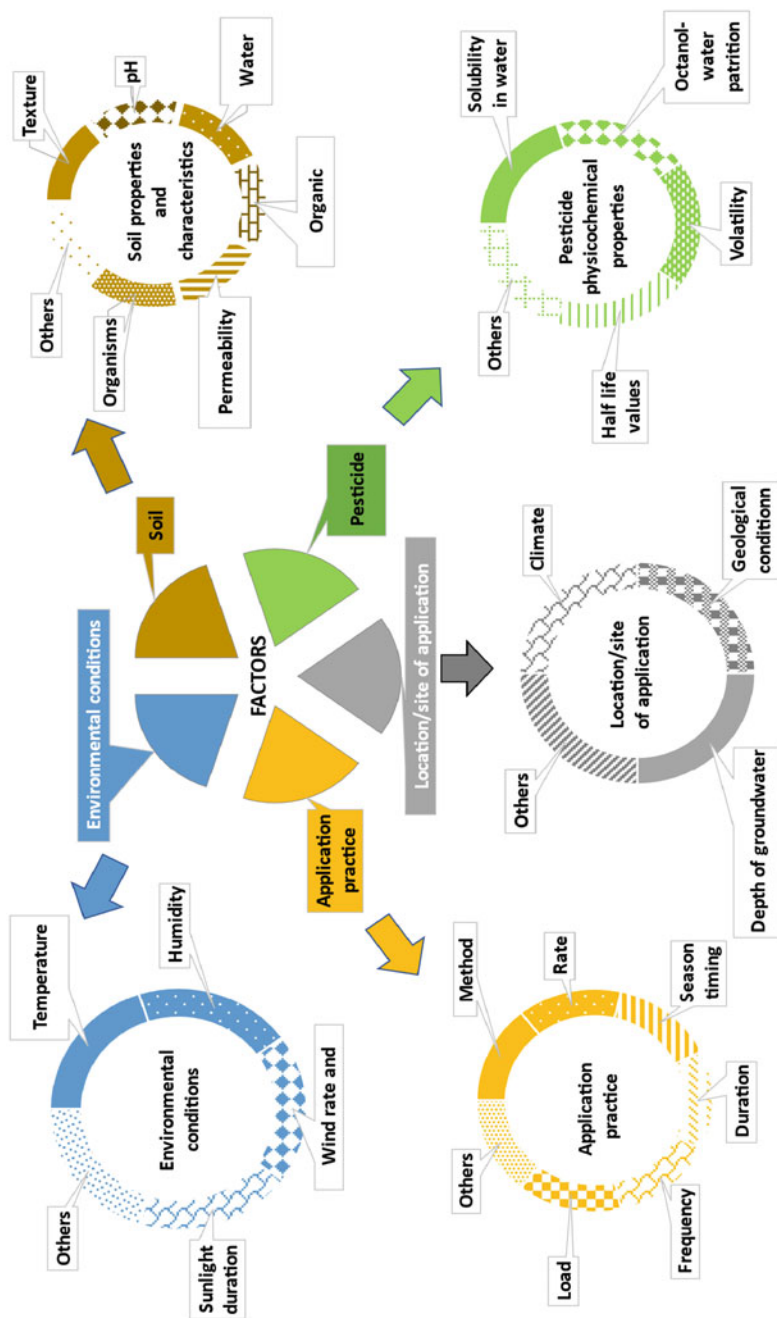
Fig. 2 Principal factors that affect the environmental fate of pesticides [Adapted from Pietrzak et al. [10], after Perez-Lucas et al. [11] and modified]

2.1 Sorption on Soil

Sorption of organic pesticides' molecules onto the solid phase constituents of soil (such as clay minerals, organic matter (OM), oxides and hydroxides of aluminum and iron) is one of the most important and primary processes that can occur either via a reversible or a non-reversible mechanism and therefore influence the amount of the pesticide that remains mobile in soil-water systems or not. When present in the soil many pesticides are bound to soil colloids (clay, OM), and consequently become less readily available to plants than the molecules that are not adsorbed and continue to move in the soil solution.

Several reviews, overviews, and meta-analysis studies on the sorption of pesticides among other POPs have been published in the past few years [8, 10–19]. According to the conclusions and findings of all published review works, the general agreement that sorption of pesticides by soils has been stated and reported.

Moreover, according to the findings of the present review in the same period of the last 5.5 years (2016–2021), a large number of modeling studies dealing with the pesticides transport and mobility in soils, leaching risk assessments, sorption data (such as adsorption constants K_{oc}), subsurface fate and dynamics have been published [20–34].

Numerous theoretical and empirical sorption and desorption isotherm models have been used for the kinetics of the studied processes. Undoubtedly, (ad)sorption and/or desorption isotherms are frequently described by linear and nonlinear models among which Freundlich, Langmuir, Elovich, and Henry isotherm adsorption models are included which fit well the acquired experimental data. In Eq. 1 the logarithmic Freundlich model is described:

$$\frac{x}{m} = C_s = K_F * C_e^{1/n} \tag{1}$$

where K_F is the Freundlich equilibrium constant (usually in $\mu g^{(1-1/n)}\, mL^{1/n} g^{-1}$), C_e is the concentration of the selected and studied pesticide (usually in $\mu g\, mL^{-1}$) after the equilibration, C_s is the concentration of the (ad)sorbed pesticide in soil matrix ($\mu g\, g^{-1}$), and finally $1/n$ is the linearity degree.

With the condition that the adsorption of pesticides' reactive groups over the soils' particulates proceeds through a homogeneous distribution onto the adsorbents' surface and that no later interactions occur between adjacent adsorbed molecules that occupy a single surface site, the Langmuir adsorption isotherm can be applied which is described by the mathematical formulations of Eqs. 2 (nonlinear form) and 3 (linear form):

$$q_e = \frac{K_L * b * C_e}{1 + b * C_e} \tag{2}$$

$$\frac{C_e}{q_e} = \frac{1}{K_L * q_m} + \frac{C_e}{q_m} \tag{3}$$

where q_e and K_L are the concentration of adsorbed pesticide and the adsorption equilibrium constant, respectively, whereas q_m and C_e are the maximum adsorption capacity and the concentration of the pesticide compound in soil-water system, correspondingly after the equilibration.

A multilayer adsorption is described by Elovich's model that is expressed by the mathematical expression of Eq. 4:

$$\frac{q_e}{q_m} = b_e * C_e^{-\frac{q_e}{q_m}} \tag{4}$$

Among the several main mechanisms that have been proposed to explain the adsorption of pesticides onto the soil colloid components, van der Waals force attraction (dipole–dipole interactions), hydrophobic bonding, hydrogen bonding, charge transfer (electrostatic attraction), ion exchange, and ligand exchange mechanisms are included. Depending on the nature and physicochemical characteristics of pesticide molecules and soil constituents (acidity or basicity, solubility, charge distribution on the molecule, polarity, molecule size, polarizability, etc.) simultaneously mechanisms may occur [14, 15, 18, 30, 32].

2.2 Leaching in Soil

Frequently, the movement of solute pesticides occurs through the soil profile by the effect of water, rainwater, or irrigation water. In this way, the vertical transportation of several pesticides into the soil column by runoff is often observed and the removal of those molecules from topsoil into lower subsoil depths takes place. This process is known by the term leaching and via this phenomenon, the downward migration of organic pollutants through the unsaturated zone to groundwater is possible to happen. Therefore, the potential displacement of organic pesticides from the soil surface and root zone to aquifers which are consequently vulnerable to pollution toward pesticides used in crop production is a subject on which the scientific interest has been focused.

Diffusion and mass flow phenomena that take place simultaneously may be involved in the leaching process of pesticides through soil in the solution phase. According to the published scientific literature, numerous models have been developed and evaluated that describe the leaching of organic pesticides in the root zone and the intermediate vadose zone, and the flushing of residual solute mass in the aquifer [25, 32, 33].

3 Results and Discussion

3.1 Overview of Found Data Published in the Last 5.5 Years Regarding the Transportation Behavior of Pesticides in Soils

The search was based on "Scopus Database" using as keywords the terms "pesticide," and "soil," and "sorption" or "desorption" or "leaching" process. Only original research publications since 2016 were considered, while all critical reviews and overviews published in the same period were excluded. Target pollutants are tested either individually or in mixture with other toxic pollutants.

Numerous scientific publications have arisen by researchers in the last 5.5 years concerning the investigations on the distribution and mobility of pesticides into soil compartments after their entrance into the field. More specific, during the current overview a great number of publications, overall 228 reports retrieved by "Scopus Database" have been found for the period 2016–2021 (during 01/01/2016 to 30/06/2021) regarding several different pesticides that belong to a wide variety of chemical families and have been investigated for their efficiency to be (ad)sorbed, desorbed on soils, and transported into groundwater.
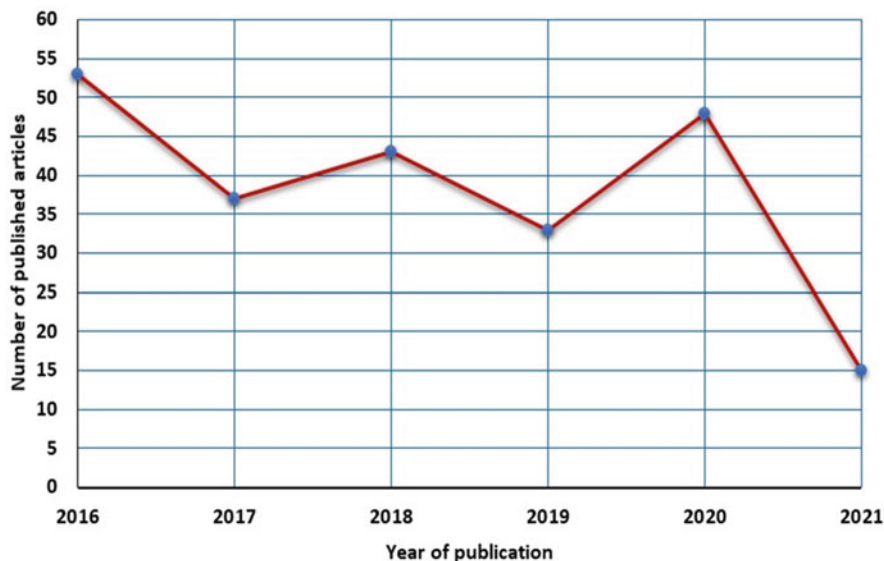
The annual number of records published for each year overviewed on investigating the (ad)sorption, desorption, and leaching processes of pesticides in natural soil substrates is illustrated in Fig. 3. In this point it must be underlined the fact that the survey for 2021 is restricted only to the first half of the year (from 01/01/2021 to 30/06/2021) that explains the low number of findings. In general, a slightly variable annual number of scientific published data regarding the theme is noticed that approaches the mean value of 40 reports per year (Fig. 3).

Table 1 provides a summary of all the 228 reviewed published data found during the present review work for each individual pesticide compound reported. The search was based on "Scopus Database" using as keywords the terms pesticide, soil, and sorption or desorption or leaching process. Only original research publications since 2016 were considered, while all critical reviews and overviews published in the same period were excluded. Target pollutants are tested either individually or in mixture with other toxic pollutants.

According to the findings of the current review it is observed that among the overall 186 individual pesticides for which evaluation of adsorption/desorption capacity on soil, leaching, and transportation process has been surveyed the triazine herbicide atrazine is the one on which scientific interest has been focused (24 reviewed articles, Table 1), followed by the organophosphorus insecticide chlorpyrifos (21 reviewed articles, Table 1), the nicotinoid insecticide imidacloprid (15 reviewed articles, Table 1), the organophosphorus insecticide glyphosate (13 reviewed articles, Table 1), and the systemic fungicide metolachlor (13 reviewed articles, Table 1).

Hence, it can be stated that the scientific interest has been focused on the most commonly used and frequently detected pesticides or/and the pesticides exhibiting

Fig. 3 Annual number of records published during the period from 01/01/2016 to 30/06/2021 regarding the (ad)sorption, desorption, and leaching processes of pesticides into soil/water systems. The plotted data have been located by "Scopus Database" by entering the keywords "pesticide," and "soil," and "sorption" or "desorption" or "leaching"

the longer half-lives that can remain in soil at levels above several hundreds of µg kg^{-1} and therefore pose a higher ability to threat exposed ecosystems and humans through food chain.

Based on the gathered and reviewed information of Tables 1 and 2 was created after the classification of each pesticide compound into 20 main chemical groups and one last group that was named "others" containing all the compounds that could not be classified to any of the previous 20 ones, such as aminomethylphosphonic acids, thiadiazines, triketones, uracils, nitriles, dicarboximides, anthranilic diamides; halogenated pyrroles; benzoylureas; pyridazinones; dimethoxybenzenes chloro substituted; isoxazolidinones; pyrazole carboxamides; disulfides; thiazole carboxamides; benzofuranyl alkylsulfonates; organobromines; thiadiazoles; phosphoramido compounds; phenylamides; dinitroanilines; isoxazoles; pyrimidines, phenols, etc.

As shown from the obtained information, it is obvious that the majority of the studies ($\approx$ 18%) are dealing with the chemical group of organophosphorus pesticides and their transportation behavior in soils (Fig. 4). Afterward, the chemical groups of amide and acetamide herbicides and fungicides (with 12 totally studied chemical compounds), sulfonylurea herbicides (among which the most studied compounds were sulfometuron-methyl with five reports and nicosulfuron with four reports) and conazole fungicides (among which the most surveyed molecules were tebuconazole with 12 reports and penconazole with four reports) are following in the

Table 1 Reports reviewed in the current overview regarding the scientific published data on (ad)sorption/desorption and leaching of pesticides in natural soil matrices. The search was based on "Scopus Database" and only original research publications since 2016 are included. Reports are presented in alphabetical order of the pesticides' name

No.	Pesticide name	Chemical group	Process studied	Reference(s)
1	Abamectin	Avermectin	(Ad)sorption/ desorption	[35, 36]
			Dissipation	[36]
2	Acetamiprid	Neonicotinoid insecticides	(Ad)sorption/ desorption	[37–39]
			Vertical mobility	[39]
3	Acetochlor	Anilide herbicides (Chloroacetanilides)	(Ad)sorption/ desorption	[40]
4	Alachlor	Anilide herbicides (Chloroacetanilides)	(Ad)sorption/ desorption	[41–45]
			Leaching	[41, 45]
5	Ametryn	Triazine herbicides (Thiotriazines)	Vertical transport	[24]
			Leaching	[46]
6	Aminocyclopyrachlor	Pyrimidine, cyclopropane and organochlorine pesticides	(Ad)sorption/ desorption	[47, 48]
			Leaching	[47, 48]
7	*AMPA* (Aminomethylphosphonic acid)	Aminomethylphosphonic acids	Vertical mobility	[1]
8	Atrazine (and transformation product: 2-hydroxyatrazine)	Triazine herbicides	(Ad)sorption/ desorption	[34, 35, 49–66]
			Leaching	[46, 53, 66–68]
			Runoff in soil	[53]
			Vertical mobility	[24]
			Dissipation	[58]
9	Azimsulfuron	Sulfonylurea herbicides (*N*-sulfonylureas)	(Ad)sorption/ desorption	[69]

10	Azinphos-methyl	Organophosphorus insecticides	(Ad)sorption/desorption	[28]
11	Azoxystrobin	Strobilurin fungicides (Aryloxypyrimidines)	(Ad)sorption/desorption	[70–72]
			Desorption	
			Leaching	[70]
			Vertical mobility	[72]
12	Benomyl	Carbamate fungicides (Benzimidazoles)	(Ad)sorption/desorption	[73]
13	Bentazone	Other herbicides: Thiadiazines	(Ad)sorption/desorption	[74, 75]
			Leaching	[21]
			Dissipation	[76, 77]
14	Benzobicyclon	Other herbicides: Carbobicyclics (chloro-substituted), Triketones	Dissipation	[29]
15	Bifenthrin	Pyrethroid insecticides	(Ad)sorption/desorption	[78]
16	Bispyribac-sodium	Benzoic acid herbicides	(Ad)sorption/desorption	[79–81]
			Leaching	[79–81]
			Dissipation	[79, 81]
17	Boscalid	Amide herbicides (Pyridinecarboxamide)	(Ad)sorption/desorption	[71, 75]
			Leaching	[82, 83]
			Dissipation	[77]
18	Bromacil	Uracil herbicides	Adsorption/desorption and vertical mobility	[84]
19	Bromoxynil	Nitrile herbicides (phenols)	Dissipation	[85]
20	Butachlor	Anilide herbicides (Acetanilides)	Dissipation	[86]

(continued)

Table 1 (continued)

No.	Pesticide name	Chemical group	Process studied	Reference(s)
			Adsorption/desorption	[87]
21	Cadusafos	Organophosphorus insecticides	Adsorption/desorption	[71, 88]
			Dissipation	[88]
			Plant uptake	[88]
22	Captan	Dicarboximide fungicides (Phthalimides)	Adsorption/desorption	[89]
23	Carbaryl	Carbamate insecticides	Adsorption/desorption	[50, 90, 91]
			Leaching	[91]
24	Carbendazim	Carbamate fungicides	Adsorption/desorption	[92–94]
25	Carbofuran	Carbamate insecticides	Adsorption/desorption	[41, 90, 95–97]
			Leaching	[41]
			Vertical mobility	[24]
26	Chlorantraniliprole	Anthranilic diamides	Adsorption/desorption	[98]
27	Chlorfenapyr	Other pesticides: Halogenated pyrroles	Adsorption/desorption	[99]
28	Chlorfenvinphos	Organophosphorus insecticides	Adsorption/desorption	[28, 45, 100]
			Leaching	[45]
29	Chlorfluazuron	Chitin synthesis inhibitors and benzoylureas (insect growth regulators)	Adsorption/desorption	[101]
30	Chloridazon	Other herbicides: Pyridazinones	Leaching	[102]
31	Chloroneb	Other fungicides: Dimethoxybenzenes chloro substituted	Adsorption/desorption	[71]
32	Chlorotoluron	Phenylurea herbicides	Adsorption/desorption	[20, 23, 103–106]
33	Chlorothalonil	Organochlorine fungicides (Dinitriles)	Adsorption/desorption	[107–109]
			Leaching	[107]
34	Chlorpyrifos (and metabolite 3,5,6-trichloro-2-pyridinol)	Organophosphorus insecticides	Adsorption/desorption	[28, 45, 58, 89, 91, 100, 108–123]
			Leaching	[45, 91, 112, 117]

#	Pesticide	Group	Process	References
			Dissipation	[58, 121, 122]
35	Chlorpyrifos-methyl	Organophosphorus insecticides	Adsorption/desorption	[100]
36	Chlorsulfuron	Sulfonylurea herbicides	Adsorption/desorption	[124]
37	Clomazone	Other herbicides: Isoxazolidinones	Adsorption/desorption	[80, 124–126]
			Leaching	[83, 126]
			Dissipation	[126]
38	Cymoxanil	Acetamide	Adsorption/desorption	[127]
			Leaching	[128]
			Dissipation	[129]
39	Clothianidin	Neonicotinoid insecticides	Adsorption/desorption	[37, 71, 130–136]
			Plant uptake	[131]
40	Crotoxyphos	Organophosphorus insecticides	Adsorption/desorption	[28]
41	Cyantraniliprole	Pyrazole carboxamides insecticides	Adsorption/desorption	[137]
42	Cypermethrin	Pyrethroid insecticides	Adsorption/desorption	[89, 99, 138]
43	2-Chlorophenol	Organochlorine insecticides, phenols	Adsorption/desorption	[139]
44	DDT (dichlorodiphenyltrichloroethane)	Organochlorine insecticides	Adsorption/desorption	[140, 141]
45	Deltamethrin	Pyrethroid insecticides	Adsorption/desorption	[138]
46	Demeton	Organophosphorus insecticides	Adsorption/desorption	[28]
47	Diazinon	Organophosphorus insecticides	Adsorption/desorption	[28, 71, 108, 110, 142]
48	Dichlorvos	Organophosphorus insecticides	Adsorption/desorption	[28, 115]
49	Diclocymet	Amide fungicides	Adsorption/desorption	[71]
50	Dicofol	Organochlorine acaricides	Adsorption/desorption	[89]
51	Dicrotophos	Organophosphorus insecticides	Adsorption/desorption	[28]
52	Difenoconazole	Conazole fungicides	Adsorption/desorption, and plant uptake	[143]
53	Diflufenican	Pyridine herbicides (pyridine carboxamides)	Adsorption/desorption	[144]
			Leaching	[83]
			Dissipation	[76]

(continued)

Table 1 (continued)

No.	Pesticide name	Chemical group	Process studied	Reference(s)
54	Dimethenamid	Amide herbicides (Chloroacetamides)	Adsorption/desorption	[138, 145, 146]
			Dissipation	[145]
55	Dimethoate	Organophosphorus insecticides	Adsorption/desorption	[28, 71, 114, 142]
56	Dinotefuran	Neonicotinoid insecticides	Adsorption/desorption	[71, 134]
57	Disulfoton	Organophosphorus insecticides	Adsorption/desorption	[28]
58	Diuron	Phenylurea herbicides	Adsorption/desorption	[20, 84, 103, 147–159]
			Leaching	[67, 117, 159–161]
			Dissipation	[145]
			Vertical mobility	[24, 84]
59	2,4-D (2,4-Dichlorophenoxyacetic acid)	Phenoxy herbicides	Adsorption/desorption	[34, 90, 150, 162–166]
			Dissipation	[85]
			Diffusion	[164]
			Vertical mobility	[166]
60	2,4-DB (4-(2,4-Dichlorophenoxy) butyric acid)	Phenoxy herbicides	Adsorption/desorption	[56]
61	2,4-Dichlorophenol	Organochlorine insecticides, phenols	Adsorption/desorption	[139]
62	DMDS (Dimethyldisulfide)	Disulfides	Adsorption/desorption	[167]
63	2,6-Dimethylphenol	Phenols	Adsorption/desorption	[139]
64	Endosulfan	Organochlorine insecticides	Adsorption/desorption	[121, 123, 168]
			Dissipation	[121]
65	Epoxiconazole	Conazole fungicides	Adsorption/desorption	[58, 169]
			Dissipation	[58, 76]
66	Ethaboxam	Thiazole carboxamide fungicides	Adsorption/desorption	[170]
67	Ethion	Organophosphorus insecticides	Adsorption/desorption	[28, 89]
68	Ethiprole	Pyrazole insecticides (Phenylpyrazoles)	Adsorption/desorption	[71]

69	Ethofumesate	Other herbicides: Benzofuranyl alkylsulfonates	Adsorption/desorption, and leaching	[26]
70	Ethoprophos	Organophosphorus insecticides	Adsorption/desorption, and leaching	[41]
71	Ethylene dibromide	Organobromines	Leaching	[68]
72	Etridiazole	Thiadiazole fungicides	Adsorption/desorption, and leaching	[41]
73	Fenamiphos	Phosphoramido insecticides	Adsorption/desorption	[88, 171]
			Vertical mobility	[171]
			Dissipation	[88]
74	Fenarimol	Pyrimidine fungicides	Adsorption/desorption	[138, 146]
75	Fenchlorphos	Organophosphorus insecticides	Adsorption/desorption	[28]
76	Fenitrothion	Organophosphorus insecticides	Adsorption/desorption	[28, 71]
77	Fenobucarb	Carbamate insecticides	Adsorption/desorption	[71, 134]
78	Fenthion	Organophosphorus insecticides	Adsorption/desorption	[28, 71, 126]
79	Fipronil (and degradation products: fipronil desulfinyl, fipronil sulfone, fipronil sulfide)	Pyrazole insecticides (Phenylpyrazoles)	Adsorption/desorption	[49, 65, 71, 172]
80	Flonicamid	Other insecticides: Pyridines	Leaching	[82]
81	Fluazifop	Phenoxy herbicides (Aryloxy-phenoxypropionates)	Adsorption/desorption	[173]
82	Flucetosulfuron	Sulfonylurea herbicides	Adsorption/desorption, and leaching	[174]
83	Fludioxonil	Other fungicides: Phenylpyrroles	Adsorption/desorption, and leaching	[70]
84	Flufenacet	Anilide herbicides (Oxyacetanilides)	Adsorption/desorption	[23, 104, 106]
85	Flumetsulam	Anilide herbicides (Triazolopyrimidines)	Adsorption/desorption	[163]
86	Flumioxazin	N-phenylphthalimide herbicides	Adsorption/desorption	[50]
87	Flusilazole	Conazole fungicides	Adsorption/desorption	[58, 175]

Table 1 (continued)

No.	Pesticide name	Chemical group	Process studied	Reference(s)
88	Fosthiazate	Organophosphorus nematicides	Leaching	[175]
			Dissipation	[58]
			Adsorption/desorption	[71, 131, 134, 176]
			Plant uptake	[131]
89	Flutolanil	Amide fungicides (Benzamides)	Adsorption/desorption	[71, 131, 134]
			Plant uptake	[131]
90	Fluxapyroxad	Pyrazolecarboxamide (anilide) fungicides	Adsorption/desorption	[177]
91	Glyphosate	Organophosphorus herbicides	Adsorption/desorption	[51, 152, 154, 157, 178–182]
			Leaching	[68, 117, 178]
			Dissipation	[76]
			Vertical mobility	[1]
92	Hexazinone	Triazinone herbicides	Adsorption/desorption	[50, 147, 149, 151, 153, 183–186]
			Leaching	[68, 160, 161, 185, 186]
93	Hexaconazole	Conazole fungicides	Adsorption/desorption	[105, 187]
94	Indaziflam	Alkylazine herbicides (Fluoroalkyltriazines)	Adsorption/desorption	[188]
95	Imazamox	Imidazolinone herbicides	Adsorption/desorption	[189]
96	Imazapic	Imidazolinone herbicides	Adsorption/desorption	[190]
97	Imazapyr	Imidazolinone herbicides	Adsorption/desorption	[190]
98	Imazaquin (S-, and R- enantiomers)	Imidazolinone herbicides	Adsorption/desorption	[191, 192]
			Leaching	[191]
			Dissipation	[191]
99	Imidacloprid	Neonicotinoid insecticides	Adsorption/desorption	[47, 50, 63, 71, 131, 134–136, 163–196]
			Leaching	[21, 47, 193, 195, 196]
			Dissipation	[76]
			Plant uptake	[131]

100	Iodosulfuron	Sulfonylurea herbicides	Adsorption/desorption	[197]
101	Iprodione	Dicarboximide fungicides	Adsorption/desorption	[93]
102	Isoproturon	Phenylurea herbicides	Adsorption/desorption	[20, 31, 63, 66, 103, 125, 154, 197–199]
			Leaching	[66]
			Dissipation	[122]
103	Kresoxim-methyl	Strobilurin fungicides	Adsorption/desorption	[71, 72]
			Vertical mobility	[72]
104	Lambda-cyhalothrin	Pyrethroid insecticides	Adsorption/desorption	[200]
105	Linuron	Phenylurea herbicides	Adsorption/desorption	[20, 44, 103]
106	MCPA (2-methyl-4-chlorophenoxyacetic acid)	Phenoxy herbicides	Adsorption/desorption	[50, 90]
			Leaching	[76, 83, 117]
107	Na-K-DMA MCPA salt (dimethyl ammonium-potassium-sodium salt of (4-chloro-2-methylphenoxy) acetic acid)	Phenoxy herbicides	Adsorption/desorption	[201]
108	Malathion	Organophosphorus insecticides	Adsorption/desorption	[28]
109	Metaldehyde	Other pesticides: Molluscacides, Tetraoxacyclooctanes	Leaching	[202]
110	Mesotrione	Benzoylcyclohexane-1,3-dione herbicides	Adsorption/desorption	[203]
			Leaching	[202]
			Dissipation	[204]
111	Metalaxyl (R-, and S-enantiomers)	Phenylamides (acylalanines)	Adsorption/desorption	[44, 70, 71, 131, 134, 176, 205–210]
			Leaching	[70, 205, 209, 210]
			Dissipation	[207, 210]
			Plant take-up	[131]
112	Metazachlor	Pyrazole herbicides	Leaching	[68]
			Dissipation	[76]

(continued)

Table 1 (continued)

No.	Pesticide name	Chemical group	Process studied	Reference(s)
113	Methidathion	Organophosphorus insecticides	Adsorption/desorption	[71]
114	Metolachlor (and its oxanilic and ethane sulfonic acids metabolites)	Anilide herbicides (Chloroacetanilides)	Adsorption/desorption	[25, 33, 47, 61, 90, 154, 203, 211–215]
			Leaching	[25, 33, 47, 215]
			Dissipation	[86, 215]
			Transport behavior	[212]
115	Metsulfuron-methyl	Sulfonylurea herbicides	Adsorption/desorption	[50]
			Dissipation	[85]
116	Metribuzin	Triazinone herbicides	Adsorption/desorption	[185]
			Leaching	[102, 185]
117	Mevinphos	Organophosphorus insecticides	Adsorption/desorption	[28]
118	Monocrotophos	Organophosphorus insecticides	Adsorption/desorption	[28]
119	Monuron	Phenylurea herbicides	Adsorption/desorption	[20, 103]
120	Myclobutanil	Conazole fungicides	Leaching	[82]
121	Napropamide	Amide herbicides	Adsorption/desorption, and leaching	[41]
122	Nicosulfuron	Sulfonylurea herbicides	Adsorption/desorption	[216–218]
			Leaching	[202]
123	Nonylphenol mixture	Nonylphenol	Adsorption/desorption	[219]
124	2-Nitrophenol	Nitrophenol herbicides	Adsorption/desorption	[139]
125	Oxadixyl	Amide fungicides	Adsorption/desorption	[97]
126	Oxyfluorfen	Diphenyl ether herbicides	Adsorption/desorption	[176]
127	Paichongding	Neonicotinoid insecticides (cis-nitromethylene neonicotinoids)	Adsorption/desorption, and leaching	[220]
128	Parathion	Organophosphorus insecticides	Adsorption/desorption	[28, 123]
129	Parathion methyl	Organophosphorus insecticides	Adsorption/desorption	[28, 89, 123, 142]

#	Pesticide	Class	Behavior	References
130	Penconazole	Conazole fungicides	Adsorption/desorption	[22, 175, 221]
			Leaching	[82, 175, 221]
131	Pendimethalin	Dinitroaniline herbicides	Adsorption/desorption	[58, 138, 145, 176, 222, 223]
			Dissipation	[58, 145]
132	Penflufen	Organofluorine aromatic amide fungicides, Pyrazole carboximides	Adsorption/desorption	[177]
133	Penoxsulam	Amide herbicides	Adsorption/desorption	[69]
134	Penthachlorophenol	Organochlorines, phenols	Adsorption/desorption	[224–226]
			Leaching	[227]
135	Permethrin	Pyrethroid insecticides	Adsorption/desorption	[123]
136	Pethoxamid	Amide herbicides (Chloroacetamides)	Dissipation	[204]
137	Phenamacril	Strobilurin fungicide (cyanoacrylate)	Adsorption/desorption, and vertical mobility	[72]
138	Phenthoate	Organophosphorus insecticides	Adsorption/desorption	[28]
139	Phorate	Organophosphorus insecticides	Adsorption/desorption	[28]
140	Phosmet	Organophosphorus insecticides	Adsorption/desorption	[28]
141	Picloram	Pyridine herbicides	Adsorption/desorption	[189]
			Leaching	[68]
142	Pirimicarb	Carbamate insecticides	Adsorption/desorption	[123, 127]
143	Pirimiphos ethyl	Organophosphorus insecticides	Adsorption/desorption	[123]
144	Prochloraz	Amide fungicides (Imidazoles)	Adsorption/desorption	[58, 123]
			Dissipation	[58]
145	Procymidone	Dicarboximide fungicides	Adsorption/desorption	[71, 131, 134]
			Leaching	[131]
146	Prometryn	Triazine herbicides (Diamino-1,3,5-triazines)	Adsorption/desorption	[105, 123]
147	Propanil	Anilide herbicides (Acetanilides)	Vertical mobility	[24]
148	Propiconazole	Conazole fungicides	Adsorption/desorption	[27, 71]

(continued)

Table 1 (continued)

No.	Pesticide name	Chemical group	Process studied	Reference(s)
			Leaching	[83]
149	Propyzamide	Amide herbicides (Benzamides)	Adsorption/desorption and leaching	[228]
150	Prosulfocarb	Thiocarbamate herbicide	Adsorption/desorption	[106]
			Leaching	[229]
			Dissipation	[230]
151	Pymetrozine	1,2,4-Triazine antifeedants (insect growth regulators)	Adsorption/desorption	[231]
152	Pyrasulfotole	Isoxazole herbicides	Dissipation	[85]
153	Pyrimethanil	Pyrimidine fungicides (Aminopyrimidines)	Adsorption/desorption	[75]
			Dissipation	[77]
154	Quinclorac	Benzoic acid herbicides (Quinolines carboxylic acids)	Adsorption/desorption	[223]
155	Quinoxyfen	Other fungicides	Adsorption/desorption	[122]
156	Quizalofop-P-ethyl	Phenoxy herbicides (Aryloxyphenoxypropionic acids)	Adsorption/desorption	[157]
157	Sedaxane	Pyrazole-4-carboxylic acid amide fungicides (Organofluorines and pyrazole carboxamides)	Adsorption/desorption and leaching	[70]
158	Siduron	Phenylurea herbicides	Adsorption/desorption and leaching	[232]
159	Simazine	Triazine herbicides	Leaching	[233]
			Adsorption/desorption	[234, 235]
160	Sulfentrazone	Substituted triazole herbicides	Adsorption/desorption	[163, 178]
			Leaching	[178]
161	Sulfometuron-methyl	Sulfonylurea herbicides	Adsorption/desorption	[147, 149, 236]
			Leaching	[160, 161]

162	Sulfotep	Organophosphorus insecticides	Adsorption/desorption and leaching	[142]
163	Tebuconazole	Conazole fungicides	Adsorption/desorption	[41, 58, 122, 127, 131, 169, 179, 207, 237, 238]
			Leaching	[41, 128]
			Dissipation	[58, 125, 129, 207]
			Plant take-up	[131]
164	Tebuthiuron	Urea herbicides (Dimethylureas)	Adsorption/desorption	[183, 186]
			Leaching	[186]
165	Terbufos	Organophosphorus insecticides	Adsorption/desorption	[28]
166	Terbuthylazine	Triazine herbicides (Chlorotriazines)	Adsorption/desorption	[50, 173, 189, 203]
			Dissipation	[76]
167	Terbutryn	Triazine herbicides	Adsorption/desorption and leaching	[26]
168	Tetraconazole	Conazole fungicides	Adsorption/desorption	[71]
169	Tetradifon	Tetrachlorodiphenyl sulfone acaricides	Adsorption/desorption	[71]
170	Thiabendazole	Thoazole fungicides (Benzimidazoles)	Adsorption/desorption and leaching	[70]
171	Thiacloprid	Neonicotinoid insecticides	Adsorption/desorption	[37, 71, 131, 134–136, 138, 238–241]
			Leaching	[239]
			Uptake	[131]
172	Thiamethoxam	Neonicotinoid insecticides	Adsorption/desorption	[37, 70, 133, 242]
			Leaching	[70, 196]
			Dissipation	[242]
			Uptake	[242]
173	Thiencarbazone-methyl	N-sulfonylurea herbicides (sulfonyl-amino-carbonyl-triazolinones)	Dissipation	[85]

Table 1 (continued)

No.	Pesticide name	Chemical group	Process studied	Reference(s)
174	Thifensulfuron-methyl	Sulfonylurea herbicides	Dissipation	[85]
175	Thiram	Dithiocarbamate fungicides	Adsorption/desorption	[243]
176	Thymol	Phenols	Adsorption/desorption	[244]
177	Tolclofos-methyl	Organophosphorus fungicides	Adsorption/desorption	[71, 134]
178	Triadimefon	Conazole fungicides	Adsorption/desorption	[123]
179	Triadimenol	Triazoles	Adsorption/desorption	[127]
180	Triasulfuron	Sulfonylurea herbicides (N-sulfonylureas)	Adsorption/desorption	[106, 245, 246]
			Dissipation	[204]
181	Tribenuron-methyl	Sulfonylurea herbicides	Dissipation	[85]
182	Trichlorfon (or Metrifonate)	Organophosphorus insecticides	Adsorption/desorption	[28]
183	Triclosan	Polychloro phenoxy phenols	Adsorption/desorption	[156]
184	Triclopyr	Pyridine herbicides	Adsorption/desorption	[173]
185	Trifloxystrobin	Strobilurin fungicides	Adsorption/desorption	[71]
186	Triflumezopyrim	Pyridopyrimidinone insecticides	Adsorption/desorption	[247]

Table 2 Classification of reports reviewed in the current overview regarding the recently published scientific published data on (ad)sorption/desorption and leaching of pesticides in natural soil matrices. The search was based on "Scopus Database" and only original research publications since 2016 are included

	Chemical groups	No. of target pesticides	Pesticide compounds (number of found and reviewed data)
1	Amide and acetamide herbicides, and fungicides	12	Boscalid (5); Cymoxanil (3); Diclocymet (1); Dimethenamid (3); Flutolanil (3); Napropamide (1); Oxadixyl (1); Penflufen (1); Penoxsulam (1); Pethoxamid (1); Prochloraz (2); Propyzamide (1)
2	Anilide herbicides, and fungicides	8	Acetochlor (1); Alachlor (5); Butachlor (2); Flufenacet (3); Flumetsulam (1); Fluxapyroxad (1); Metolachlor (13); Propanil (1)
3	Benzoic acid herbicides	2	Bispyribac-sodium (3); Quinclorac (1)
4	Carbamate, thiocarbamate, and dithio-carbamate insecticides, herbicides, and fungicides	8	Benomyl (1); Carbaryl (3); Carbendazim (3); Carbofuran (6); Fenobucarb (2); Pirimicarb (2); Prosulfocarb (3); Thiram (1)
5	Conazole fungicides	10	Difenoconazole (1); Epoxiconazole (3); Flusilazole (2); Hexaconazole (2); Myclobutanil (1); Penconazole (4); Propiconazole (3); Tebuconazole (12); Tetraconazole (1); Triadimefon (1)
6	Diphenyl ether herbicides	1	Oxyfluorfen (1)
7	Imidazolinone herbicides	4	Imazamox (1); Imazapic (1); Imazapyr (1); Imazaquin (2)
8	Neonicotinoid insecticides	7	Acetamiprid (3); Clothianidin (9); Dinotefuran (2); Imidacloprid (15); Paichongding (1); Thiacloprid (10); Thiamethoxam (5)
9	Organochlorine insecticides, fungi-cides, and acaricides	8	Aminocyclopyrachlor (2); Chlorothalinil (3); 2-Chlorophenol (1); DDT (2); Dicofol (1), 2,4-Dichlorophenol (1); Endosulfan (3); Pentachlorophenol (4)
10	Organophosphorus insecticides, herbi-cides, fungicides, and nematicides	33	Azinphos-methyl (1); Cadusafos (2); Chlorfenvinphos (3); Chlorpyrifos (21); Chlorpyrifos-methyl (1); Crotoxyphos (1); Demeton (1); Diazinon (5); Dichlorvos (2); Dicrotophos (1); Dimethoate (4); Disulfoton (1); Ethion (2); Ethoprophos (1); Fenchlorphos (1); Fenitrothion (2); Fenthion (3); Fosthiazate (4); Glyphosate (13) Malathion (1); Methidathion (1); Mevinphos (1);

Table 2 (continued)

|	Chemical groups	No. of target pesticides	Pesticide compounds (number of found and reviewed data)
			Monocrotophos (1); Parathion (2); Parathion methyl (4); Phenthoate (1); Phorate (1); Phosmet (1); Pirimiphos-ethyl (1); Sulfotep (1); Terbufos (1); Trichlorfon (or Metrifonate) (1); Toclofos-methyl (1)
11	Phenoxy herbicides	6	2,4-D (9); 2,4-dB (1); Fluazifop (1); MCPA (5); Na-K-DMA MCPA salt (1); Quizalofop-P-ethyl (1)
12	Phenylurea herbicides	6	Chlorotoluron (6); Diuron (21); Isoproturon (9); Linuron (3); Monuron (2); Siduron (1)
13	Pyrazole	3	Ethiprole (1); Fipronil (4); Metazachlor (2)
14	Pyrethroid insecticides	5	Bifenthrin (1); Cypermethrin (3); Deltamethrin (1); Lambda-cyhalothrin (1); Permethrin (1)
15	Pyridine and pyridine carboxamides insecticides and herbicides	5	Boscalid (5); Diflufenican (3); Flonicamid (1); Picloram (2); Triclopyr (1)
16	Strobilurin fungicides	4	Azoxystrobin (3); Kresoxim-methyl (2); Phenamacril (1); Trifloxystrobin (1)
17	Sulfonylurea herbicides	11	Azimsulfuron (1); Chlorsulfuron (1); Flucetosulfuron (1); Iodosulfuron (1); Metsulfuron-methyl (2); Nicosulfuron (4); Sulfometuron-methyl (5); Thiencarbazone-methyl (1); Thifensulfuron-methyl (1); Triasulfuron (4); Tribenuron-methyl (1)
18	Triazine herbicides	8	Ametryn (2); Atrazine (24); Indaziflam (1); Prometryn (2); Pymetrozine (1); Simazine (4); Terbuthylazine (5); Terbutryn (1)
19	Triazinone herbicides	2	Hexazinone (12); Metribuzin (2)
20	Urea herbicides	1	Tebuthiuron (2)
21	Others: Aminomethylphosphonic acids, Thiadiazines, Triketones, Uracils, Nitriles, Dicarboximides, Anthranilic diamides; Halogenated pyrroles; Benzoylureas; Pyridazinones; Dimethoxybenzenes chloro substituted; Isoxazolidinones; Pyrazole carboxamides; Disulfides; Thiazole Carboxamides; Benzofuranyl alkylsulfonates; Organobromines; Thiadiazoles; Phosphoramido	42	Abamectin (2); *AMPA (1);* Bentazone (5); Benzobicyclon (1); Bromacil (1); Bromoxynil (1); Captan (1); Chlorantraniliprole (1); Chlorfenapyr (1); Chlorfluazuron (1); Chloridazon (1); Chloroneb (1); Clomazone (4); Cyantraniliprole (1); DMDS (1); Ethaboxam (1); Ethofumesate (1); Ethylene dibromide (1); Etridiazole (1); Fenamiphos (2); Fenarimol (2); Fludioxonil (1); Flumioxazin (1);

(continued)

Table 2 (continued)

Chemical groups	No. of target pesticides	Pesticide compounds (number of found and reviewed data)
compounds; Phenylamides; Dinitroanilines; Isoxazoles; Pyrimidines, Phenols, etc.		Iprodione (1); Metaldehyde (1); Mesotrione (3); Metalaxyl (12); 2-Nitrophenol (1), Nonylphenol (1); Pendimethalin (6); Procymidone (3); Pyrasulfotole (1); Pyrimethanil (2); Quinoxyfen (1); Sedaxane (1); Sulfentrazone (2); Tetradifon (1); Thiabendazole (1); Thymol (1); Triadimenol (1); Triclosan (1); Triflumezopyrim (1)
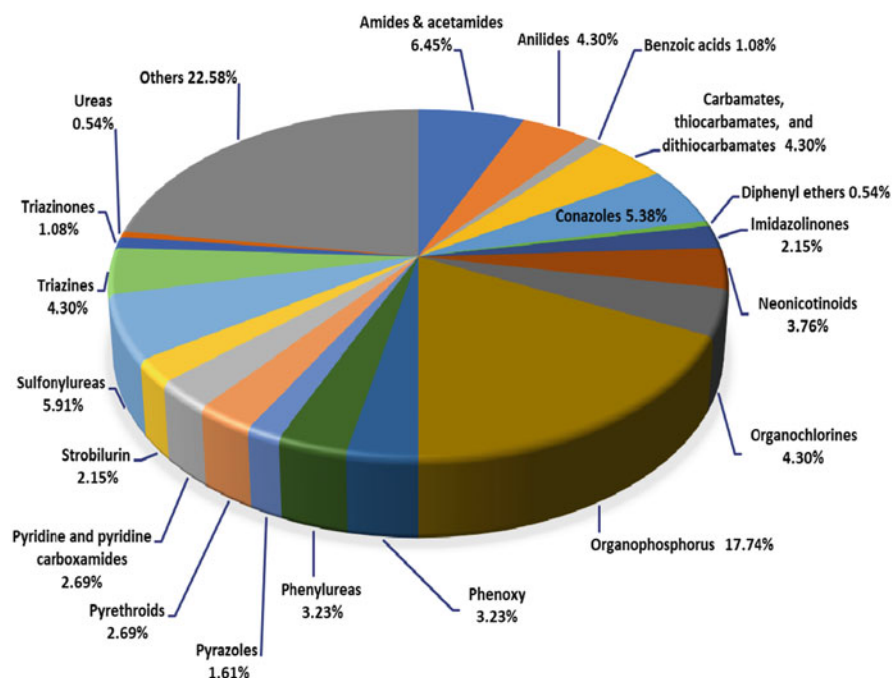
Fig. 4 Overall relative frequency of reports for different chemical groups of pesticides concerning their (ad)sorption/desorption and leaching phenomena in natural soil matrices overviewed in present review. The search was based on "Scopus Database" using as keywords the terms pesticide, soil, and sorption or desorption or leaching; only original research publications since 2016 were considered, while all critical reviews and overviews published in the same period were excluded. Target pollutants are tested either individually or in mixture with other toxic chemicals

second, third, and fourth place by scoring almost 6.5%, 6%, and 5.5% of relative literature found, respectively.

In Table 3 detailed information is presented regarding the recently published scientific published data on the performed experimental procedures for the assessment of some selected pesticides' transportation capacity and the main findings of some selected reviewed articles. According to the reviewed records addressed in this overview most studies employed and applied the OECD 106 guideline of batch equilibrium method for adsorption-desorption proposed by the Organization for Economic Co-operation and Development (OECD) [248] while the use of soil columns is also an alternative method preferred in a lower number of published research.

Furthermore, from the selected data that are presented in Table 3 it is obvious that there is a great variation between the estimated adsorption and desorption coefficient values of pesticides depended not only on the physicochemical properties of the tested soils but also on the characteristics of the pesticides. This observation is in accordance with other data published previously in research and review studies which highlighted the fact that besides the various sorption parameters which can be observed and measured for the same pesticide in different soil matrices, also a variability among different pesticide compounds adsorbed on the same soil matrix can exist [8, 14, 18, 145]. In the study of Zhang et al. [135] who investigated the sorption, desorption, and degradation kinetics of three neonicotinoid insecticides in four agricultural soils of different texture (two loam and two clay loam type) and different physicochemical properties such as cation exchange capacity (CEC), OM content, and pH a wide variety of sorption and desorption parameters were reported. For instance, the values of Freundlich equilibrium constant K_F (in $(mg/kg)(mg/L)^{-n}$) for clothianidin were calculated between the range of 0.992 and 3.39, whereas the same parameter of sorption affinity for the other two selected neonicotinoids imidacloprid and thiacloprid varied between 1.01–3.42 and 1.16–9.06, correspondingly. Low sorption of all three neonicotinoids was generally observed that was mainly affected by the SOM content following the order thiacloprid $>$ imidacloprid $\approx$ clothianidin [135].

Many of the reported data were explained by the phenomenon of hysteresis in soil (ad)sorptive and/or desorptive processes. Based on our observation sorption-desorption hysteresis phenomena have been reported in several overviewed bibliographies influencing and controlling the distribution of pesticides into soil-water-biota systems [57, 60, 125, 173, 174, 199]. As reported in the literature, the effect of desorption hysteresis may be observed when the desorption of adsorbed pesticide molecules is not allowed to occur immediately due to the high-strength chemical bonds that were developed in the sorption process [57, 60, 125, 173, 174, 199]. Usually, hysteresis is quantified in terms of the extra Gibbs free energies of high-energy sorption sites that are sorbate- and sorbent-dependent, varying across sorption isotherms [125]. In the recently published study of Đurović-Pejčev et al. [125] regarding the adsorption-desorption behavior of clomazone in two Serbian agricultural the hysteresis effect that was observed in both tested soils increased with the increase of clomazone's initial concentration in the soil-water system, whereas the percentage of desorbed amount during successive desorption cycles decreased. On the contrary,

Table 3 Detailed information contained in selected scientific reports reviewed within the current overview regarding the published data on (ad)sorption/desorption and leaching of pesticides in natural soil matrices. The illustrated research results were retrieved by "Scopus Database" by using as keywords the terms pesticide, soil, and sorption or desorption or leaching. Target PPP pollutants were tested either individually or in mixture with other toxic substances. Only original research publications since 2016 are included, whereas critical reviews and overviews published in the same period were excluded

Pesticide name (chemical class)	Soil content and physicochemical properties								Experimental method/ Isotherm model	Estimated parameters		Reference
	Type (texture)	% Sand	% Silt	% Clay	CEC (cmol kg⁻¹)	% OC	pH	Other information available		Sorption process	Desorption process	
Acetamiprid (neonicotinoid)	Arable soil (clay loam)	54.4	20.8	24.8	20.4	3.43	5.9 (in water)	%HAs = 1.72; % FAs = 0.22 Major soil minerals: Kaolinite, vermiculite-chlorite intermediate structures, and Illite. Minerals (g kg⁻¹): $Al_{pyz} = 5.1^{a}$; $Fe_{pyz} = 0.62^{a}$; $Al_{ox} = 13^{b}$; $Fe_{ox} = 6.7^{b}$; $Si_{ox} = 1.0^{b}$; $Al_{DCB} = 1.1^{c}$; $Fe_{DCB} = 6.9^{c}$	Batch equilibrium/ Freundlich	$K_F = 8.580$ $1/n_F = 0.8910$ $R^2 = 0.9896$		[38]
Bromacil (substituted uracil)	Agricultural soil	13	10	77		2.03	4.2		Batch equilibrium/ Freundlich	$K_F = 0.37$ $1/n_F = 0.64$ $K_{oc} = 18.43$		[84]
Chlorpyrifos (organophosphate)	Field soil (sandy loam)	89.5	6.8	3.7		1.52	7.53 (in water)	Total N (g kg⁻¹) = 0.44; P_2O_5 (g kg⁻¹) = 0.02; K_2O (g kg⁻¹) = 0.043 Soil microbial biomass carbon (mg C kg⁻¹) = 160.2	Batch equilibrium/ Freundlich	Active ingredient: $K_F = 195.2$ $n_F = 0.700$ $R^2 = 0.988$ $K_{oc} = 12,842.6$ Commercial formulation: $K_F = 211.4$ $n_F = 0.501$ $R^2 = 0.987$ $K_{oc} = 13,906.9$		[122]

Table 3　(continued)

Pesticide name (chemical class)	Soil content and physicochemical properties								Experimental method/ Isotherm model	Estimated parameters		Reference
	Type (texture)	% Sand	% Silt	% Clay	CEC (cmol kg^{-1})	% OC	pH	Other information available		Sorption process	Desorption process	
Clothianidin (neonicotinoid)	Black soil (loam)	52	42	6	61.3	3.08	7.2 (in CaCl$_2$)	Available nutrients (mg kg^{-1}); $N = 279$, $P = 52.2$; electrical conductivity (dS m^{-1})^d = 524	Batch equilibrium/ Freundlich	$K_F = 3.39$ $n_F = 0.853$ $R^2 = 0.986$	$K_F = 5.05$ $n_F = 0.723$ $R^2 = 0.971$	[135]
	Fluvo-aquic soil (loam)	49	42	9	18.3	1.26	4.9 (in CaCl$_2$)	Available nutrients (mg kg^{-1}); $N = 158$, $P = 29.6$; electrical conductivity (dS m^{-1})^d = 80.1		$K_F = 1.08$ $n_F = 0.991$ $R^2 = 0.996$	$K_F = 1.86$ $n_F = 0.977$ $R^2 = 0.982$	
	Paddy soil (clay loam)	32	46	22	14.2	1.43	4.4 (in CaCl$_2$)	Available nutrients (mg kg^{-1}); $N = 115$, $P = 22.7$; electrical conductivity (dS m^{-1})^d = 34.1		$K_F = 2.75$ $n_F = 0.779$ $R^2 = 0.956$	$K_F = 4.04$ $n_F = 0.594$ $R^2 = 0.951$	
	Red soil (clay loam)	48	34	18	11.9	0.110	3.8 (in CaCl$_2$)	Available nutrients (mg kg^{-1}); $N = 33.8$, $P = 2.10$; electrical conductivity (dS m^{-1})^d = 157		$K_F = 0.992$ $n_F = 0.998$ $R^2 = 0.975$	$K_F = 1.32$ $n_F = 0.921$ $R^2 = 0.976$	[133]
	Vegetable garden soil (silt loam) Depth fractions: • 0–130 mm • 130–250 mm			19.3 23.3 18.3	10.9 (0–130 mm) 11.9 (130–250 mm) 12.1 (250–400 mm)	0.31 0.14 0.08	6.85 (0–130 mm) 6.96 (130–250 mm) 5.65 (250–400 mm)		Batch equilibrium/ Henry's linear	(0–130 mm): $K_d = 1.40$; $R^2 = 0.99$; $K_{oc} = 451$ (130–250 mm): $K_d = 1.21$ $R^2 = 0.99$; $K_{oc} = 864$ (250–400 mm): $K_d = 0.62$	(0–130 mm): $K_d = 0.53$; $R^2 = 0.92$ (130–250 mm): $K_d = 1.05$ $R^2 = 0.99$ (250–400 mm):	

Pesticide	Soil							Characteristics	Method/Model	Sorption parameters		References
	• 250–400 mm									$R^2 = 0.99$; $K_{oc} = 775$	$K_d = 0.52$ $R^2 = 0.98$	
	Farm soil (fine sandy loam) Depth fractions: • 0–130 mm • 130–250 mm • 250–400 mm	17.0 31.3 30.3	18.9 (0–130 mm) 19.8 (130–250 mm) 20.8 (250–400 mm)			0.30 0.24 0.21	6.08 (0–130 mm) 6.59 (130–250 mm) 6.38 (250–400 mm)			(0–130 mm): $K_d = 1.45$; $R^2 = 0.99$; $K_{oc} = 483$ (130–250 mm): $K_d = 1.17$; $R^2 = 0.99$; $K_{oc} = 487$ (250–400 mm): $K_d = 1.13$; $R^2 = 0.99$; $K_{oc} = 538$	(0–130 mm): $K_d = 0.79$; $R^2 = 0.99$ (130–250 mm): $K_d = 0.74$; $R^2 = 0.99$ (250–400 mm): $K_d = 0.82$; $R^2 = 0.99$	
	Farm soil (fine sandy loam) Depth fractions: • 0–130 mm • 130–250 mm • 250–400 mm	14.5 34.3 38.3	20.3 (0–130 mm) 22.9 (130–250 mm) 19.6 (250–400 mm)			0.64 0.40 0.37	7.72 (0–130 mm) 8.06 (130–250 mm) 7.92 (250–400 mm)			(0–130 mm): $K_d = 1.94$; $R^2 = 0.99$; $K_{oc} = 303$ (130–250 mm): $K_d = 1.62$; $R^2 = 0.99$; $K_{oc} = 405$ (250–400 mm): $K_d = 1.48$; $R^2 = 0.99$; $K_{oc} = 400$	(0–130 mm): $K_d = 0.30$; $R^2 = 0.83$ (130–250 mm): $K_d = 0.23$; $R^2 = 0.94$ (250–400 mm): $K_d = 0.50$; $R^2 = 0.96$	
Diuron (Dimethylurea)	Agricultural soil	13	10	77		2.03	4.2	Available nutrients (mg kg^{-1}); $N = 279$, $P = 52.2$; electrical	Batch equilibrium/Freundlich	$K_F = 4.30$ $1/n_F = 0.81$ $K_{oc} = 212.06$		[84]
Imidacloprid (neonicotinoid)	Black soil (loam)	52	42	6	61.3	3.08	7.2 (in CaCl$_2$)		Batch equilibrium/Freundlich	$K_F = 3.42$ $n_F = 0.862$ $R^2 = 0.997$	$K_F = 3.76$ $n_F = 0.725$ $R^2 = 0.975$	[135]

(continued)

Table 3 (continued)

Pesticide name (chemical class)	Type (texture)	% Sand	% Silt	% Clay	CEC (cmol kg⁻¹)	% OC	pH	Other information available	Experimental method/ Isotherm model	Sorption process	Desorption process	Reference
								conductivity (dS m^{-1})^d = 524				
	Fluvo-aquic soil (loam)	49	42	9	18.3	1.26	4.9 (in CaCl$_2$)	Available nutrients (mg kg^{-1}); N = 158, P = 29.6; electrical conductivity (dS m^{-1})^d = 80.1		K_F = 2.36 n_F = 0.987 R^2 = 0.953	K_F = 3.27 n_F = 0.919 R^2 = 0.953	
	Paddy soil (clay loam)	32	46	22	14.2	1.43	4.4 (in CaCl$_2$)	Available nutrients (mg kg^{-1}); N = 115, P = 22.7; electrical conductivity (dS m^{-1})^d = 34.1		K_F = 2.62 n_F = 0.805 R^2 = 0.969	K_F = 3.50 n_F = 0.650 R^2 = 0.963	
	Red soil (clay loam)	48	34	18	11.9	0.110	3.8 (in CaCl$_2$)	Available nutrients (mg kg^{-1}); N = 33.8, P = 2.10; electrical conductivity (dS m^{-1})^d = 157		K_F = 1.01 n_F = 1.02 R^2 = 0.994	K_F = 1.20 n_F = 1.02 R^2 = 0.927	
Isoproturon (Phenylurea)	Field soil (Sandy loam)	89.5	6.8	3.7		1.52	7.53 (in CaCl$_2$)	Total N (g kg^{-1}) = 0.44; P$_2$O$_5$ (g kg^{-1}) = 0.02; K$_2$O (g kg^{-1}) = 0.043 Soil microbial biomass carbon (mg C kg^{-1}) = 160.2	Batch equilibrium/ Freundlich	Active ingredient: K_F = 4.00 n_F = 0.885 R^2 = 0.974 K_{foc} = 263.3 Commercial formulation: K_F = 4.99 n_F = 0.725 R^2 = 0.998 K_{oc} = 328.3		[122]

Pesticide (class)	Soil					pH	Soil properties	Method	Parameters	Ref
Simazine (Triazine)	Grassland soil (Sandy loam)	89.5	6.8			5.94 ± 0.15	Water holding capacity (%) = 74.97; Electrical conductivity ($\mu S\ m^{-1}$) = 87.73; Total carbon (%) = 3.10; Total nitrogen (%) = 0.34; DOC ($g\ kg^{-1}$) = 15.25	Batch equilibrium/L and Freundlich	$K_L = 0.0037$; $q_m = 15.75$; $R^2 = 0.192$; $K_F = 0.005$; $n_F = 0.940$; $R^2 = 0.988$	[233]
Tebuconazole (Triazole)	Field soil (Sandy loam)			3.7	1.52	7.53 (in water)	Total N ($g\ kg^{-1}$) = 0.44; P_2O_5 ($g\ kg^{-1}$) = 0.02; K_2O in ($g\ kg^{-1}$) = 0.043; Soil microbial biomass carbon (mg C kg^{-1}) = 160.2	Batch equilibrium/Freundlich	Active ingredient: $K_F = 21.9$; $n_F = 0.923$; $R^2 = 0.960$; $K_{oc} = 1,439.9$; Commercial formulation: $K_F = 30.1$; $n_F = 0.855$; $R^2 = 0.997$; $K_{oc} = 1,980.4$	[122]
Thiacloprid (neonicotinoid)	Black soil (loam)	52	42	61.3	3.08	7.2 (in $CaCl_2$)	Available nutrients (mg kg^{-1}): $N = 279$, $P = 52.2$; electrical conductivity (dS m^{-1})^d = 524	Batch equilibrium/Freundlich	$K_F = 9.06$; $n_F = 0.806$; $R^2 = 0.998$; $K_F = 10.9$; $n_F = 0.717$; $R^2 = 0.987$	[135]
	Fluvo-aquic soil (loam)	49	42	18.3	1.26	4.9 (in $CaCl_2$)	Available nutrients (mg kg^{-1}): $N = 158$, $P = 29.6$; electrical conductivity (dS m^{-1})^d = 80.1		$K_F = 3.40$; $n_F = 0.842$; $R^2 = 0.995$; $K_F = 4.28$; $n_F = 0.770$; $R^2 = 0.984$	
	Paddy soil (clay loam)	32	46	14.2	1.43	4.4 (in $CaCl_2$)	Available nutrients (mg kg^{-1}): $N = 115$, $P = 22.7$; electrical conductivity (dS m^{-1})^d = 34.1		$K_F = 4.70$; $n_F = 0.719$; $R^2 = 0.994$; $K_F = 5.49$; $n_F = 0.645$; $R^2 = 0.955$	

(continued)

Table 3 (continued)

Pesticide name (chemical class)	Type (texture)	% Sand	% Silt	% Clay	CEC (cmol kg⁻¹)	% OC	pH	Other information available	Experimental method/ Isotherm model	Sorption process	Desorption process	Reference
	Red soil (clay loam)	48	34	18	11.9	0.110	3.8 (in CaCl₂)	Available nutrients (mg kg⁻¹): $N = 33.8$, $P = 2.10$; electrical conductivity (dS m⁻¹)ᵈ = 157		$K_F = 1.16$ $n_F = 0.984$ $R^2 = 0.996$	$K_F = 1.55$ $n_F = 0.943$ $R^2 = 0.989$	
	Agricultural soil	31	58	11	8.1	1.2	8.1	Calcaric fluvisol devoted to different irrigated crops such as corn, tobacco, and fruit trees. $CaCO_3(\%) = 26$ Electrical conductivity (dS m⁻¹)ᵈ = 1.2	Batch equilibrium and column/ Freundlich and Henry's linear	$K_F = 5.3$; $1/n_F = 0.60$ $R^2 = 0.989$ / $K_d = 4.0$ $R^2 = 0.882$ $K_{oc} = 331$		[239]
Thiamethoxam (neonicotinoid)	Vegetable garden soil (silt loam) Depth fractions: • 0–130 mm • 130–250 mm • 250–400 mm			19.3 23.3 18.3	10.9 (0–130 mm) 11.9 (130–250 mm) 12.1 (250–400 mm)	0.31 0.14 0.08	6.85 (0–130 mm) 6.96 (130–250 mm) 5.65 (250–400 mm)		Batch equilibrium/ Henry's linear	(0–130 mm): $K_d = 1.45$; $R^2 = 0.99$; $K_{oc} = 468$ (130–250 mm): $K_d = 1.19$ $R^2 = 0.99$; $K_{oc} = 850$ (250–400 mm): $K_d = 0.59$ $R^2 = 0.99$; $K_{oc} = 738$	(0–130 mm): $K_d = 0.62$; $R^2 = 0.93$ (130–250 mm): $K_d = 0.34$; $R^2 = 0.99$ (250–400 mm): $K_d = 0.14$; $R^2 = 0.98$	[133]
	Farm soil (fine sandy loam) Depth fractions:			17.0 31.3 30.3	18.9 (0–130 mm) 19.8 (130–)	0.30 0.24 0.21	6.08 (0–130 mm) 6.59 (130–)			(0–130 mm): $K_d = 1.48$; $R^2 = 0.99$; $K_{oc} = 493$ (130–250 mm):	(0–130 mm): $K_d = 0.65$; $R^2 = 0.98$ (130– 250 mm):	

Soil content and physicochemical properties / Estimated parameters

Depth						
• 0–130 mm • 130–250 mm • 250–400 mm	250 mm 20.8 (250–400 mm)	250 mm 6.38 (250–400 mm)		$K_d = 1.20$; $R^2 = 0.99$; $K_{oc} = 500$ (250–400 mm): $K_d = 1.12$; $R^2 = 0.99$; $K_{oc} = 533$	$K_d = 0.49$; $R^2 = 0.93$; (250–400 mm): $K_d = 0.60$; $R^2 = 0.96$
Farm soil (fine sandy loam) Depth fractions: • 0–130 mm • 130–250 mm • 250–400 mm	14.5 34.3 38.3	20.3 (0–130 mm) 22.9 (130–250 mm) 19.6 (250–400 mm)	0.64 0.40 0.37	7.72 (0–130 mm) 8.06 (130–250 mm) 7.92 (250–400 mm)	(0–130 mm): $K_d = 2.03$; $R^2 = 0.99$; $K_{oc} = 317$ (130–250 mm): $K_d = 1.69$; $R^2 = 0.99$; $K_{oc} = 422$ (250–400 mm): $K_d = 1.51$; $R^2 = 0.99$; $K_{oc} = 408$	(0–130 mm): $K_d = 0.33$; $R^2 = 0.86$ (130–250 mm): $K_d = 0.48$; $R^2 = 0.83$ (250–400 mm): $K_d = 0.47$; $R^2 = 0.98$

CEC cation exchange capacity, *OC* organic carbon, *DOC* dissolved organic carbon

[a]Pyz: Pyrophosphate-extractable

[b]Ox: Oxalate-extractable

[c]DCB: dithionite-extractable counterparts

[d]Measured in deionized water (w:v = 1:5)

decreased hysteresis coefficient of the atrazine desorption with increasing its concentration in the case of low value of initial atrazine concentration was reported by Huang et al. [57], while in the case that the initial atrazine concentration was high acted reversely, indicating that the mechanism for delaying desorption in the sorbents varied with the initial atrazine concentration.

3.2 Effects of Selected Factors on Pesticide Sorption and Leaching in Soils

3.2.1 Impact of Soil Organic Matter

Several published studies have shown that soil OM (SOM) content is regarded as one of the most crucial and predominant soil characteristics that control the extent to which sorption of organic hydrophobic molecules in natural soils happens [10, 118, 249].

As it has been well established in the relevant bibliography the chemical composition, physicochemical properties or characteristics, and nature of OM differ between soils originating from variable regions. Among the several different key factors on which the nature of SOM is dependent, the origin and age of the soil matrix, the occurring environmental conditions, and the practicable agricultural methods are included [118, 183]. For instance, according to the results a survey conducted by Xu et al. [250] regarding the carbon stabilization in aggregate fractions responding to straw input levels under different soil fertility levels it was found that varied rates of organic C occurred based on the soil fertility and plant input levels.

SOM in general consists of vegetal and animal detritus at different levels of decomposition and mineralization. SOM is correlated with the fertility of the soil as it is considered to play the primary role of the soil carbon sink, whereas its concentration varies between 1 and 6% overall. A wide range of saturated and unsaturated complex organic molecules with aromatic, aliphatic, hydrophilic, and hydrophobic substances are included in the diverse composition of SOM. Among other organic compounds carbohydrates, fats, lignins, proteins, and humic substances (fulvic acid (FA), humic acid (HA), and humin) are included. The allocation of contained functional groups (oxygenated: -OH, -COOH, -C$=$O, -C-O-C-, -C-O-O-C, etc.; nitrogen containing amine and amide: -NH$_2$, -NH, aromatic ring, etc.) which act as sites of adsorption determine and regulate the degree of pesticides' sorption on the soil surface and therefore the leaching behavior of pesticides into aquifers.

The recent findings of the study conducted by Wang et al. [62] regarding the FT-IR spectra characterization of soil-derived dissolved organic matter (DOM) for the investigation of atrazine binding during the sorption process onto black soil indicated that main compositions of soil DOM among others mainly contained proteins, polysaccharides, and humic substances that significantly enhanced the adsorption efficiency of atrazine by soil.

Numerous studies have shown that a positive correlation between SOM and adsorption coefficient values, for instance for alachlor ($R^2 = 0.80$) [42] ($R^2 = 0.87$) [43], carbendazim ($R^2 = 0.77$) [94], chlorpyrifos ($R^2 = 0.82$, $p < 0.001$) [119], endosulfan ($R^2 = 0.96$) [168], flucetosulfuron ($r = 0.910$) [174], iodosulfuron ($R^2 = 0.87$) [197], and triasulfuron ($r = 0.987$) [246].

In order to estimate the influence of SOM quality in the abamectin and atrazine K_{OC} values the quality of contained HAs was analyzed by Novotny et al. [35] through the means of ^{13}C solid state Nuclear Magnetic Resonance (^{13}C NMR) and Principal Component (PC) Regression. Negative loadings for aliphatic compounds and positive loadings for aryl C, typical of partially oxidized pyrogenic C were reported. Because no correlation between K_F values and SOM was observed, the normalized by OC values (K_{OC})were obtained that varied within the range of 1,100–11,400 mL g^{-1} for abamectin and 30–150 mL g^{-1} for atrazine. The SOM content was not enough to explain the wide K_{OC} variation, whereas on the contrary the chemical structure of SOM could. Acquired results showed strong correlation of HAs with the abamectin K_{OC} values ($R^2 = 0.91$, $p < 5 \ 10^{-8}$) and weaker with atrazine K_{OC} ($R^2 = 0.63$, $p < 0.0001$), in addition to a smaller standardized slope for abamectin than for atrazine (1.01 and 0.76 respectively), which were explained by the higher hydrophobicity of abamectin, being thus more prone to interact with the polycondensed aryl groups from the pyrogenic C.

According to Parolo et al. [118], who investigated the sorption behavior of the nonionic pesticide chlorpyrifos on 12 representative natural soils of the North Patagonian Argentinian region the process of sorption was mainly affected by soil aliphatic components that were measured by FT-IR analysis on the whole soil samples. The values of normalized by the organic carbon (OC) content sorption coefficients varied between 9,000 and 20,000 L kg^{-1} (for %OC content 1.25–6.82), while a significant relationship between chlorpyrifos sorption (K_{OC}) and the variables pH and A/B height band ratio (band A: aliphatic components, 2,947–2,858 cm^{-1} and band B: hydrophilic components, 1,647–1,633 cm^{-1}) was found and reported ($R^2 = 0.66$). Based on the derived model, $K_{OC} = 22,757 + 4,364$ A/B $-1,564$ pH, it was observed that the ratio of the peaks' height A/B seemed to influence favoring sorption whereas on the contrary soil pH seemed to have a significant opposite effect on sorption.

Recently, a positive correlation was reported by Mendes et al. [183] among SOM, clay content, and sorption K values of tebuthiuron and hexazinone in soil samples taken from an agricultural area of São Paulo, Brazil. The values of sorption coefficients K for the two tested pesticides after using the batch equilibrium method ranged from 1.2 to 2.9 mL g^{-1} for tebuthiuron and from 0.4–0.6 mL g^{-1} for hexazinone, respectively.

Humic substances and their relation to the sorption of eight selected agricultural pesticides (atrazine, carbaryl, flumioxazin, hexazinone, imidacloprid, MCPA, metsulfuron-methyl, and terbuthylazine) in eight volcanic soils that differed in the fulvic and humic constituents of their OM were evaluated by Alister et al. [50] and published results of their study indicated that HA content regulated the sorption between pesticide and soil, especially through the carboxylic groups.

The study of Gaonkar et al. [115] focusing on the evaluation of soil organic amendments and their impacts on the sorption of organophosphate pesticides on an alluvial soil highlighted that the net effect of the application of organic amendments was an increase in the sorption of two selected organophosphates, dichlorvos, and chlorpyrifos that depended on both the nature of DOM and pesticide properties, whereas according to the spectroscopic characterization large amounts of highly humified and aromatic material were mainly contained in used organic amendments.

The significance that SOM has in the environmental fate of acetamiprid, as well as the investigation of the interactions between acetamiprid and three fractions of humic substances was surveyed by Murano et al. [38] by performing batch equilibrium experiments by using various combinations of a field soil sample and three different fractions prepared (HAs, FAs, and humin isolated from the same soil). Based on the reported Freundlich isotherm constant values for the tested fractions (K_F: 6.100 for humin, 4.179 for HAs and 4.756 for FAs) interactions of hydrophobic nature between humin and HAs or FAs were revealed, in which their dissociated carboxyl and phenolic groups became oriented to face the soil solution.

The influence of soil organic components determined by ^{13}C CP/MAS NMR spectroscopy on the sorption of chlorpyrifos was assessed by Savini et al. [119] who reported that whereas aryl C relative proportion was positively correlated with K_{OC} values, on the contrary, the correlation between alkyl C and O-aryl C proportions with K_{OC} data is negative ($R^2 = 0.82$, $p < 0.001$).

According to the research of Ćwieląg-Piasecka et al. [90] who compared the effect of two types of organic sorbents, HAs, and biochar, on the sorption-desorption processes of different polar pesticides (carbamates, phenoxyacetic acids, and aniline derivatives), the investigated HA exhibited high affinity to polar, ionic pesticides of high water solubility, which were adsorbed via specific interactions with HA functional groups. Specifically, HAs exhibited strong affinity for the ionic substances (percentage uptakes: 74.6 and 67.9% initial dose of 2,4-D and MCPA, respectively) and much weaker retention of nonionic carbamates (35.4% of carbofuran and 10.2% of carbaryl sorbed).

The published work of Chitolina et al. [184] investigating the Influence of soil depth on sorption and desorption processes of hexazinone revealed that the small differences that were observed in OC content between soil depths (of 0–10, 10–20, and 20–30 cm) affected hexazinone retention and the corresponding decreasing order of determined Freundlich coefficients (K_F) values were 0.18, 0.11, and 0.08 $g^{(1-1/n)}$ $L^{1/n}$ kg^{-1}.

Furthermore, the impact of exogenous OM (composted sheep manure) on the sorption and leaching of boscalid, flonicamide, myclobutanil, and penconazole pesticides was assessed by Pérez-Lucas et al. [82] and the obtained results of the conducted equilibrium experiments on an agricultural soil (SE Spain) showed that the sorption capacity of amended soil was significantly increased in all cases minimizing their potential for groundwater pollution. In addition, leaching experiments indicated with amended soil columns significantly limited the vertical movement of the pesticides in leachates especially for the cases of boscalid and penconazole.

3.2.2 Impact of Soil Inorganic Components

Minerals and rocks are the predominant inorganic soil components that are formed through lithogenesis and subjected to further diverse changes that are dependent on several factors and processes such as diagenesis, metamorphism, erosion, deposition, weathering, and transport [251]. The average chemical constituents of minerals (as natural inorganic compounds of Earth's crust) are oxygen (50% w/w), Si (25% w/w) and mainly Al^{3+}, Fe^{3+}, Fe^{2+}, Mg^{2+}, Ca^{2+}, Na^+, and K^+ cations (the rest 25% w/w) [251].

According to the overviewed data of the present study the clay minerals group (kaolinites, smectites, vermiculites, illites, and chlorites) has been demonstrated as the most important inorganic fraction for the sorption of synthetic pesticides. Inorganic portion of soil that is mainly the clay fraction contained in cases of soil matrices which are characterized with low OM contents is very important for the adsorption process of organic pesticides [110]. Therefore, apart from the SOM that has by definition high compatibility and strong association affinity for many non-polar pesticides (thus offers adsorption sites for such molecules especially into soils with >3% OM) clay minerals also play an important role and have a substantial contribution to the process of sorption, specifically in the case of polar pesticides and soils and sediments with low OM content [252].

A wide diversity of mechanisms through which pesticides can be (ad)sorbed from soil/water systems on soil clay mineral has been reported in the relative bibliography, including H bonding, hydrophobic bonding, van der Waals interactions, anion exchange, cation exchange, and ligand exchange pathways [244].

The effects of clay content in soil on the sorption process of two organophosphorus pesticides diazinon and chlorpyrifos were examined by Copaja et al. [110] in a natural soil sample (Chile) and in a soil modified with clay addition (1% of kaolinite or/and montmorillonite). Acquired results showed that the addition of both clays into the soil resulted in increased amounts of both pesticides retained in the soil and hence lowered the possible contamination of the groundwater.

These results are in accordance with the positive correlation that was found and reported by Mendes et al. [183] among clay content, SOM, and tebuthiuron and hexazinone sorption K_d values (in the range of 1.2–2.9 mL g^{-1} and 0.4–0.6 mL g^{-1}, for tebuthiuron and hexazinone, respectively).

The results of Bošković et al. [169] who conducted a study concerning the adsorption of the two conazole fungicides (epoxiconazole and tebuconazole) in 20 soils from the Czech Republic in relation to soil properties were very interesting. More specifically, among the "basic" (TOC, pH, clay), "advanced" (surface area, minerals) soil properties, and K_d coefficients that were evaluated in the multivariate analysis revealed for both fungicides a strong negative correlation with soil pH, and a lower positive correlation with soil organo-mineral complex (by means of TOC, clay, and surface area) and C and N in SOM. No correlation of adsorption parameters with particle sizes or CEC was observed.

According to the published data of Kumari et al. [174], regarding the investigation of the adsorption-desorption and leaching of the sulfonylurea herbicide flucetosulfuron in three Indian soils the acquired K_F exhibited positive correlation with OC content ($r = 0.910$) and clay content ($r = 0.746$). On the contrary a negative correlation with soil pH ($r = -0.635$) was revealed.

The statistical multivariate tests conducted in the survey of Sidoli et al. [211] regarding the adsorption data of the herbicide S-metolachlor and two of its metabolites (metolachlor ethane sulfonic acid and metolachlor oxanilic acid) on 17 surface soils and three geological solids related the highest K_d values for the herbicide S-metolachlor with the soils and geological solids with the highest OC and clay-fraction contents. Similarly, the sorption values of the new insecticide cyantraniliprole in different types of soils (Russia) were studied by Kolupaeva et al. [137] via the batch equilibrium method and obtained K_{OC} closely correlated with the OC and clay contents.

In a recent survey of Agbaogun et al. [103] on the adsorption behavior of five phenylurea herbicides by tropical soils (18 differently composed soils originating from southwestern Nigeria) statistically significant correlations (Pearson) were delivered between sorption parameters (K_d, K_f, and n) and specific soil and herbicide properties, among which pH, CEC, OC content, content of amorphous Fe and Mn oxides, clay/silt mass proportions, as well as molecular descriptors of octanol-water partition coefficient (log K_{ow}) and molecular mass (MW) of the moderately hydrophobic herbicides, were included. Furthermore, the estimated $K_{d.mineral}$ values of diuron (2.71), linuron (1.98), monuron (0.85), chlorotoluron (0.59), and isoproturon (0.56) reported in the same survey indicated that $K_{d.mineral}$ contributed between 15 and 40% to the $K_{d\ average}$ reported for these compounds, a fact that is implying that soil mineral fractions, vis-à-vis clay minerals, and the amorphous metal oxides, also contributed fairly significantly (about 15–40%) to the sorption of the five test compounds in the soils. Moreover, the intercorrelations between the basic properties of the soils used in this study revealed that extractable Fe and Mn oxides are significantly high and positive correlated with clay and silt contents and negative correlations with sand content [103].

Hiller et al. [201] tested the adsorption of Na-K-DMA MCPA salt (dimethyl ammonium-potassium-sodium salt of (4-chloro-2-methylphenoxy)acetic acid) on three agricultural soils by using column experiments and demonstrated the effect of clay and OC content on Na-K-DMA MCPA salt sorption despite the fact that small number of soil samples were tested. In a previously published survey of Peng et al. [247] both clay content and OM of soils were found to be important factors affecting the adsorption of triflumezopyrim in water-soil environment system. In the study of Rodríguez-Liébana and Peña [146] examining the adsorption-desorption capacity of dimethenamid and fenarimol onto three agricultural soils and how these processes are affected by treated wastewater and fresh sewage sludge-derived dissolved OC reported that in the case of fenarimol's adsorption by the soil OC content seemed to be the major factor controlling the process, whereas in the case of the adsorption of dimethenamid the mineral fraction played the key role, especially in the matrix where clay:organic content ratio was high.

In a work of Marín-Benito et al. [26] studying and comparing the effect on the mobility of ethofumesate and terbutryn in soils and two organoclays (swelling and non-swelling clays modified with octadecyltrimethylammonium) was observed that the effect of the organoclay barriers was more significant for ethofumesate, whereas for terbutryn the effect of organoclays was close to that of certain organic residues. The effect of soil organo-inorganic compounds different in particle size on butachlor sorption was surveyed by Huang et al. [87] and results showed that the clay fraction was the highest in butachlor adsorption capacity but the lowest in desorption rate, while the sand fraction was the lowest in adsorption capacity but the highest in desorption rate. The published results of Ahmad [238, 246] regarding a pedospheric sorption investigation of the sulfonyl urea herbicide triasulfuron via regression correlation and regression analysis in selected soils gave a positive correlation between K_d and clay content ($r = 0.980$).

In the study of Prado et al. [166] regarding the mobility of the pesticide 2,4-D in clay soils it was concluded that the preferential flow caused by both high clay content and the presence of macrofauna pores significantly reduced the buffering capacity of the soil, increasing the risk of contamination by herbicides of the underlying aquifer. The addition of synthetic clay (oleate-modified hydrotalcite) by Gámiz et al. [207] to an agricultural soil affected the sorption, leaching, persistence, and enantiomeric composition of soil residues of two chiral fungicides, tebuconazole and metalaxyl. Specifically, the addition of clay at a rate of 1% increased metalaxyl soil sorption coefficient (K_d) from 0.34 to 3.14 L kg^{-1} and that of tebuconazole from 2.4 to 47.4 L kg^{-1}.

Based on the regression equation that was proposed Gao et al. [231] for the sorption prediction of pymetrozine on six different soil samples: log $K_F = 4.3708 - 4.5709 \times$ log (pH in 0.01 mol·L^{-1} CaCl$_2$) + 0.4700 $\times$ log OC % + 0.0057 $\times$ sand (%) + 0.0022 $\times$ CEC (clay), with $R^2 = 0.9982$, the clay content of soil positively affected the sorption of pymetrozine.

According to the findings of current review it is observed most of the found and overviewed articles investigating how soil inorganic minerals can affect the adsorption-desorption behavior of pesticides in the soil is focused mainly on crystal silicate clay mineral (for example, montmorillonite and kaolinite), while on the opposite the scientists focusing on soil metal oxides, such as iron oxides, aluminum oxide, are much less in number. In this direction of research was the study of Huang et al. [57] on the effects of amorphous Fe oxides on adsorption-desorption of atrazine in soil. Based on the conclusions of the study amorphous Fe oxides with relatively high specific surface area and relatively big number of protons donating functional groups demonstrated a relatively high sorption capacity and affinity for atrazine even though their complexation with SOM contained in natural soil inhibits their direct adsorption capacity.

The role of soil iron oxides (IOs) in the distribution and interactions of penta-chlorophenol in soils was investigated by Diagboya et al. [225] and batch sorption studies were conducted on whole soils and soils selectively treated to remove IOs (IOR) and OM (OMR). As revealed by the kinetic models, sorption equilibrium occurred faster in the IOR soils than the untreated and OMR soils and therefore iron

oxides played greater roles in the sorption of pentachlorophenol than the OM content.

The influence of Al-oxide on pesticide sorption to woody biochars with different surface areas (SA) was investigated by Shou et al. [199]. The published results of this survey revealed the enhanced sorption of the pesticide isoproturon to the Al-oxide-treated low-SA biochar that was positively related to the increased mesopore area.

3.2.3 Impact of Pesticides' Physicochemical Properties

The chemical structure of a pesticide and some specific characteristics of its molecules determine its sorption behavior and its affinity to be sorbed on soil colloids. The nature of functional groups contained in the compound is a crucial factor. Several functional groups such as carboxyl, carbonyl, alcoholic and amino moieties are very important as they govern the process of binding. Enhanced adsorption capacity has been observed with the presence of the below functional groups in pesticides molecules in the increasing order: R_3N^+, $-CONH_2$, $-OH$, $-NHCOR$, $-NH_2$, $-OCOR$, and $-NHR$ [18]. Especially the ability of amino group to be protonated (which is a property dependent on pK value of the molecule) leads to the sorption as cations, and thus is very important. Moreover, the participation of amino and carbonyl moieties into hydrogen bonding has also been revealed [18].

A study on the soil sorption of six basic (pirimicarb, pirimiphos ethyl, prochloraz, prometryn, quinoxyfen, and triadimefon), and six neutral (α-endosulfan, chlorpyrifos, fenthion, parathion, parathion methyl, and cis permethrin) pesticides was conducted by Vitoratos et al. [123] and based on the experimental data that were acquired hydrophobic, electrostatic, and polar interactions were implied.

The charge characteristic of pesticides, the equal or unequal distribution of electrons in its molecule producing temporary or permanent polarity, correspondingly, its weak or strong tendency to donate or adopt protons are only some of the pesticide properties that determine the mobility of pesticides into the soil-water bulk systems.

The sorption behavior of both ionizable and nonionizable pesticides in the presence of HA in soils was investigated by Ćwieląg-Piasecka et al. [90] and high affinity of investigated HA to polar, ionic pesticides of high water solubility, which are sorbed via specific interactions with HA functional groups.

Moreover, water solubility and hydrophobicity or lipophilicity, expressed with means of octanol/water partition coefficient (K_{ow} or log K_{ow}), are two of the most important physicochemical properties whose impacts on the sorption have been evaluated in several scientific surveys [20, 28, 122, 134]. Rodríguez-Liébana et al. [138] evaluated the adsorption behavior of six different pesticides (α-cypermethrin, deltamethrin, pendimethalin, thiacloprid, dimethenamid, and fenarimol) that differed in hydrophobicity (range of log K_{ow} values: 1.26–5.8) in three organic poor soils (% OC content ≤1.2%). Obtained results indicated lower kinetic rates for the more hydrophobic pesticides (log K_{ow} ≥ 4.6) compared with the other compounds under

study. According to the intraparticle diffusion model that was used, a strong contribution of a rapid initial adsorption on soil surface for thiacloprid, dimethenamid, and fenarimol was observed, while moderate contribution for the hydrophobic pesticides was achieved.

3.2.4 Impact of Carbon-Rich Organic Amendments Applied to Soils

Numerous recent studies have confirmed the advantages and benefits that are gained in the improvement of soil characteristics (including fertility, adsorption capacity, leaching and remediation by the reduction of the contamination of the neighboring terrestrial and aquatic areas) after the application of a wide variety of carbon-rich by-products (which are known with the term biochar) that are prepared by the application of the pyrolysis technique on low cost by-products, agrowastes, and organic materials under high temperatures in the absence of oxygen [14, 16, 84]. Several different functional groups present in the structure of these biochars play an important role and lead to a stronger adsorption of the organic pesticides' molecules. In general, it is well known that under higher temperature of pyrolysis the produced biochars have more aromatic units and pores for capturing more sorbates.

According to the results of Chin-Pampillo et al. [84], the addition of three different pyrolyzed agrowastes of pineapple stubble, palm oil fiber and coffee hull, as amendments in a tropical soil it was observed that the sorption behavior and persistence of bromacil and diuron was affected. More specific, the two first amendments resulted in an increase of bromacil's sorption of three to four-fold and a three to six-fold change in diuron's sorption, while the addition of the third biochar had little effect. Similarly, the published results of a survey conducted by Aldana et al. [67] on the effects of biochar addition on the leaching and sorption of the agrochemicals atrazine, diuron, enrofloxacin, oxytetracycline, and tetracycline in tropical soils showed that sorption was higher in biochar-amended soils than soils without biochar amendment and the used biochars were produced from mixed softwood, rice husk, and miscanthus straw, after pyrolyzed at 700°C.

In a recently published study of Cheng et al. [233] it is reported that overall the application of biochar in agricultural soils combined with arbuscular mycorrhizal fungi inoculation can influence the decomposition and leaching of simazine, mitigate its accumulation in the topsoil, and consequently reduce the availability of the studied pesticide. Based on the findings of a review conducted by Siedt et al. [249] regarding the comparison of straw, compost, and biochar on the fate of pesticides in agriculture soils it is concluded that although biochar has the higher effectiveness of all in increasing the sorption capacity of soils however it cannot surpass straw and compost regarding the other aspects investigated (such as transformation and retention of nutrients, soil microbial communities, etc.). The impact of biochar addition to soils and sediments samples from four sites along Litani river basin on the adsorption behavior of three commonly used herbicides fluazifop, terbuthylazine, and triclopyr was assessed by Kchour et al. [173] and based on the derived results of the survey K_{ads} values in biochar treated matrices increased

considerably in comparison with the non-treated ones. Furthermore, according to the same study in the presence of biochar the phenomenon of sorption was not reversible, and hysteresis occurred.

Bentazone sorption and desorption studies executed by Ponnam et al. [74] revealed that the introduction of biochar not only improved several characteristics of the soil among which pesticide adsorption efficiency is included (pH, CEC, electrical conductivity), but also that lowered the desorption levels and thus enhanced soil quality. In a separate survey, Ponnam et al. [95] reported the same pattern of attitude for the case of carbofuran that was irreversibly sorbed by moderately acidic soil amended with biochar. The effects of raw feedstock and biochar (produced from soybean residues, sugarcane bagasse, and wood chips (grape)) amendments on sorption-desorption and leaching potential of the pesticides aminocyclopyrachlor, metolachlor, and imidacloprid were studied by Mendes et al. [47], and decreased availability of metolachlor and imidacloprid in soil was observed via increased sorption process. For the case of aminocyclopyrachlor the availability differed between the use of raw feedstock and biochar, while the most important impact on pesticide behavior was derived from biochar produced from wood chips pyrolysis. Reduced dissipation of thiamethoxam in a biochar-amended agricultural soil was reported by You et al. [242].

Numerous published data during the period 2016–2021 have demonstrated the increased adsorption efficiencies that were achieved (and possible lower pesticide leaching mitigation) after biochar amendments applied on different soils and for several pesticides, such as for acetamiprid [39], acetochlor [40], atrazine in the presence of Cd(II) [52] or not [60, 63, 64], bentazone [75, 77], boscalid [75, 77], cadusafos [88], carbaryl [90], carbofuran [90], chlorothalonil [109], chlorpyrifos [116, 117], clomazone [80], clothianidin [136], difenoconazole [143], 2,4-dichlorophenoxyacetic acid (2,4-D) [90], diuron [117, 148], fenamiphos [88], glyphosate [117, 180, 182], imazapic [190], imazapyr [190], imazamox [189], imidacloprid [63, 136], isoproturon [63], 4-chloro-2-methylphenoxyacetic acid (MCPA) [90, 120], metalaxyl [206, 207], metolachlor [90, 214], picloram [189], pyrimethanil [75, 77], simazine [235, 253], tebuconazole [207], terbuthylazine [189], and thiacloprid [136, 240, 241].

The published results of Ćwieląg-Piasecka et al. [90] who examined the biochar as specific sorbents of several carbamate, phenoxyacetic acids, and aniline derivatives pesticides indicated that the biochar that was produced from wheat straw and used in the study preferentially attracted nonionic pesticides with relatively high log K_{ow} values and low water solubility probably because of its moderately hydrophobic character. Therefore, the principal mechanism of pesticides' attraction to biochar that was proposed was the hydrophobic bonding.

According to the findings of García-Jaramillo et al. [69], the role of biochar and biochar water-extractable substances on the sorption of pesticides onto soils is depended on soil and biochar properties and time of application, and these parameters need proper consideration before the application because reduction or increase in the mobility of ionizable organic compounds may occur. That was based on their observation that, in spite the enhanced soil sorption capacity of the herbicides

azimsulfuron and penoxsulam that was observed after the application of raw biochar as soil amendment in two rice paddy soils, on the contrary, lessened azimsulfuron adsorption was reported in the washed biochar soil samples than in the washed biochar. This was attributed possibly due to the reduction of polar groups of biochar through washing step, which had no effect on penoxsulam adsorption.

3.2.5   Impact of Pesticide Mixture Interactions

It has been well documented that the co-presence of pesticides in chemical mixtures promotes changes in its behavior into soil due to synergistic or antagonistic phenomena that may occur [147, 153, 160].

The leaching of three selected pesticides, diuron, hexazinone, and sulfometuron-methyl, applied in soils with contrasting textures (sandy or clayey) and by two different modes, alone and in mixture was investigated by Dos Reis et al. [160]. The results of soil column experiments showed that when herbicides were applied in mixture of the commercial mixture diuron + hexazinone + sulfometuron-methyl, interactions among them could potentially promote changes in herbicide behavior in the soil. Hexazinone was reported to have the greater leaching potential and mobility along the soil profile compared to the other two studied molecules, whereas diuron remained at the top layer of the soil, and hence indicated that this herbicide has low soil mobility.

In a similar study conducted by Sousa et al. [153] regarding the sorption and desorption of diuron, hexazinone and their mixture in soils with different attributes it was revealed that in all tested soils, diuron and hexazinone showed higher sorption coefficients K_F values when mixed. Carneiro et al. [147] surveyed the way that herbicide mixtures can affect the adsorption processes in soils under sugarcane cultivation. For that purpose, the sorption process of diuron, hexazinone, and sulfometuron-methyl in isolated and mixed conditions was examined. Results of the study refer that herbicide mixtures reduced the maximum adsorption (qe) in ≈50 (diuron), 56 (hexazinone), and 55% (sulfometuron-methyl) compared to isolated tests. Also, herbicide mixtures reduced the sorption rate (K_F) 24 (diuron), 89 (hexazinone), and 66% (sulfometuron-methyl) compared to conditions isolated tests.

4   Conclusions and Future Perspectives

Regardless of their mode of application several different pesticide compounds that are unavoidably used in the terrestrial environment mainly for agricultural purposes (protection of crop quality and quantity) reach the soil and are subjected to biotic and abiotic processes which affect their distribution and transportation into the soil-water-biota systems. Binding to soil particles, known as sorption, desorption into the soil bulk, and vertical removal from topsoil into lower subsoil depths by leaching

are unquestionably the predominant abiotic phenomena that influence their behavior and bioavailability into these ecosystems.

According to the findings of the current overview a great number of publications, overall 228 reports, have been found for the period 2016–2021 (from 01/01/2016 to 30/06/2021) regarding the sorption, desorption, and leaching of several different pesticides which belong to a wide variety of chemical groups. Obtained data revealed that the evaluation of adsorption/desorption capacity on soil, leaching, and transportation process for 186 individual pesticides, in total, have been investigated and reported in the scientific literature published in the last 5.5 years. Moreover, atrazine (triazine herbicide) is the pesticide on which scientific interest has been focused, followed by chlorpyrifos (organophosphorus insecticide), imidacloprid (nicotinoid insecticide), glyphosate (organophosphorus insecticide), and metolachlor (systemic fungicide). Results showed that the scientific interest has been focused either on the most used and thus frequently detected pesticides or/and on the pesticides that exhibit the longer half-lives and can remain in the water and soil at high levels (above several hundreds of $\mu g\ L^{-1}$ or $\mu g\ kg^{-1}$) and therefore pose a higher ability to threat exposed ecosystems and humans through the food chain.

Different sorption, desorption, and leaching attributes, behaviors, affinities, and characteristics were observed within the overviewed data indicating that the transportation and distribution fate of applied pesticides is dependent upon the combination of the studied soil/pesticide system. In general, among the most important soil factors that can affect the studied processes both OM and clay contents were included, whereas soil pH and CEC played a secondary role. Extended research concerning the enhancement of pesticide sorption and reduction of leaching into aquifers by a variety of different biochar amendments has been conducted.

A knowledge gap concerning the impact of pesticide mixture interactions on the adsorption on soils' colloids, leaching potential, and mobility of pesticides along the soil profile is observed, as the overviewed surveys examining this topic are very scarce. Therefore, more surveys in this direction must be conducted in future research, since it is indisputable fact that chemical cocktails can promote variations in the behavior of individual pesticide compounds into the soil via possible and simultaneous synergistic or antagonistic phenomena.

References

1. Erban T, Stehlik M, Sopko B et al (2018) The different behaviors of glyphosate and AMPA in compost-amended soil. Chemosphere 207:78–83. https://doi.org/10.1016/j.chemosphere.2018.05.004
2. Zhang C, Tian D, Yi XH et al (2019) Occurrence, distribution, and seasonal variation of five neonicotinoid insecticides in surface water and sediment of the Pearl Rivers, South China. Chemosphere 217:437–446. https://doi.org/10.1016/j.chemosphere.2018.11.024

3. Zhang C, Yi X, Chen C et al (2020) Contamination of neonicotinoid insecticides in soil-water-sediment systems of the urban and rural areas in a rapidly developing region: Guangzhou, South China. Environ Int 139:105719. https://doi.org/10.1016/j.envint.2020.105719

4. Zambito MR, Capri E, Russo E et al (2020) First evaluation of pesticides occurrence in groundwater of Tidone Valley, an area with intensive viticulture. Sci Total Environ 736:139730. https://doi.org/10.1016/j.scitotenv.2020.139730

5. Philippe V, Neveen A, Marwa A et al (2021) Occurrence of pesticide residues in fruits and vegetables for the eastern mediterranean region and potential impact on public health. Food Control 119:107457. https://doi.org/10.1016/j.foodcont.2020.107457

6. Pico Y, El-Sheikh MA, Alfarhan AH et al (2018) Target vs non-target analysis to determine pesticide residues in fruits from Saudi Arabia and influence in potential risk associated with exposure. Food Chem Toxicol 111:53–63. https://doi.org/10.1016/j.fct.2017.10.060

7. WHO (2020) World Health Organization recommended classification of pesticides by hazard and guidelines to classification (2019 edition). Licence: CC BY-NC-SA 3.0 IGO. World Health Organization, Geneva

8. Liu T, Xu S, Lu S et al (2019) A review on removal of organophosphorus pesticides in constructed wetland: performance, mechanism and influencing factors. Sci Total Environ Part 2(651):2247–2268. https://doi.org/10.1016/j.scitotenv.2018.10.087

9. Mamy L, Bonnot K, Benoit P et al (2021) Assessment of pesticides volatilization potential based on their molecular properties using the TyPol tool. J Hazard Mater 415:125613. https://doi.org/10.1016/j.jhazmat.2021.125613

10. Pietrzak D, Kania J, Kmiecik E et al (2020) Fate of selected neonicotinoid insecticides in soil–water systems: current state of the art and knowledge gaps. Chemosphere 255:126981. https://doi.org/10.1016/j.chemosphere.2020.126981

11. Perez-Lucas G, Vela N, El Aatik A, Navarro S (2018) Environmental risk of groundwater pollution by pesticide leaching through the soil profile. In: Larramendy M, Sonia Soloneski S (eds) Pesticides – use and misuse and their impact in the environment. IntechOpen, pp 1–27. https://doi.org/10.5772/intechopen.82418

12. Meftaul IM, Venkateswarlu K, Dharmarajan R et al (2020) Controversies over human health and ecological impacts of glyphosate: is it to be banned in modern agriculture? Environ Pollut Part A 263:114372. https://doi.org/10.1016/j.envpol.2020.114372

13. Penn C, Gonzalez J, Williams M et al (2020) The past, present, and future of blind inlets as a surface water best management practice. Crit Rev Environ Sci Technol 50:743–768. https://doi.org/10.1080/10643389.2019.1642836

14. Khalid S, Shahid M, Murtaza B et al (2020) A critical review of different factors governing the fate of pesticides in soil under biochar application. Sci Total Environ 711:134645. https://doi.org/10.1016/j.scitotenv.2019.134645

15. Ren X, Zeng G, Tang L et al (2018) Sorption, transport and biodegradation – an insight into bioavailability of persistent organic pollutants in soil. Sci Total Environ 610–611:1154–1163. https://doi.org/10.1016/j.scitotenv.2017.08.089

16. Liu Y, Lonappan L, Kaur Brar S et al (2018) Impact of biochar amendment in agricultural soils on the sorption, desorption, and degradation of pesticides: a review. Sci Total Environ 645:60–70. https://doi.org/10.1016/j.scitotenv.2018.07.099

17. Jarvis N (2018) Meta-analysis of pesticide sorption in subsoil. Environ Toxicol Chem 37:755–761. https://doi.org/10.1002/etc.4011

18. Sadegh-Zadeh F, Abd Wahid S, Jalili B (2017) Sorption, degradation and leaching of pesticides in soils amended with organic matter: a review. Adv Environ Technol 3:119–132. https://doi.org/10.22104/aet.2017.1740.1100

19. Lewis SE, Silburn DM, Kookana RS et al (2016) Pesticide behavior, fate, and effects in the tropics: an overview of the current state of knowledge. J Agric Food Chem 64:3917–3924. https://doi.org/10.1021/acs.jafc.6b01320

20. Agbaogun BK, Alonso JM, Buddenbaum H et al (2021) Modelling of the adsorption of urea herbicides by tropical soils with an adaptive-neural-based fuzzy inference system. J Chemom 35:3335. https://doi.org/10.1002/cem.3335

21. Faúndez Urbina CA, van den Berg F, van Dam JC et al (2020) Parameter sensitivity of SWAP–PEARL models for pesticide leaching in macroporous soils. Vadose Zone J 19:20075. https://doi.org/10.1002/vzj2.20075

22. Kuo DTF, Shih YH (2020) Meta-analysis on penconazole sorption to soils – modeling variability of K_{OC} and nonlinear isotherm parameters. Geoderma 376:114536. https://doi.org/10.1016/j.geoderma.2020.114536

23. Marín-Benito JM, Mamy L, Carpio MJ et al (2020) Modelling herbicides mobility in amended soils: calibration and test of PRZM and MACRO. Sci Total Environ 717:137019. https://doi.org/10.1016/j.scitotenv.2020.137019

24. Jaramillo M, Grischek T, Boernick H et al (2019) Evaluation of riverbank filtration in the removal of pesticides: an approximation using column experiments and contaminant transport modeling. Clean Technol Environ Pol 21:179–199. https://doi.org/10.1007/s10098-018-1627-y

25. Kupfersberger H, Klammler G, Schuhmann A et al (2018) Modeling subsurface fate of s-metolachlor and metolachlor ethane sulfonic acid in the westliches leibnitzer feld aquifer. Vadose Zone J 17:170030. https://doi.org/10.2136/vzj2017.01.0030

26. Marín-Benito JM, Sánchez-Martín MJ, Ordax JM et al (2018) Organic sorbents as barriers to decrease the mobility of herbicides in soils. Modelling of the leaching process. Geoderma 313:205–216. https://doi.org/10.1016/j.geoderma.2017.10.033

27. Paszko T, Jankowska M (2018) Modeling the effect of adsorption on the degradation rate of propiconazole in profiles of Polish Luvisols. Ecotox Environ Saf 161:584–593. https://doi.org/10.1016/j.ecoenv.2018.05.093

28. Daré JK, Silva CF, Freitas MP (2017) Revealing chemophoric sites in organophosphorus insecticides through the MIA-QSPR modeling of soil sorption data. Ecotox Environ Saf 144:560–563. https://doi.org/10.1016/j.ecoenv.2017.06.072

29. Williams KL, Gladfelder JJ, Quigley LL et al (2017) Dissipation of the herbicide benzobicyclon hydrolysate in a model California rice field soil. J Agric Food Chem 65:9200–9207. https://doi.org/10.1021/acs.jafc.7b03679

30. Arthur E, Tuller M, Moldrup P et al (2016) Evaluation of theoretical and empirical water vapor sorption isotherm models for soils. Wat Resour Res 52:190–205. https://doi.org/10.1002/2015WR017681

31. Filipović V, Coquet Y, Pot V et al (2016) Modeling water and isoproturon dynamics in a heterogeneous soil profile under different urban waste compost applications. Geoderma 268:29–40. https://doi.org/10.1016/j.geoderma.2016.01.009

32. Jarvis N (2016) Extended sorption partitioning models for pesticide leaching risk assessments: can we improve upon the Koc concept? Sci Total Environ 539:294–303. https://doi.org/10.1016/j.scitotenv.2015.09.002

33. Sidoli P, Lassabatere L, Angulo-Jaramillo R et al (2016) Experimental and modeling of the unsaturated transports of S-metolachlor and its metabolites in glaciofluvial vadose zone solids. J Contam Hydrol 190:1–14. https://doi.org/10.1016/j.jconhyd.2016.04.001

34. Singh B, Farenhorst A, McQueen R et al (2016) Near-infrared spectroscopy as a tool for generating sorption input parameters for pesticide fate modeling. Soil Sci Soc Am J 80:604–612. https://doi.org/10.2136/sssaj2015.03.0118

35. Novotny EH, Turetta APD, Resende MF et al (2020) The quality of soil organic matter, accessed by 13C solid state nuclear magnetic resonance, is just as important as its content concerning pesticide sorption. Environ Pollut 266:115298. https://doi.org/10.1016/j.envpol.2020.115298

36. Dionisio AC, Rath S (2016) Abamectin in soils: analytical methods, kinetics, sorption and dissipation. Chemosphere 151:17–29. https://doi.org/10.1016/j.chemosphere.2016.02.058

37. Dankyi E, Gordon C, Carboo D et al (2018) Sorption and degradation of neonicotinoid insecticides in tropical soils. J Environ Sci Health Part B Pest Food Contam Agric Wastes 53:587–594. https://doi.org/10.1080/03601234.2018.1473965

38. Murano H, Suzuki K, Kayada S et al (2018) Influence of humic substances and iron and aluminum ions on the sorption of acetamiprid to an arable soil. Sci Total Environ 615:1478–1484. https://doi.org/10.1016/j.scitotenv.2017.09.120

39. Wang H, Huang Y, Shen C et al (2016) Co-transport of pesticide acetamiprid and silica nanoparticles in biochar-amended sand porous media. J Environ Qual 45:1749–1759. https://doi.org/10.2134/jeq2016.02.0073

40. Li Y, Liu X, Wu X et al (2018) Effects of biochars on the fate of acetochlor in soil and on its uptake in maize seedling. Environ Pollut 241:710–719. https://doi.org/10.1016/j.envpol.2018.05.079

41. Park WP, Chang KM, Hyun HN et al (2020) Sorption and leaching characteristics of pesticides in volcanic ash soils of Jeju Island, Korea. Appl Biol Chem 63:71. https://doi.org/10.1186/s13765-020-00555-5

42. Ahmad KS (2018) Sorption and Juglans regia-derived activated carbon-mediated removal of aniline-based herbicide Alachlor from contaminated soils. Environ Earth Sci 77:437. https://doi.org/10.1007/s12665-018-7633-x

43. Ahmad KS (2018) Evaluating the adsorption potential of Alachlor and its subsequent removal from soils via activated carbon. Soil Sed Contam 27:249–266. https://doi.org/10.1080/15320383.2018.1470604

44. Marín-Benito JM, Herrero-Hernández E, Rodríguez-Cruz MS et al (2017) Study of processes influencing bioavailability of pesticides in wood-soil systems: effect of different factors. Ecotoxicol Environ Saf 139:454–462. https://doi.org/10.1016/j.ecoenv.2017.02.012

45. Pérez-Lucas G, Vela N, Escudero JA et al (2017) Valorization of organic wastes to reduce the movement of priority substances through a semiarid soil. Water Air Soil Pollut 228:119. https://doi.org/10.1007/s11270-017-3305-9

46. Portocarrero R, Aparicio V, De Gerónimo E et al (2019) Soil properties of sugarcane fields controlling triazine leaching potential. Soil Res 57:729–737. https://doi.org/10.1071/SR18342

47. Mendes KF, de Sousa RN, Goulart MO et al (2020) Role of raw feedstock and biochar amendments on sorption-desorption and leaching potential of three 3H- and 14C-labelled pesticides in soils. J Radioanal Nuc Chem 324:1373–1386. https://doi.org/10.1007/s10967-020-07128-2

48. Francisco JG, Mendes KF, Pimpinato RF et al (2017) Aminocyclopyrachlor sorption-desorption and leaching from three Brazilian soils. J Envion Sci Health B 52:470–475. https://doi.org/10.1080/03601234.2017.1301758

49. Yadav S, Singh N (2021) Increased sorption of atrazine and fipronil in the sugarcane trash ash–mixed soils of northern India. J Soil Sci Plant Nutr 21:1263–1276. https://doi.org/10.1007/s42729-021-00438-8

50. Alister C, Araya M, Cordova A et al (2020) Humic substances and their relation to pesticide sorption in eight volcanic soils. Planta Daninha 38:020171636. https://doi.org/10.1590/S0100-83582020380100021

51. de Freitas SM, Langaro AC, de Jesus Passos ABR et al (2020) Adsorption mechanisms of atrazine isolated and mixed with glyphosate formulations in soil. PLoS One 15:0242350. https://doi.org/10.1371/journal.pone.0242350

52. Jing S, Lan MX, Wen W et al (2020) Adsorption characteristics of atrazine on different soils in the presence of Cd(II). Ads Sci Technol 38:225–239. https://doi.org/10.1177/0263617420928845

53. Lima JM, Aquino RF, Magalhães CAS et al (2020) Lime and phosphate effects on atrazine sorption, leaching and runoff in soil. Ciencia e Agrotecnologia 44:022919. https://doi.org/10.1590/1413-7054202044022919

54. Shan R, Chen Y, Meng L et al (2020) Rapid prediction of atrazine sorption in soil using visible near-infrared spectroscopy. Spectr Acta Part A Mol Biomol Spectr 224:117455. https://doi.org/10.1016/j.saa.2019.117455

55. Yu H, Liu Y, Shu X et al (2020) Equilibrium, kinetic and thermodynamic studies on the adsorption of atrazine in soils of the water fluctuation zone in the three-gorges reservoir. Environ Sci Eur 32:27. https://doi.org/10.1186/s12302-020-00303-y

56. Hüffer T, Metzelder F, Sigmund G et al (2019) Polyethylene microplastics influence the transport of organic contaminants in soil. Sci Total Environ 657:242–247. https://doi.org/10.1016/j.scitotenv.2018.12.047

57. Huang Y, Liu Z, Wei L et al (2018) Effects of amorphous Fe oxides on adsorption-desorption of atrazine in soil. Acta Pedol Sin 55:148–158. https://doi.org/10.11766/trxb201705170220

58. Neuwirthová N, Bílková Z, Vašíčková J et al (2018) Concentration/time-dependent dissipation, partitioning and plant accumulation of hazardous current-used pesticides and 2-hydroxyatrazine in sand and soil. Chemosphere 203:219–227. https://doi.org/10.1016/j.chemosphere.2018.03.177

59. Salazar-Ledesma M, Prado B, Zamora O et al (2018) Mobility of atrazine in soils of a wastewater irrigated maize field. Agric Ecosyst Environ 255:73–83. https://doi.org/10.1016/j.agee.2017.12.018

60. Deng H, Feng D, He JX et al (2017) Influence of biochar amendments to soil on the mobility of atrazine using sorption-desorption and soil thin-layer chromatography. Ecol Eng 99:381–390. https://doi.org/10.1016/j.ecoleng.2016.11.021

61. Jaikaew P, Malhat F, Boulange J et al (2017) Aspect of the degradation and adsorption kinetics of atrazine and metolachlor in andisol soil. Hell Plant Prot J 10:1–14. https://doi.org/10.1515/hppj-2017-0001

62. Wang Y, Zhang X, Zhang X et al (2017) Characterization of spectral responses of dissolved organic matter (DOM) for atrazine binding during the sorption process onto black soil. Chemosphere 180:531–539. https://doi.org/10.1016/j.chemosphere.2017.04.063

63. Jin J, Kang M, Sun K et al (2016) Properties of biochar-amended soils and their sorption of imidacloprid, isoproturon, and atrazine. Sci Total Environ 550:504–513. https://doi.org/10.1016/j.scitotenv.2016.01.117

64. Ouyang W, Zhao X, Tysklind M et al (2016) Typical agricultural diffuse herbicide sorption with agricultural waste-derived biochars amended soil of high organic matter content. Water Res 92:156–163. https://doi.org/10.1016/j.watres.2016.01.055

65. Silva RO, Scorza Júnior RP, Bonfá MRL et al (2016) Degradation and sorption of fipronil and atrazine in Latossols with organic residues from sugarcane crop. Cienc Rural 46:1172–1177. https://doi.org/10.1590/0103-8478cr20150696

66. Tahir M, Hassan AU, Maqbool S et al (2016) Sorption and leaching potential of isoproturon and atrazine in low organic carbon soil of Pakistan under a wheat-maize rotation. Pedosphere 26:687–698. https://doi.org/10.1016/S1002-0160(15)60077-7

67. Aldana GO, Hazlerigg C, Lopez-Capel E et al (2021) Agrochemical leaching reduction in biochar-amended tropical soils of Belize. Eur J Soil Sci 72:1243–1255. https://doi.org/10.1111/ejss.13021

68. Ratchawang S, Chotpantarat S (2019) The leaching potential of pesticides in Song Phi Nong district, Suphan Buri province, Thailand. Environ Asia 12:112–120. https://doi.org/10.14456/ea.2019.51

69. García-Jaramillo M, Trippe KM, Helmus R et al (2020) An examination of the role of biochar and biochar water-extractable substances on the sorption of ionizable herbicides in rice paddy soils. Sci Total Environ 706:135682. https://doi.org/10.1016/j.scitotenv.2019.135682

70. Smalling KL, Hladik ML, Sanders CJ et al (2018) Leaching and sorption of neonicotinoid insecticides and fungicides from seed coatings. J Environ Sci Health Part B Pest Food Contam Agric Wastes 53:176–183. https://doi.org/10.1080/03601234.2017.1405619

71. Motoki Y, Iwafune T, Seike N et al (2016) Effect of time-dependent sorption on the dissipation of water-extractable pesticides in soils. J Agric Food Chem 64:4478–4486. https://doi.org/10.1021/acs.jafc.6b01028

72. Wu P, Wu WZ, Han ZH et al (2016) Desorption and mobilization of three strobilurin fungicides in three types of soil. Environ Monit Assess 188:363. https://doi.org/10.1007/s10661-016-5372-6

73. Ahmad KS (2018) Sorption-desorption characteristics of benzimidazole based fungicide benomyl on physicochemical properties of selected Pakistani soils and their minerals. Pak J Sci Ind Res Ser B Biol Sci 61:59–67. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85054003097&partnerID=40&md5=ed42c5f4306d8d05cec41146219ee6ee

74. Ponnam V, Reddy RA, Sumalatha B (2020) Sorption and desorption studies for the removal of bentazone using biochar amended soil. Ind J Ecol 47:128–131. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85093070810&partnerID=40&md5=903eec4b740b65d29a477c8530ace121

75. Mukherjee S, Weihermüller L, Tappe W et al (2016) Sorption-desorption behaviour of bentazone, boscalid and pyrimethanil in biochar and digestate based soil mixtures for biopurification systems. Sci Total Environ 559:63–73. https://doi.org/10.1016/j.scitotenv.2016.03.145

76. Tauchnitz N, Kurzius F, Rupp H et al (2020) Dissipation of bentazone, pyrimethanil and boscalid in biochar and digestate based soil mixtures for biopurification systemscase study in the Querne/Weida catchment, Central Germany. Environ Pollut 267:115186. https://doi.org/10.1016/j.envpol.2020.115186

77. Mukherjee S, Tappe W, Weihermueller L et al (2016) Dissipation of bentazone, pyrimethanil and boscalid in biochar and digestate based soil mixtures for biopurification systems. Sci Total Environ 544:192–202. https://doi.org/10.1016/j.scitotenv.2015.11.111

78. Kah M, Weniger AK, Hofmann T (2016) Impacts of (nano)formulations on the fate of an insecticide in soil and consequences for environmental exposure assessment. Environ Sci Technol 50:10960–10967. https://doi.org/10.1021/acs.est.6b02477

79. Gómez S, Fernández D, Peña D et al (2019) Behaviour of bispyribac-sodium in aerobic and anaerobic rice-growing conditions with and without olive-mill waste amendment. Soil Till Res 194:104333. https://doi.org/10.1016/j.still.2019.104333

80. Gámiz B, Velarde P, Spokas KA et al (2017) Biochar soil additions affect herbicide fate: importance of application timing and feedstock species. J Agric Food Chem 65:3109–3117. https://doi.org/10.1021/acs.jafc.7b00458

81. López-Piñeiro A, Sánchez-Llerena J, Peña D et al (2016) Transition from flooding to sprinkler irrigation in Mediterranean rice growing ecosystems: effect on behaviour of bispyribac sodium. Agric Ecosyst Environ 223:99–107. https://doi.org/10.1016/j.agee.2016.03.003

82. Pérez-Lucas G, El Aatik A, Vela N et al (2020) Exogenous organic matter as strategy to reduce pesticide leaching through the soil. Arch Agron Soil Sci 67:934–945. https://doi.org/10.1080/03650340.2020.1768531

83. Holten R, Larsbo M, Jarvis N et al (2019) Leaching of five pesticides of contrasting mobility through frozen and unfrozen soil. Vadose Zone J 18:180201. https://doi.org/10.2136/vzj2018.11.0201

84. Chin-Pampillo JS, Perez-Villanueva M, Masis-Mora M et al (2021) Amendments with pyrolyzed agrowastes change bromacil and diuron's sorption and persistence in a tropical soil without modifying their environmental risk. Sci Total Environ 772:145515. https://doi.org/10.1016/j.scitotenv.2021.145515

85. Cessna AJ, Knight JD, Ngombe D et al (2017) Effect of temperature on the dissipation of seven herbicides in a biobed matrix. Can J Soil Sci 97:717–731. https://doi.org/10.1139/cjss-2017-0017

86. Torabi E, Wiegert C, Guyot B et al (2020) Dissipation of S-metolachlor and butachlor in agricultural soils and responses of bacterial communities: insights from compound-specific

isotope and biomolecular analyses. J Environ Sci (China) 92:163–175. https://doi.org/10.1016/j.jes.2020.02.009

87. Huang Y, Liu Z, Wei L et al (2017) Effect of soil organo-inorganic compounds different in particle size on butachlor sorption. Acta Pedol Sin 54:400–409. https://doi.org/10.11766/trxb201605130237

88. Abdel Ghani SB, Al-Rehiayani S, El Agamy M et al (2018) Effects of biochar amendment on sorption, dissipation, and uptake of fenamiphos and cadusafos nematicides in sandy soil. Pest Manag Sci 74:2652–2659. https://doi.org/10.1002/ps.5075

89. Kumari D, John S (2020) Sorption capacity of pesticides on soil in a predominant apple cultivation area. Soil Sed Contam 29:107–119. https://doi.org/10.1080/15320383.2019.1684876

90. Ćwieląg-Piasecka I, Medyńska-Juraszek A, Jerzykiewicz M et al (2018) Humic acid and biochar as specific sorbents of pesticides. J Soils Sed 18:2692–2702. https://doi.org/10.1007/s11368-018-1976-5

91. Latini LA, Indaco MM, Aguiar MB et al (2018) An integrated approach for assessing the migration behavior of chlorpyrifos and carbaryl in the unsaturated soil zone. J Environ Sci Health Part B Pest Food Contam Agric Wastes 53:469–475. https://doi.org/10.1080/03601234.2018.1455353

92. Ahmad KS (2020) Fungicidal methyl-2-benzimidazole carbamate adsorption in soil and remediation via prunus dulcis derived activated carbon. Rev Inter Contam Amb 36:429–442. https://doi.org/10.20937/RICA.53544

93. Tortella GR, Rubilar O, Cea M et al (2019) Sorption parameters of carbendazim and iprodione in the presence of copper nanoparticles in two different soils. J Soil Sci Plant Nutr 19:469–476. https://doi.org/10.1007/s42729-019-00037-8

94. Ahmad KS (2019) Arachis hypogaea derived activated carbon steered remediation of Benzimidazole based fungicide adsorbed soils. Chem Ecol 35:576–591. https://doi.org/10.1080/02757540.2019.1600678

95. Ponnam V, Mandapati RN, Bankupalli S (2020) Irreversible sorption of carbofuran by moderately acidic soil amended with biochar. Bioint Res Appl Chem 10:5224–5228. https://doi.org/10.33263/BRIAC102.224228

96. Cáceres T, Maestroni B, Islam M et al (2019) Sorption of 14 C-carbofuran in Austrian soils: evaluation of fate and transport of carbofuran in temperate regions. Environ Sci Pollut Res 26:986–990. https://doi.org/10.1007/s11356-018-3730-3

97. Mosquera-Vivas CS, Obregon-Neira N, Celis-Ossa RE et al (2016) Degradation and thermodynamic adsorption process of carbofuran and oxadicyl in a Colombian agricultural soil profile. Agron Colomb 34:92–100. https://doi.org/10.15446/agron.colomb.v34n1.53325

98. Redman ZC, Tjeerdema RS (2018) Impact of simulated California rice-growing conditions on chlorantraniliprole partitioning. J Agric Food Chem 66:1765–1772. https://doi.org/10.1021/acs.jafc.7b05775

99. Al-Smadi BM, Al Oran EH, Abu Hajar HA (2019) Adsorption-desorption of cypermethrin and chlorfenapyr on Jordanian soils. Arab J Geosci 12:465. https://doi.org/10.1007/s12517-019-4614-7

100. Isakovski MK, Maletić S, Tamindžija D et al (2020) Impact of hydrochar and biochar amendments on sorption and biodegradation of organophosphorus pesticides during transport through Danube alluvial sediment. J Environ Manag 274:111156. https://doi.org/10.1016/j.jenvman.2020.111156

101. Shaheen I, Ahmad KS, Zahra T (2019) Evaluating the fate of agrochemical through adsorption and desorption studies of chlorfluazuron in selected agricultural soils. J King Saud Univ Sci 31:612–617. https://doi.org/10.1016/j.jksus.2017.12.005

102. Flores-Céspedes F, Daza-Fernández I, Villafranca-Sánchez M et al (2018) Lignin and ethylcellulose in controlled release formulations to reduce leaching of chloridazon and metribuzin in light-textured soils. J Hazard Mater 343:227–234. https://doi.org/10.1016/j.jhazmat.2017.09.012

103. Agbaogun BK, Fischer K (2020) Adsorption of phenylurea herbicides by tropical soils. Environ Monit Assess 192:212. https://doi.org/10.1007/s10661-020-8160-2

104. Marín-Benito JM, Carpio MJ, Sánchez-Martín MJ et al (2019) Previous degradation study of two herbicides to simulate their fate in a sandy loam soil: effect of the temperature and the organic amendments. Sci Total Environ 653:1301–1310. https://doi.org/10.1016/j.scitotenv.2018.11.015

105. Suddaby LA, Beulke S, van Beinum W et al (2016) Long-term experiments to investigate irreversibility in sorption of pesticides to soil. Chemosphere 162:40–47. https://doi.org/10.1016/j.chemosphere.2016.07.062

106. García-Delgado C, Marín-Benito JM, Sánchez-Martín MJ et al (2020) Organic carbon nature determines the capacity of organic amendments to adsorb pesticides in soil. J Hazard Mater 390:122162. https://doi.org/10.1016/j.jhazmat.2020.122162

107. Wang Z, Yang L, Cheng P et al (2021) Adsorption, degradation and leaching migration characteristics of chlorothalonil in different soils. Eur J Rem Sens 54(S2):238–247. https://doi.org/10.1080/22797254.2020.1771216

108. Báez ME, Espinoza J, Silva R et al (2017) Influence of selected cyclodextrins in sorption-desorption of chlorpyrifos, chlorothalonil, diazinon, and their main degradation products on different soils. Environ Sci Pollut Res 24:20908–20921. https://doi.org/10.1007/s11356-017-9652-7

109. De Souza AJ, De Andrade PAM, De Araújo Pereira AP et al (2017) The depleted mineralization of the fungicide chlorothalonil derived from loss in soil microbial diversity. Sci Rep 7:14646. https://doi.org/10.1038/s41598-017-14803-0

110. Copaja SV, Gatica-Jeria P (2021) Effects of clay content in soil on pesticides sorption process. J Chil Chem Soc 65:5086–5092. https://doi.org/10.4067/S0717-97072021000105086

111. Das A, Jaswal V, Yogalakshmi KN (2020) Degradation of chlorpyrifos in soil using laccase immobilized iron oxide nanoparticles and their competent role in deterring the mobility of chlorpyrifos. Chemosphere 246:125676. https://doi.org/10.1016/j.chemosphere.2019.125676

112. Liu H, Guan Z, Cheng J et al (2020) Effects of intermittent irrigation on reactive transport behavior of chlorpyrifos in paddy field. Nongye Gongcheng Xuebao/Trans Chin Soc Agric Eng 36:214–220. https://doi.org/10.11975/j.issn.1002-6819.2020.01.025

113. Schwantes D, Celso Gonçalves A, Jr Conradi Junior É et al (2020) Determination of chlorpyrifos by GC/ECD in water and its sorption mechanism study in a RHODIC FERRALSOL. J Environ Health Sci Eng 18:149–162. https://doi.org/10.1007/s40201-020-00448-1

114. Ben Salem A, Chaabane H, Caboni P et al (2019) Environmental fate of two organophosphorus insecticides in soil microcosms under Mediterranean conditions and their effect on soil microbial communities. Soil Sed Contam 28:285–303. https://doi.org/10.1080/15320383.2018.1564733

115. Gaonkar OD, Nambi IM, Govindarajan SK (2019) Soil organic amendments: impacts on sorption of organophosphate pesticides on an alluvial soil. J Soils Sed 19:566–578. https://doi.org/10.1007/s11368-018-2080-6

116. Aziz H, Murtaza G, Usman M et al (2018) Enhancing chlorpyrifos sorption potential of agricultural soil by biochar and compost addition. Pak J Agric Sci 55:833–841. https://doi.org/10.21162/PAKJAS/18.7463

117. Cederlund H, Börjesson E, Stenström J (2017) Effects of a wood-based biochar on the leaching of pesticides chlorpyrifos, diuron, glyphosate and MCPA. J Environ Manag 191:28–34. https://doi.org/10.1016/j.jenvman.2017.01.004

118. Parolo ME, Savini MC, Loewy RM (2017) Characterization of soil organic matter by FT-IR spectroscopy and its relationship with chlorpyrifos sorption. J Environ Manag 196:316–322. https://doi.org/10.1016/j.jenvman.2017.03.018

119. Savini MC, Loewy RM, Nicotra VE et al (2017) Contribution of soil components on the sorption of chlorpyrifos. Water Air Soil Pollut 228:36. https://doi.org/10.1007/s11270-016-3153-z

120. Zhao Y, Wendling LA, Wang C et al (2017) Behavior of chlorpyrifos and its major metabolite TCP (3,5,6-trichloro-2-pyridinol) in agricultural soils amended with drinking water treatment residuals. J Soils Sed 17:889–900. https://doi.org/10.1007/s11368-016-1586-z

121. Dores EFGC, Spadotto CA, Weber OLS et al (2016) Environmental behavior of chlorpyrifos and endosulfan in a tropical soil in central Brazil. J Agric Food Chem 64:3942–3948. https://doi.org/10.1021/acs.jafc.5b04508

122. Papadopoulou ES, Karas PA, Nikolaki S et al (2016) Dissipation and adsorption of isoproturon, tebuconazole, chlorpyrifos and their main transformation products under laboratory and field conditions. Sci Total Environ 569–570:86–96. https://doi.org/10.1016/j.scitotenv.2016.06.133

123. Vitoratos A, Fois C, Danias P et al (2016) Investigation of the soil sorption of neutral and basic pesticides. Water Air Soil Pollut 227:397. https://doi.org/10.1007/s11270-016-3076-8

124. Cara IG, Rusu BG, Raus L et al (2017) Sorption potential of alkaline treated straw and a soil for sulfonylurea herbicide removal from aqueous solutions: an environmental management strategy. Chemosphere 186:360–366. https://doi.org/10.1016/j.chemosphere.2017.07.140

125. Đurović-Pejčev RD, Radmanović SB, Tomić ZP et al (2020) Adsorption–desorption behaviour of clomazone in Regosol and Chernozem agricultural soils. J Serb Chem Soc 85:809–819. https://doi.org/10.2298/JSC190917122D

126. Fernández D, Gómez S, Albarrán Á et al (2020) How the environmental fate of clomazone in rice fields is influenced by amendment with olive-mill waste under different regimes of irrigation and tillage. Pest Manag Sci 76:1795–1803. https://doi.org/10.1002/ps.5705

127. Álvarez-Martín A, Rodríguez-Cruz MS, Andrades MS et al (2016) Application of a biosorbent to soil: a potential method for controlling water pollution by pesticides. Environ Sci Pollut Res 23:9192–9203. https://doi.org/10.1007/s11356-016-6132-4

128. Álvarez-Martín A, Sánchez-Martín MJ, Ordax JM et al (2017) Leaching of two fungicides in spent mushroom substrate amended soil: influence of amendment rate, fungicide ageing and flow condition. Sci Total Environ 584–585:828–837. https://doi.org/10.1016/j.scitotenv.2017.01.126

129. Álvarez-Martín A, Sánchez-Martín MJ, Pose-Juan E et al (2016) Effect of different rates of spent mushroom substrate on the dissipation and bioavailability of cymoxanil and tebuconazole in an agricultural soil. Sci Total Environ 550:495–503. https://doi.org/10.1016/j.scitotenv.2016.01.151

130. Beringer CJ, Goyne KW, Lerch RN et al (2021) Clothianidin decomposition in Missouri wetland soils. J Environ Qual 50:241–251. https://doi.org/10.1002/jeq2.20175

131. Motoki Y (2020) Studies on the sorption behavior and plant uptake of pesticides in Japanese soils. J Pest Sci 16:159–165. https://doi.org/10.1584/JPESTICS.J20-05

132. Kah M, Walch H, Hofmann T (2018) Environmental fate of nanopesticides: durability, sorption and photodegradation of nanoformulated clothianidin. Environ Sci Nano 5:882–889. https://doi.org/10.1039/c8en00038g

133. Li Y, Su P, Li Y et al (2018) Adsorption-desorption and degradation of insecticides clothianidin and thiamethoxam in agricultural soils. Chemosphere 207:708–714. https://doi.org/10.1016/j.chemosphere.2018.05.139

134. Motoki Y, Iwafune T, Seike N et al (2018) Comparison of soil sorption parameters of pesticides measured by batch and centrifugation methods using an andosol. J Pestic Sci 43:277–282. https://doi.org/10.1584/jpestics.D18-015

135. Zhang P, Ren C, Sun H et al (2018) Sorption, desorption and degradation of neonicotinoids in four agricultural soils and their effects on soil microorganisms. Sci Total Environ 615:59–69. https://doi.org/10.1016/j.scitotenv.2017.09.097

136. Zhang P, Sun H, Ren C et al (2018) Sorption mechanisms of neonicotinoids on biochars and the impact of deashing treatments on biochar structure and neonicotinoids sorption. Environ Pollut 234:812–820. https://doi.org/10.1016/j.envpol.2017.12.013

137. Kolupaeva V, Nyukhina I, Belik A (2020) Study of cyantraniliprole sorption in soils of Russia. E3S Web Conf 169:01022. https://doi.org/10.1051/e3sconf/202016901022

138. Rodríguez-Liébana JA, Peña A (2020) Differences in the sorption kinetics of various non-ionisable pesticides in a limited number of agricultural soils from the Mediterranean basin. J Environ Manag 276:111336. https://doi.org/10.1016/j.jenvman.2020.111336

139. Yu C, Bi E (2016) Evaluating nonlinear sorption of four substituted phenols to agriculture soils using expanded polyparameter linear free energy relationship. Water Air Soil Pollut 228:414. https://doi.org/10.1007/s11270-017-3596-x

140. Ahmed SM, Taha MR, Taha OME (2018) Kinetics and isotherms of dichlorodiphenyltrichloroethane (DDT) adsorption using soil–zeolite mixture. Nanotechnol Environ Eng 3:4. https://doi.org/10.1007/s41204-017-0033-8

141. Juhasz AL, Herde P, Smith E (2016) Oral relative bioavailability of dichlorodiphenyltrichloroethane (DDT) in contaminated soil and its prediction using in vitro strategies for exposure refinement. Environ Res 150:482–488. https://doi.org/10.1016/j.envres.2016.06.039

142. Alfonso LF, Germán GV, María del Carmen PC et al (2017) Adsorption of organophosphorus pesticides in tropical soils: the case of karst landscape of northwestern Yucatan. Chemosphere 166:292–299. https://doi.org/10.1016/j.chemosphere.2016.09.109

143. Cheng J, Lee X, Gao W et al (2017) Effect of biochar on the bioavailability of difenoconazole and microbial community composition in a pesticide-contaminated soil. Appl Soil Ecol 121:185–192. https://doi.org/10.1016/j.apsoil.2017.10.009

144. Svendsen SB, Carvalho PN, Bollmann UE et al (2020) A comparison of the fate of diflufenican in agricultural sandy soil and gravel used in urban areas. Sci Total Environ 715:136803. https://doi.org/10.1016/j.scitotenv.2020.136803

145. Kočárek M, Kodešová R, Sharipov U et al (2018) Effect of adjuvant on pendimethalin and dimethenamid-P behaviour in soil. J Hazard Mater 354:266–274. https://doi.org/10.1016/j.jhazmat.2018.04.073

146. Rodríguez-Liébana JA, Peña A (2018) Adsorption-desorption of dimethenamid and fenarimol onto three agricultural soils as affected by treated wastewater and fresh sewage sludge-derived dissolved organic carbon. J Environ Manag 217:592–599. https://doi.org/10.1016/j.jenvman.2018.03.119

147. Carneiro GDOP, Souza MDF, Lins HA et al (2020) Herbicide mixtures affect adsorption processes in soils under sugarcane cultivation. Geoderma 379:114626. https://doi.org/10.1016/j.geoderma.2020.114626

148. Petter FA, Ferreira TS, Sinhorin AP et al (2019) Biochar increases diuron sorption and reduces the potential contamination of subsurface water with diuron in a sandy soil. Pedosphere 29:801–809. https://doi.org/10.1016/S1002-0160(17)60434-X

149. Silva TS, Souza MF, Teófilo TMS et al (2019) Use of neural networks to estimate the sorption and desorption coefficients of herbicides: a case study of diuron, hexazinone, and sulfometuron-methyl in Brazil. Chemosphere 236:124333. https://doi.org/10.1016/j.chemosphere.2019.07.064

150. Spuler MJ, Briceño G, Duprat F et al (2019) Sorption kinetics of 2,4-D and diuron herbicides in a urea-fertilized Andisol. J Soil Sci Plant Nutr 19:313–320. https://doi.org/10.1007/s42729-019-00031-0

151. Takeshita V, Mendes KF, Christoffoleti PJ et al (2019) Sorption-desorption isotherms of diuron alone and in a mixture in soils with different physico-chemical properties. Afr J Agric Res 14:672–679. https://doi.org/10.5897/AJAR2019.13885

152. Dollinger J, Dagès C, Samouelian A et al (2018) Contrasting soil property patterns between ditch bed and neighbouring field profiles evidence the need of specific approaches when assessing water and pesticide fate in farmed landscapes. Geoderma 309:50–59. https://doi.org/10.1016/j.geoderma.2017.09.006

153. Sousa GV, Pereira GAM, Teixeira MFF et al (2018) Sorption and desorption of diuron, hexazinone and mix (diuron + hexazinone) in soils with different attributes. Planta Daninha 36:018176803. https://doi.org/10.1590/S0100-83582018360100097

154. Dollinger J, Dagès C, Voltz M (2017) Using fluorescent dyes as proxies to study herbicide removal by sorption in buffer zones. Environ Sci Pollut Res 24:11752–11763. https://doi.org/10.1007/s11356-017-8703-4

155. Keren Y, Borisover M, Schaumann GE et al (2017) Land disposal of olive mill wastewater enhances ability of soil to sorb diuron: temporal persistence, and the effects of soil depth and application season. Agric Ecosyst Environ 236:43–51. https://doi.org/10.1016/j.agee.2016.11.013

156. Borisover M, Keren Y, Usyskin A et al (2016) Effects of γ-irradiation of original and organic matter-amended soils on the sorption of triclosan and diuron from aqueous solutions. Chemosphere 152:62–70. https://doi.org/10.1016/j.chemosphere.2016.02.091

157. Dollinger J, Dagès C, Negro S et al (2016) Variability of glyphosate and diuron sorption capacities of ditch beds determined using new indicator-based methods. Sci Total Environ 573:716–726. https://doi.org/10.1016/j.scitotenv.2016.08.168

158. Regitano JB, Rocha WSD, Bonfleur EJ et al (2016) Effect of soil water content on the distribution of diuron into organomineral aggregates of highly weathered tropical soils. J Agric Food Chem 64:3935–3941. https://doi.org/10.1021/acs.jafc.5b04664

159. Rubio-Bellido M, Morillo E, Villaverde J (2016) Effect of addition of HPBCD on diuron adsorption–desorption, transport and mineralization in soils with different properties. Geoderma 265:196–203. https://doi.org/10.1016/j.geoderma.2015.11.022

160. Dos Reis FC, Tornisielo VL, Pimpinato RF et al (2017) Leaching of diuron, hexazinone, and sulfometuron-methyl applied alone and in mixture in soils with contrasting textures. J Agric Food Chem 65:2645–2650. https://doi.org/10.1021/acs.jafc.6b05127

161. Mendes KF, Inoue MH, Goulart MO et al (2016) Leaching of a mixture of hexazinone, sulfometuron-methyl, and diuron applied to soils of contrasting textures. Water Air Soil Pollut 227:1–9. https://doi.org/10.1007/s11270-016-2954-4

162. Buerge IJ, Pavlova P, Hanke I et al (2020) Degradation and sorption of the herbicides 2,4-D and quizalofop-P-ethyl and their metabolites in soils from railway tracks. Environ Sci Eur 32:150. https://doi.org/10.1186/s12302-020-00422-6

163. Spadotto CA, Locke MA, Bingner RL et al (2020) Estimating sorption of monovalent acidic herbicides at different pH levels using a single sorption coefficient. Pest Manag Sci 76:2693–2698. https://doi.org/10.1002/ps.5815

164. Babey T, Vieublé-Gonod L, Rapaport A et al (2017) Spatiotemporal simulations of 2,4-D pesticide degradation by microorganisms in 3D soil-core experiments. Ecol Model 344:48–61. https://doi.org/10.1016/j.ecolmodel.2016.11.006

165. Shoji R, Makino H (2017) Change in sorption of copper and 2,4-dichlorophenoxyacetic acid dimethlyamine in coexistence of calcium onto soil humic acid with different degrees of humus. Kagaku Kogaku Ronbunshu 43:358–366. https://doi.org/10.1252/kakoronbunshu.43.358

166. Prado B, Strozzi AG, Huerta E et al (2016) 2,4-D mobility in clay soils: impact of macrofauna abundance on soil porosity. Geoderma 279:87–96. https://doi.org/10.1016/j.geoderma.2016.06.007

167. Conkle JL, Cabrera JA, Thomas JE et al (2016) Effects of CO_2 dissolution on phase distribution and degradation of dimethyl disulfide in soils under grape production. Pest Manag Sci 72:349–353. https://doi.org/10.1002/ps.4004

168. Ahmad KS (2019) Adsorption removal of endosulfan through Saccharum officinarum derived activated carbon from selected soils. J Cent South Univ 26:146–157. https://doi.org/10.1007/s11771-019-3989-7

169. Bošković N, Brandstatter-Scherr K, Sedlacek P et al (2020) Adsorption of epoxiconazole and tebuconazole in twenty different agricultural soils in relation to their properties. Chemosphere 261:127637. https://doi.org/10.1016/j.chemosphere.2020.127637

170. Ahmad KS (2018) Exploring the potential of Juglans regia-derived activated carbon for the removal of adsorbed fungicide Ethaboxam from soils. Environ Monit Assess 190:737. https://doi.org/10.1007/s10661-018-7119-z

171. Cáceres T, Venkateswarlu K (2018) Sorption and mobility of 14C-fenamiphos in Brazilian soils. Environ Monit Assess 190:109. https://doi.org/10.1007/s10661-018-6493-x
172. Cryder Z, Greenberg L, Richards J et al (2019) Fiproles in urban surface runoff: understanding sources and causes of contamination. Environ Pollut 250:754–761. https://doi.org/10.1016/j.envpol.2019.04.060
173. Kchour H, Pinna MV, Nassif N et al (2020) Impact of biochar on herbicide pollution in the Litani river basin. Fresenius Environ Bull 29:11119–11128. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85099356138&partnerID=40&md5=05d88c5ff101e110c7a4556760cc5dfc
174. Kumari U, Singh SB, Singh N (2020) Sorption and leaching of flucetosulfuron in soil. J Environ Sci Health Part B Pest Food Contam Agric Wastes 55:550–557. https://doi.org/10.1080/03601234.2020.1733363
175. Aït Hammi K, Nieto-Latorre E, Ureña-Amate MD et al (2019) Effect of peat addition on sorption and leaching of triazole fungicides in Oran Soils. J Chem 2019:9019817. https://doi.org/10.1155/2019/9019817
176. Huang B, Yan D, Wang X et al (2019) Soil fumigation alters adsorption and degradation behavior of pesticides in soil. Environ Pollut 246:264–273. https://doi.org/10.1016/j.envpol.2018.12.003
177. Gulkowska A, Buerge IJ, Poiger T et al (2016) Time-dependent sorption of two novel fungicides in soils within a regulatory framework. Pest Manag Sci 72:2218–2230. https://doi.org/10.1002/ps.4256
178. Langaro AC, Souza MF, Pereira GAM et al (2020) Influence of glyphosate formulations on the behavior of sulfentrazone in soil in mixed applications. Toxics 8(123):1–15. https://doi.org/10.3390/toxics8040123
179. Albers CN, Ernstsen V, Johnsen AR (2019) Soil domain and liquid manure affect pesticide sorption in macroporous clay till. J Environ Qual 48:147–155. https://doi.org/10.2134/jeq2018.06.0222
180. Hall KE, Spokas KA, Gámiz B et al (2018) Glyphosate sorption/desorption on biochars – interactions of physical and chemical processes. Pest Manag Sci 74:1206–1212. https://doi.org/10.1002/ps.4530
181. Cassigneul A, Benoit P, Bergheaud V et al (2016) Fate of glyphosate and degradates in cover crop residues and underlying soil: a laboratory study. Sci Total Environ 545-546:582–590. https://doi.org/10.1016/j.scitotenv.2015.12.052
182. Kumari KGID, Moldrup P, Paradelo M et al (2016) Soil properties control glyphosate sorption in soils amended with birch wood biochar. Water Air Soil Pollut 227:174. https://doi.org/10.1007/s11270-016-2867-2
183. Mendes KF, Wei MCF, Furtado IF et al (2021) Spatial distribution of sorption and desorption process of 14C-radiolabelled hexazinone and tebuthiuron in tropical soil. Chemosphere 264:128494. https://doi.org/10.1016/j.chemosphere.2020.128494
184. Chitolina GM, Mendes KF, Almeida CS et al (2020) Influence of soil depth on sorption and desorption processes of hexazinone. Planta Daninha 38:020217734. https://doi.org/10.1590/S0100-83582020380100016
185. Mendes KF, Sousa RN, Takeshita V et al (2019) Cow bone char as a sorbent to increase sorption and decrease mobility of hexazinone, metribuzin, and quinclorac in soil. Geoderma 343:40–49. https://doi.org/10.1016/j.geoderma.2019.02.009
186. Toniêto TAP, Pierri L, Tornisielo VL et al (2016) Fate of tebuthiuron and hexazinone in green-cane harvesting system. J Agric Food Chem 64:3960–3966. https://doi.org/10.1021/acs.jafc.5b04665
187. Maznah Z, Halimah M, Bin Sahid I et al (2016) Adsorption-desorption of hexaconazole in soils with respect to soil properties, temperature, and pH. Turkish J Agric Food Sci Technol 4:493–497. https://doi.org/10.24925/turjaf.v4i6.493-497.669

188. Alonso DG, de Oliveira Jr RS, Koskinen WC et al (2016) Sorption and desorption of indaziflam degradates in several agricultural soils. Sci Agric 73:169–176. https://doi.org/10.1590/0103-9016-2015-0106

189. Gámiz B, Velarde P, Spokas KA et al (2019) Changes in sorption and bioavailability of herbicides in soil amended with fresh and aged biochar. Geoderma 337:341–349. https://doi.org/10.1016/j.geoderma.2018.09.033

190. Yavari S, Malakahmad A, Sapari NB et al (2016) Sorption-desorption mechanisms of imazapic and imazapyr herbicides on biochars produced from agricultural wastes. J Environ Chem Eng 4:3981–3989. https://doi.org/10.1016/j.jece.2016.09.003

191. López-Cabeza R, Gámiz B, Cornejo J et al (2017) Behavior of the enantiomers of the herbicide imazaquin in agricultural soils under different application regimes. Geoderma 293:64–72. https://doi.org/10.1016/j.geoderma.2017.01.024

192. Castanho GM, de Toledo RA, Shim H et al (2016) Electroanalytical procedure and sorption studies for imazaquin in different soils. Int J Environ Anal Chem 96:530–541. https://doi.org/10.1080/03067319.2016.1172217

193. Satkowski LE, Goyne KW, Anderson SH et al (2018) Imidacloprid sorption and transport in cropland, grass buffer, and riparian buffer soils. Vadose Zone J 17:170139. https://doi.org/10.2136/vzj2017.07.0139

194. Castillo Diaz JM, Martin-Laurent F, Beguet J et al (2017) Fate and effect of imidacloprid on vermicompost-amended soils under dissimilar conditions: risk for soil functions, structure, and bacterial abundance. Sci Total Environ 579:1111–1119. https://doi.org/10.1016/j.scitotenv.2016.11.082

195. Leiva JA, Nkedi-Kizza P, Morgan KT et al (2017) Imidacloprid transport and sorption nonequilibrium in single and multilayered columns of Immokalee fine sand. PLoS One 12:0183767. https://doi.org/10.1371/journal.pone.0183767

196. Wettstein FE, Kasteel R, Garcia Delgado MF et al (2016) Leaching of the neonicotinoids thiamethoxam and imidacloprid from sugar beet seed dressings to subsurface tile drains. J Agric Food Chem 64:6407–6415. https://doi.org/10.1021/acs.jafc.6b02619

197. Ahmad KS (2019) Adsorption evaluation of herbicide iodosulfuron followed by cedrus deodora sawdust-derived activated carbon removal. Soil Sed Contam 28:65–80. https://doi.org/10.1080/15320383.2018.1536692

198. Li R, Dörfler U, Munch JC, Schroll R (2017) Enhanced degradation of isoproturon in an agricultural soil by a Sphingomonas sp. strain and a microbial consortium. Chemosphere 168:1169–1176. https://doi.org/10.1016/j.chemosphere.2016.10.084

199. Shou J, Dong H, Li J et al (2016) Influence of Al-oxide on pesticide sorption to woody biochars with different surface areas. Environ Sci Pollut Res 23:19156–19163. https://doi.org/10.1007/s11356-016-6932-6

200. Peng Y, Xiao D, Yu G et al (2019) Effect of an eco-friendly o/w emulsion stabilized with amphiphilic sodium alginate derivatives on lambda-cyhalothrin adsorption–desorption on natural soil minerals. J Environ Sci (China) 78:230–238. https://doi.org/10.1016/j.jes.2018.09.025

201. Hiller E, Jurkovič L (2020) Soil sorption and degradation of Agritox herbicide formulation containing Na-K-DMA MCPA salt as an active ingredient. Acta Geologica Slovaca 12:35–42. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85097232098&partnerID=40&md5=7e9a1f63425c9ce777b6beb4f92bcbba

202. Cueff S, Alletto L, Bourdat-Deschamps M et al (2020) Water and pesticide transfers in undisturbed soil columns sampled from a Stagnic Luvisol and a Vermic Umbrisol both cultivated under conventional and conservation agriculture. Geoderma 377:114590. https://doi.org/10.1016/j.geoderma.2020.114590

203. Mendes KF, dos Reis MR, Inoue MH et al (2016) Sorption and desorption of mesotrione alone and mixed with S-metolachlor+ terbuthylazine in Brazilian soils. Geoderma 280:22–28. https://doi.org/10.1016/j.geoderma.2016.06.014

204. Pose-Juan E, Marín-Benito JM, Sánchez-Martín MJ et al (2018) Dissipation of herbicides after repeated application in soils amended with green compost and sewage sludge. J Environ Manag 223:1068–1077. https://doi.org/10.1016/j.jenvman.2018.07.026

205. Bassil J, Azzi V, Naveau A et al (2021) Influence of metalaxyl and CGA 62828 adsorption on the leaching behavior of metal-contaminated soils. Clean Soil Air Water 49:2000277. https://doi.org/10.1002/clen.202000277

206. Parlavecchia M, D'Orazio V, Loffredo E (2019) Wood biochars and vermicomposts from digestate modulate the extent of adsorption-desorption of the fungicide metalaxyl-m in a silty soil. Environ Sci Pollut Res 26:35924–35934. https://doi.org/10.1007/s11356-019-06729-z

207. Gámiz B, López-Cabeza R, Facenda G et al (2016) Effect of synthetic clay and biochar addition on dissipation and enantioselectivity of tebuconazole and metalaxyl in an agricultural soil: laboratory and field experiments. Agric Ecosyst Environ 230:32–41. https://doi.org/10.1016/j.agee.2016.05.017

208. Gámiz B, Facenda G, Celis R (2016) Evidence for the effect of sorption enantioselectivity on the availability of chiral pesticide enantiomers in soil. Environ Pollut 213:966–973. https://doi.org/10.1016/j.envpol.2016.03.052

209. Gámiz B, Pignatello JJ, Cox L et al (2016) Environmental fate of the fungicide metalaxyl in soil amended with composted olive-mill waste and its biochar: an enantioselective study. Sci Total Environ 541:776–783. https://doi.org/10.1016/j.scitotenv.2015.09.097

210. López-Cabeza R, Cornejo J, Celis R (2016) Evaluation of an organo-layered double hydroxide and two organic residues as amendments to immobilize metalaxyl enantiomers in soils: a comparative study. J Environ Manag 181:135–145. https://doi.org/10.1016/j.jenvman.2016.06.019

211. Sidoli P, Devau N, Jaramillo RA et al (2020) Reactivity of vadose-zone solids to S-metolachlor and its two main metabolites: case of a glaciofluvial aquifer. Environ Sci Pollut Res 27:22865–22877. https://doi.org/10.1007/s11356-020-08579-6

212. Dollinger J, Lin CH, Udawatta RP et al (2019) Influence of agroforestry plant species on the infiltration of S-Metolachlor in buffer soils. J Contam Hydrol 225:103498. https://doi.org/10.1016/j.jconhyd.2019.103498

213. Cassigneul A, Benoit P, Nobile C et al (2018) Behaviour of S-metolachlor and its oxanilic and ethanesulfonic acids metabolites under fresh vs. partially decomposed cover crop mulches: a laboratory study. Sci Total Environ 631–632:1515–1524. https://doi.org/10.1016/j.scitotenv.2018.03.143

214. Trigo C, Spokas KA, Hall KE et al (2016) Metolachlor sorption and degradation in soil amended with fresh and aged biochars. J Agric Food Chem 64:3141–3149. https://doi.org/10.1021/acs.jafc.6b00246

215. Marín-Benito JM, Herrero-Hernández E, Ordax JM et al (2021) The role of two organic amendments to modify the environmental fate of S-metolachlor in agricultural soils. Environ Res 195:110871. https://doi.org/10.1016/j.envres.2021.110871

216. Cueff S, Alletto L, Dumény V et al (2021) Adsorption and degradation of the herbicide nicosulfuron in a stagnic Luvisol and Vermic Umbrisol cultivated under conventional or conservation agriculture. Environ Sci Pollut Res 28:15934–15946. https://doi.org/10.1007/s11356-020-11772-2

217. Cara IG, Topa D, Calistru AE et al (2020) Agri-wastes as a low-cost adsorbent for nicosulfuron herbicide. Environ Eng Manag J 19:335–343. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85090960342&partnerID=40&md5=8ffe7745e9a00c23c883b6453918dba8

218. Caceres-Jensen L, Rodríguez-Becerra J, Escudey M et al (2019) Nicosulfuron sorption kinetics and sorption/desorption on volcanic ash-derived soils: proposal of sorption and transport mechanisms. J Hazard Mater 385:121576. https://doi.org/10.1016/j.jhazmat.2019.121576

219. Jiang L, Yang Y, Jia LX et al (2018) Effects of earthworm casts on sorption-desorption, degradation, and bioavailability of nonylphenol in soil. Environ Sci Pollut Res 25:7968–7977. https://doi.org/10.1007/s11356-017-1130-8

220. Xie H, Wang J, Du X et al (2017) Adsorption and leaching of paichongding a new pesticide in three typical soils. Acta Pedol Sin 54:118–127. https://doi.org/10.11766/trxb201604200104
221. Jiang L, Lin JL, Jia LX et al (2016) Effects of two different organic amendments addition to soil on sorption-desorption, leaching, bioavailability of penconazole and the growth of wheat (*Triticum aestivum* L.). J Environ Manag 167:130–138. https://doi.org/10.1016/j.jenvman.2015.10.013
222. Luks AK, Zegarski T, Nowak KM et al (2021) Fate of pendimethalin in soil and characterization of non-extractable residues (NER). Sci Total Environ 753:141870. https://doi.org/10.1016/j.scitotenv.2020.141870
223. Kaur P, Makkar A, Kaur P et al (2018) Temperature dependent adsorption-desorption behaviour of pendimethalin in Punjab soils. Bull Environ Contam Toxicol 100:167–175. https://doi.org/10.1007/s00128-017-2235-y
224. Smaranda C, Rosca M, Vasilachi IC et al (2020) Equilibrium studies on the sorption of organochlorine pesticide in agricultural soil. In: 8th E-health and bioengineering conference, Romania. IEEE. https://doi.org/10.1109/EHB50910.2020.9280210
225. Diagboya PN, Olu-Owolabi BI, Adebowale KO (2016) Distribution and interactions of pentachlorophenol in soils: the roles of soil iron oxides and organic matter. J Contam Hydrol 191:99–106. https://doi.org/10.1016/j.jconhyd.2016.04.005
226. Olu-Owolabi BI, Diagboya PN, Okoli CP et al (2016) Sorption behaviour of pentachlorophenol in sub-Saharan tropical soils: soil types sorption dynamics. Environ Earth Sci 75:1494. https://doi.org/10.1007/s12665-016-6307-9
227. Smaranda C, Bulgariu L, Rosca M et al (2016) Evaluation of pentachlorophenol leaching potential in natural soils. In: 2015 E-health bioeng conf EHB 2015. IEEE, p 7391488. https://doi.org/10.1109/EHB.2015.7391488
228. Khan MA, Brown CD (2017) Influence of commercial formulation on the sorption and leaching behaviour of propyzamide in soil. Sci Total Environ 578:158–166. https://doi.org/10.1016/j.scitotenv.2016.11.011
229. Barba V, Marín-Benito JM, García-Delgado C et al (2019) Assessment of ^{14}C-prosulfocarb dissipation mechanism in soil after amendment and its impact on the microbial community. Ecotox Environ Saf 182:109395. https://doi.org/10.1016/j.ecoenv.2019.109395
230. Barba V, Marín-Benito JM, Sánchez-Martín MJ et al (2020) Transport of 14C-prosulfocarb through soil columns under different amendment, herbicide incubation and irrigation regimes. Sci Total Environ 701:134542. https://doi.org/10.1016/j.scitotenv.2019.134542
231. Gao M, Li Y, Yang H et al (2016) Sorption and desorption of pymetrozine on six Chinese soils. Front Environ Sci Eng 10:1–10. https://doi.org/10.1007/s11783-014-0715-4
232. Jiang R, Wang M, Chen W (2018) Characterization of adsorption and desorption of lawn herbicide siduron in heavy metal contaminated soils. Chemosphere 204:483–491. https://doi.org/10.1016/j.chemosphere.2018.04.045
233. Cheng H, Wang J, Tu C et al (2021) Arbuscular mycorrhizal fungi and biochar influence simazine decomposition and leaching. GCB Bioenergy 13:708–718. https://doi.org/10.1111/gcbb.12802
234. de Sosa LL, Glanville HC, Marshall MR et al (2018) Quantifying the contribution of riparian soils to the provision of ecosystem services. Sci Total Environ 624:807–819. https://doi.org/10.1016/j.scitotenv.2017.12.179
235. Lee S, Han J, Ro HM (2018) Interpreting the pH-dependent mechanism of simazine sorption to Miscanthus biochar produced at different pyrolysis temperatures for its application to soil. Korean J Chem Eng 35:1468–1476. https://doi.org/10.1007/s11814-018-0054-4
236. Obregón Alvarez D, Mendes KF, Tosi M et al (2021) Sorption-desorption and biodegradation of sulfometuron-methyl and its effects on the bacterial communities in Amazonian soils amended with aged biochar. Ecotox Environ Saf 207:111222. https://doi.org/10.1016/j.ecoenv.2020.111222

237. Siek M, Paszko T (2019) Factors affecting coupled degradation and time-dependent sorption processes of tebuconazole in mineral soil profiles. Sci Total Environ 690:1035–1047. https://doi.org/10.1016/j.scitotenv.2019.06.409

238. Raunaq A, Kumar LS, Arya S et al (2017) Adsorption-desorption of tebuconazole in three soils. Pest Res J 29:82–87

239. Rodríguez-Liébana JA, Mingorance MD, Peña A (2018) Thiacloprid adsorption and leaching in soil: effect of the composition of irrigation solutions. Sci Total Environ 610–611:367–376. https://doi.org/10.1016/j.scitotenv.2017.08.028

240. Zhang P, Sun H, Min L et al (2018) Biochars change the sorption and degradation of thiacloprid in soil: insights into chemical and biological mechanisms. Environ Pollut 236:158–167. https://doi.org/10.1016/j.envpol.2018.01.030

241. Li Y, Zhu Y, Liu X et al (2017) Bioavailability assessment of thiacloprid in soil as affected by biochar. Chemosphere 171:185–191. https://doi.org/10.1016/j.chemosphere.2016.12.071

242. You X, Jiang H, Zhao M et al (2020) Biochar reduced Chinese chive (*Allium tuberosum*) uptake and dissipation of thiamethoxam in an agricultural soil. J Hazard Mater 390:121749. https://doi.org/10.1016/j.jhazmat.2019.121749

243. Maznah Z, Halimah M, Ismail S (2016) Adsorption-desorption behavior of thiram: effect of soil type, temperature and pH. Chil J Agric Res 76:371–377. https://doi.org/10.4067/s0718-58392016000300016

244. Liu B, Chen B, Zhang J et al (2017) The environmental fate of thymol, a novel botanical pesticide, in tropical agricultural soil and water. Toxicol Environ Chem 99:223–232. https://doi.org/10.1080/02772248.2016.1198907

245. Ahmad KS, Amjad I, Ali D (2020) Adsorption and sugarcane-bagasse-derived activated carbon-based mitigation of 1-[2-(2-chloroethoxy)phenyl]sulfonyl-3-(4-methoxy-6-methyl-1,3,5-triazin-2-yl) urea-contaminated soils. Open Chem 18:1433–1443. https://doi.org/10.1515/chem-2020-0185

246. Ahmad KS (2017) Pedospheric sorption investigation of sulfonyl urea herbicide triasulfuron via regression correlation analysis in selected soils. S Afr J Chem 70:163–170. https://doi.org/10.17159/0379-4350/2017/v70a23

247. Peng JH, Ou XM, Ou J et al (2019) Adsorption of a new insecticide triflumezopyrim on soils. J Agro-Environ Sci 38:2371–2376. https://doi.org/10.11654/jaes.2019-0291

248. OECD – Organization for Economic Co-operation and Development (2000) OECD guidelines for the testing of chemicals. Paris: test number 106, adsorption – desorption using a batch equilibrium method. OECD, Paris, p 44

249. Siedt M, Schäffer A, Smith KEC et al (2021) Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. Sci Total Environ 751:141607. https://doi.org/10.1016/j.scitotenv.2020.141607

250. Xu X, Schaeffer S, Sun Z et al (2020) Carbon stabilization in aggregate fractions responds to straw input levels under varied soil fertility levels. Soil Till Res 199:104593. https://doi.org/10.1016/j.still.2020.104593

251. Blume HP, Brümmer GW, Fleige H et al (2016) Inorganic soil components—minerals and rocks. In: Blume HP, Brümmer GW, Fleige H et al (eds) Scheffer/schachtschabe, soil science. Springer, Berlin, pp 7–53. https://doi.org/10.1007/978-3-642-30942-7_2

252. Laird DA (2002) Reactions of pesticides with soil minerals. In: Dixon JB, Schulze DG (eds) Soil mineralogy with environmental applications, vol 7. Soil Science Society of America, pp 765–793. https://doi.org/10.2136/sssabookser7.c26

253. Cheng H, Jones DL, Hill P et al (2017) Biochar concomitantly increases simazine sorption in sandy loam soil and lowers its dissipation. Arch Agron Soil Sci 63:1082–1092. https://doi.org/10.1080/03650340.2016.1261117