Abstract

Background: The need for environmental protection and remediation processes has been an increasing global concern. Pesticides are used as biological agents, disinfectants, antimicrobials, and also in a mixture of some chemical substances. Their modes of application are through selective dispensing and attenuation processes which act upon any pest that compete with the production, processing, and storage of foods and also in agricultural commodities. The pests might comprise weeds, insects, birds, fish, and microbes.

Main body: Pesticides are commonly found in water surface, landfill leachate, ground water, and wastewater as pollutants. An overview of recently studied adsorption processes for the pesticide elimination from polluted water has been reported in this study utilizing activated carbon, clay materials, biomass materials, metal organic framework, graphene, and carbon-based materials as well as agricultural wastes as adsorbents. The risk assessment and cost analysis of adsorbents were also provided.

Conclusion: Evidences from literature recommend modified adsorbent and composite materials to have a prospective use in pesticide removal from wastewater. The adsorption data obtained fitted into different isotherm and kinetic models and also the thermodynamic aspect have been discussed.

Keywords: Pesticides, Adsorptive removal, Synthetic wastewater, Adsorbents, Wastewater treatment, Risk assessment

1 Background

Water is very crucial to life and the survival of living organisms in the environment, playing a vital role as well in agricultural productivity [1]. In a quest to overcoming the increasing global water demand, reuse and recycling of wastewater were given a considerable attention. Varieties of pollutants from organic and inorganic substances contaminate the wastewater. Inadequate supply of contaminant-free water continues to be an environmental challenge bedeviling several countries [2–9].

Modern farming is almost impossible without the application of pesticides. Organochlorine pesticides (OCPs) were revealed among the most tenacious class of organic pollutants which were initially limited or freeze out worldwide in the 1980s [10, 11]. Contrary to the OCPs, there are some pesticides (synthetic pyrethroids and organophosphates) that are usually categorized as being relatively less persistent and hence widely employed in pest control [12, 13]. However, to some aquatic organisms such as fish, invertebrates, and mollusks, the increased application of synthetic pyrethroids (SPs) and organophosphorus pesticides (OPPs) presents very high chronic and acute toxicity to them [14–16]. Putting all these factors into consideration, water safety cannot be guaranteed with the presence of pesticides [13, 17]. Literature reports also suggested rivers neighboring agricultural catchments to be bedeviled with serious challenges due to the rapid growing applications of pesticides [18, 19].
The crucial question now is why pesticides? Our simple response is pesticides are very popular compounds; their residues may exist in water, soil, and sediments. Their toxicity and persistence make their elimination from wastewater crucial. The next question is, why adsorption process could be an effective method for removing them? We hope to answer the question considering that adsorption phenomenon as is one of the fastest and simplest applications used in separation. It has merit in wastewater treatment based on fast kinetics, simplicity in design, and high removal capacity when compared with other methods.

The thought of this review was considered after a thorough literature search on how adsorption process was utilized the pesticides removal from wastewater for over 25 years. During our survey, we came across some well-written review articles by other researchers on pesticides [20–29] but emphasis on adsorption as the most suitable process for decontaminating wastewater polluted by pesticides were not made. The literature information consulted for this review were mostly derived from science direct database. The words "pesticide adsorption" were used for the search. An observation was made on the increasing numerical pattern of the published articles on pesticide adsorption (Fig. 1) having the lowest number (524) in 1997. In 2019, 3478 were published while additional 2194 were published from January to April 2020. Review that covers recent research information on using different adsorptive techniques for pesticide adsorption was not comprehensively reported despite the high quantity of published articles. With that into consideration, we provided the most recent information on the progress made for using activated carbon and as well as other alternative adsorbents such as clay materials, biomass materials, agricultural wastes, carbon and graphene-based adsorbents, metal organic frameworks, zeolites, nano composites, and polymeric materials that were applied in pesticide adsorption, forming the primary objective of this review article.

1.1 Pesticides and their risk assessment
Crop protection is the most popular way where pesticides are utilized in agriculture with reported global increase in their production and usage [30, 31]. Various researchers reported regular monitoring and effects of pesticides in the European waters with agricultural runoff and/or leaching as the simplest way pesticides could enter into surface waters [32–34], thereby making the ecosystem and/or living organisms vulnerable to various health hazards. Several factors were revealed to play a key role in making these pesticides dangerous for drinking water. One of the factors reported was applying the pesticides in a large scale and/or used for contrasting purposes. The soil being vulnerable to the pesticides leaching in to groundwater was another reported factor. Other relevant risk drivers include specific properties such as the toxicity, mobility, and persistence [35]. Some pesticides were classified as persistent and mobile organic compounds (PMOCs) well known for the easy bypassing of wastewater treatment processes, and thus threatening the drinking water quality [36, 37]. How pesticides occur and their concentrations in drinking water were the basis used in prioritizing them as shown in Table 1.

Pesticides were classified as high priority ones when detected in water for drinking purpose, especially when their concentration in the water source exceed 0.1 μg/L standard. This standard is based on a decree from EU Water Framework (Table 1). Meanwhile, if the concentration of pesticides and their metabolites are greater than 10% limits of water quality standard from drinking
The waste fiber of hemp (*Cannabis sativa*) was also utilized by Vukcevic et al. [49] for the activated carbon preparation that show large specific surface area of 2192 m²/g. KOH was the chemical activating agent employed in the process which gradually took place through the three apparent phases of hydrogen evolution. During the activation process, a major CO and H₂ evolution occurred as the KOH/carbonized material ratio increased and a shift in temperature was observed. Based on good correlation between porosity development as well as the CO and H₂ evolution, the process of activation took place at high temperature thereby producing a well-developed high surfaced area activated carbon. They reported the adsorbent produced by carbonization and subsequent activation of the waste hemp fibers with the ratio of 2:1 for KOH/carbonized material at 900 °C is to have the highest pesticide removal efficiency.

In a recent development, the successful preparation of mesoporous activated carbon from starch (ACS), capable of removing more than 10 pesticides from contaminated water was reported [42]. Upon comparison with other adsorbents, the ACS produced by Suo and co-workers [42] show that all the pesticide adsorption rates were greater than those obtained using graphitized carbon black (GCB) and commercial activated carbon.

### 2.3 Agricultural wastes

Agricultural wastes that contain lignin, cellulose, and hemicelluloses are generally termed as lignocellulosic materials, mainly characterized by a large number of active groups (hydroxyl, amino, methyl, carbonyl and carboxyl). The utilization of these waste materials remained a global problem, which prompted many researchers to

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**Table 1** Risk classification of pesticides [30]

| Priority class | Criteria |
|---------------|----------|
| High priority | Pesticides or relevant metabolites present in produced drinking water |
| Priority      | Pesticides or relevant metabolites present in drinking water sources > 0.1 mg/L (for 90th % of all data > LOQ) |
|               | Non-relevant metabolites present in drinking water sources > 1 mg/L (for 90th % of all data > LOQ) |
| Potential     | Pesticides or relevant metabolites present drinking water sources > 0.1 < 0.1 mg/L (for 90th % of all data > LOQ) |
| Priority      | Non-relevant metabolites present in drinking water sources > 0.1 < 1 mg/L (for 90th % of all data > LOQ) |
| Low priority  | Not detected pesticides and or relevant metabolites present drinking water sources do not exceed 0.01 mg/L |

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water sources, then they are considered as a potential priority.

### 2 Main text

#### 2.1 Pesticide removal by adsorption

There is no dearth of reports on adsorption as the best method in getting rid of pesticides from synthetic wastewater, with Table 2 summarizing how various adsorbents were applied for the removal of these pesticide contaminants.

#### 2.2 Activated carbon

The popularity of activated carbon as a very useful material in catalytic and adsorption applications is well known due to being highly porous with large surface area [69–72]. To date, there is no adsorbent material that surpass activated carbon [73–76] popularly employed in treating wastewater [68, 77–83], oil and gas industry [84], in food processing [85], remediation of air pollution [86], and pharmaceuticals [87, 88]. Activated carbon usually appears either in granular or powdered form.

Coconut shell activated carbon was employed by Ignatowicz [39] in studying the adsorption isotherms of hexachlorocyclohexane (HCH) at constant temperature, thereby revealing Langmuir, Freundlich, and Jovanovic to best describe the equilibrium generated data. The nature of isotherm shape hinted at monolayer adsorption of HCH, signaling a negligible competition between water and the HCH pesticide molecules in occupying the adsorption surface sites. In another development, Ayranci and Hoda [89] revealed how they succeeded in removing four pesticides such as diuron, ametryn, dinoseb, and aldicarb, by adsorption using high surface area carbon-cloth.

The whole process was completed in 125 min with the adsorption rate constants for the two models in an increasing order of aldicarb > diuron > ametryn > dinoseb.

Date seed activated carbon (DSAC) was reported as an efficacious adsorbent by Salman and co-workers [40] for the elimination of two pesticides (carbofuran and bentazon). Pseudo-second-order model explained the kinetic of the adsorption processes for both adsorbates which also suggested that the adsorption rate to be less reliable on the solution concentration but more dependent on the adsorption sites availability. Higher adsorption capacity was revealed in favor of carbofuran than bentazon with ethanol used as solvent in order to desorb the spent DSAC for 3 cycles, giving rise to percentage desorption 82.2 and 84.1 % for carbofuran and bentazon respectively [40]. The obtained values for DSAC adsorption capacity for removing the two pesticides affirmed the efficiency of date seed as a potent precursor in the activated carbon production on for the treatment of wastewater contaminated with bentazon and carbofuran.

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| Adsorbents                          | Pesticides                                                                 | Surface morphology                                           | Surface area (m²/g) | Total pore volume (cm³/g) | Pore size diameter (nm) | pHₚₑₙₑ | References |
|------------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------------|---------------------|---------------------------|-------------------------|---------|------------|
| Granular activated carbon (GAC F300) | Carbofuran and 2,4-dichlorophenoxyacetic acid                           | Coarse rough and porous surface                             | 731.48              | 0.45                      | –                       | –       | [38]       |
| Coconut shell based Activated carbon np-5 | Hexachlorocyclohexane                                                         | Well-developed pores on the surface                        | 1840                | 0.90                      | –                       | –       | [39]       |
| Date seed activated carbon          | Bentazon and carbofuran                                                   | –                                                            | 880.18              | 0.46                      | 2.16                    | –       | [40]       |
| Activated carbon from palm oil fronds | Bentazon, carbofuran and 2,4-dichlorophenoxyacetic acid               | Well-developed porous surface                               | 1237.13             | 0.67                      | 2.16                    | –       | [41]       |
| Mesoporous activated carbon from starch (ACS) | Atrazine, pymetrozine, acetamiprid, diuron, thiacloprid, imazalil, difenoconazole, azoxystrobin, pyraclostrobin, trifloxystrobin, and chlorantraniliprole | The ACS surface was full of micropores and mesoporous      | –                   | –                         | –                       | –       | [42]       |
| Waste rubber tire activated carbon  | Methoxychlor, methyl parathion and atrazine                             | Chemically treated sorbent is highly porous as compared to the untreated adsorbent | 981                 | 1.51                      | 3.12                    | –       | [43]       |
| Activated carbon F300              | Phenoxyacid pesticide                                                      | –                                                            | 762                 | 0.46                      | ~0.52                   | ~9.80   | [44]       |
| Olive kernels activated carbon     | Bromopropylate (BP)                                                       | Cross-interconnected pores spongy-like, surface             | 600                 | 0.30                      | –                       | –       | [45]       |
| Corn cobs activated carbon         | Bromopropylate (BP)                                                       | Cross-interconnected pores spongy-like, surface             | 630                 | 0.34                      | –                       | –       | [45]       |
| Soya stalks activated carbon       | Bromopropylate (BP)                                                       | Fibrous-like structure in nature with long ridges, resembling a series of parallel lines | 570                 | 0.31                      | –                       | –       | [45]       |
| Rapeseed stalks activated carbon   | Bromopropylate (BP)                                                       | Fibrous-like structure in nature with long ridges, resembling a series of parallel lines | 490                 | 0.28                      | –                       | –       | [45]       |
| Activated carbon NORIT_ GL 50      | Bromopropylate (BP)                                                       | Rough and porous surface                                    | 650                 | –                        | –                       | –       | [46]       |
| Activated carbon F400              | Bromopropylate (BP)                                                       | Coarse and porous surface                                   | 827                 | 0.52                      | –                       | –       | [47]       |
| Mesoporous activated carbon from coconut frond | Carbofuran | Considerable number of pores with homogeneous circle shapes with different sizes of apertures distributed on the surface | 483.64              | 0.21                      | 2.97                    | 5.80   | [48]       |
| Activated carbon from waste hemp   | Acetamiprid, dimethoate, nicosulfuron, carbofuran and atrazine             | Fibrous structure with uniform nanostructured network        | 2192                | 1.06                      | 1.79                    | –       | [49]       |
| Coconut shell activated carbon     | Malathion                                                                 | Irregular structure and porous surface with the external pore size varies from 1.14 to 2.35 μm | 850                 | 281                       | 2.18                    | –       | [50]       |
| Palm shell activated carbon        | Malathion                                                                 | Irregular structure and porous surface with the external pore size varies from 0.15 to 1.09 μm | 788                 | 261                       | 1.73                    | –       | [50]       |
| NH₄Cl-induced activated carbon     | Dazinon                                                                   | –                                                            | 1029                | 236.40                    | 2.46                    | 6.6     | [51]       |
| Graphitic carbon nanostructures from filter paper | 2,4-dichlorophenoxyacetic acid | Thin foam-like porous structure                             | 182.40              | 0.31                      | 6.88                    | –       | [52]       |
| Graphitic carbon nanostructures from cotton | 2,4-dichlorophenoxyacetic acid | Flat carbon sheets with very thin thickness.               | 27.40               | 0.03                      | 4.99                    | –       | [52]       |
| Phenyl-modified                    | Avermectin, imidacloprid,                                                 | Some ordered mesoporous                                     | 446.50              | 0.32                      | 2.80                    | –       | [53]       |
| Adsorbents                                   | Pesticides                                                                 | Surface morphology                                                                 | Surface area (m²/g) | Total pore volume (cm³/g) | Pore size diameter (nm) | pH_{pzc} | References |
|---------------------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------------|---------------------|---------------------------|-------------------------|----------|------------|
| magnetic graphene/mesoporous silica         | pyridaben, dichlorvos, acetamiprid, dursban, isocarbophos, and phoxim       | structure were overlaid with little aggregation or multilayer accumulation of the magnetic graphene sheets |                     |                           |                         |          |            |
| Mesoporous carbon from a biopolymer and clay | Dicamba Pestanal                                                            | Oriented cleavage planes on the surface                                            | 876                 | 0.04                      | 3.40                    | 4.10     | [54]       |
| Graphene oxide-based silica-coated magnetic nanoparticles functionalized with 2-phenylethylamine | Chlorpyrifos, parathion, and malathion                                       | Spherical in shape and agglomerated                                               | 133                 | 0.48                      | 17.50                   | –        | [55]       |
| SAz-1 montmorillonite with the cationic polymer hexadimethrine | Fluome-turon, diuron, terbuthylazine, simazine, mecoprop, MCPA, and clypyralid | Less aggregated morphology and flat plates                                         | 51                  | –                         | –                       | –        | [56]       |
| Alkaline modified commercial kaolin          | Methomyl                                                                    | Aggregated particles with an average diameter of 400 nm                           | 8.51                | 0.0005                    | 18.39                   |          | [57]       |
| Phosphate-modified kaolin                   | Methomyl                                                                    | Irregular curved flakes                                                           | 18.79               | 0.002                     | 12.26                   |          | [57]       |
| Layered double hydroxides                   | Alachlor and metolachlor                                                    | Thin plate-like crystal with an irregular shape and size < 10 μm                  | –                   | –                         | –                       | –        | [58]       |
|                                             |                                                                             | Presence of lamellar and layered particles distributed around the surface, dominated by the flaked aggregates and curling edges with fluffy appearance | 164.79              | 0.27                      | 6.57                    | 6.75     | [59]       |
| Magnetic copper-based metal organic framework | Thiamethoxam, imidacloprid, acetamiprid, nitenpyram, dinofuran, clothianidin, and thiacobiprid | Highly porous block-shaped structure.                                              | 250.33              | 0.83                      | –                       | –        | [60]       |
| Zr-metal organic framework functionalized magnetic graphene nanocomposites | Triflurain, atrazine, methylparathion, primophos methyl, parathion, penconazole, procyumidone, bifenthrin, and cyhalothrin | Even distribution of magnetic particles on the surface of graphene, some of them are wrapped in MOF with both of them having good core-shell structure, the thickness of materials was increased significantly after being modified with Zr-MOF | 178.1               | –                         | –                       | –        | [61]       |
| Multi-walled carbon nanotubes               | Diazinon                                                                    | Porous tubular structures of multi-walled carbon nanotubes                        | 370                 | –                         | –                       | 3–5      | [62]       |
| modified chitosan materials                 | Pentachlorophenol                                                           | Non homogeneous and quite rough surface                                           | 2.43–0.37           | 0.17–1.7 × 10^{-3}        | 4–7.7                   |          | [63]       |
| LaFe_{0.9}Co_{0.1}O_{3}                     | Vitavax                                                                     | Rough and nearly fully covered with the particles grown on it and the particle size distribution seems to be in the range 50–400 nm | 51.2                | –                         | –                       | –        | [64]       |
| LaFe_{0.1}Co_{0.9}O_{3}                     | Vitavax                                                                     | Nearly spherical with approximately uniform particle size and their distribution is ranging between 30 and 60 nm with the average diameter of about 40 nm | 42.8                | –                         | –                       | –        | [64]       |
| Pig manure-derived biochars                 | Carbaryl and atrazine                                                       | Bulk aromaticity of the biochar increased and polarity decreased with charring temperature | 218.10              | 0.32                      | 57.80                   | 6.40     | [65]       |
| Nanocrystalline                             | Diazinon and fenithrothion                                                  | Rough and scratchy surface with                                                 | 250                 | –                         | 7                       | –        | [66]       |
come up with various ways of harnessing these agricul-
tural byproducts including their utilization as adsorbents
for wastewater treatment. Complexation, hydrogen
bonding, and ion exchange were the major adsorption
mechanisms associated with agricultural solid waste
and their composites in the process of adsorbing organic
compounds. Watermelon peels were treated both chem-
ically and thermally by Memon et al. [90] to remove me-
thyl parathion (MP) pesticide from synthetic wastewater
by adsorption. The results revealed the treatments to be
very effective at low pH. Mechanism of the MP adsorp-
tion at acidic pH hinted at attractive forces playing a big
role by enhancing the interaction between the adsorbate
and adsorbent binding sites especially since the adsorbent
surface was surrounded by hydronium ions with metha-
nol being established as the best solvent in aiding de-
sorption of the MP pesticide from the adsorbent surface.

Cobas and co-workers evaluated the potentials of a
cheap biosorbent (chestnut shells) for the removal of
thiamethoxam, pirimicarb, acetamiprid, and imidaclo-
prid pesticides; the reports described the applicability of
the biosorbent in eliminating the chosen pesticides [91].

2.4 Biomass
Biomasses are very popular in studying the adsorptive
removal of pesticides. Some mechanisms of biomass and
biomass modified used in the control include mainly the
ion exchange, surface adsorption, chelation, and com-
plexation [93–95]. Wastewater contaminants in minute
quantities can be removed effectively by using the bio-
sorption method. Some of the common biomass
employed for adsorption studies are algae, fungi, and
bacteria.

### Table 2 Characteristic properties of different adsorbents employed for the adsorption of pesticides (Continued)

| Adsorbents                              | Pesticides  | Surface morphology                                                                 | Surface area (m²/g) | Total pore volume (cm³/g) | Pore size diameter (nm) | pH_{pzc} | References |
|-----------------------------------------|-------------|------------------------------------------------------------------------------------|---------------------|--------------------------|-------------------------|----------|------------|
| magnesium oxides                        |             | the particle size of 6 obtained from TEM image                                    |                     |                          |                         |          |            |
| Algerian palygorskite modified with     | Linuron     | Iron oxide particle size varies between 7 and 15 nm, with a heterogeneous          | –                   | –                        | –                       | –        | [67]       |
| magnetic iron with hydrothermal          |             | distribution of spherical particles without obvious aggregation and dispersed onto |                     |                          |                         |          |            |
| treatment (FeO Pal₁)                    |             | the palygorskite needles’ surface                                                 |                     |                          |                         |          |            |
| Algerian palygorskite modified with     | Linuron     | Iron oxide particles show square and/or hexagonal outlines and sizes from 30 to    | –                   | –                        | –                       | –        | [67]       |
| magnetic iron without hydrothermal       |             | 50 nm                                                                              |                     |                          |                         |          |            |
| treatment (FeO Pal₂)                    |             |                                                                                    |                     |                          |                         |          |            |
| Copper modified microcrystalline         | Prometryn   | Typical features of cellulose fibers informed by the dispersed netting lines and   | 6.06                | 0.01                     | 11.52                   | 11.30    | [68]       |
| cellulose                               |             | natural piral twists with some Cu²⁺ particles dispersed on the surface              |                     |                          |                         |          |            |

enable the readers to fully understand how both ionic
and non-ionic pesticides were adsorbed as well as des-
orbed on the decomposed maize residues. Based on the
provided information, compositional data analysis
(CoDa) approach was employed in building a predictive
model which utilized the sorption coefficient \( K_{oc} \).

Though there were different results based on pesticide
type, the pesticide sorption properties were greatly al-
tered. This happens during decomposition of the crop
residue due to changes in its chemical composition. For
the non-ionic molecules such as S-metolachlor and
epoxiconazole, their adsorption capacities were en-
hanced after decomposition upon comparison with gly-
phosate though glyphosate desorbed more readily from
decomposed residues. Based on that, the non-ionic pesti-
cides mobility was differently controlled by changes of
crop residues pattern during decomposition when com-
pared to ionic compounds of glyphosate. It is of para-
mount importance that the decomposition state of
mulch be given high regard when considering models in
predicting the pesticide behavior agricultural system
conservation.
The valorization of *Pleurotus mutilus* fungal biomass was reported by Behloul et al. for metribuzin pesticide biosorption [96]. Two important parts were reported in the study; physical pretreatment and the biomass characterization constituted the first part with the second part studying the various parameters (particle size, agitation, biosorbent content, temperature, pH, and metribuzin concentration) that have a very high chance of influencing the biosorption capacity of metribuzin. A very convincing result was obtained for the adsorption with a very rapid adsorption rate after about 3 h, before reaching the equilibrium. Particle size almost substantially interferes with the accumulation rate and the required time needed to reach adsorption equilibrium. Then 3.3 mg/g was determined as the optimum adsorption capacity value [96]. In a different work, immobilization of *Aspergillus laccase* was supported by utilizing peanut sand shell wheat straw. The laccase-catalyzed degradation of nine pesticide (prochloraz, isoproturon, penoxsulam, mfenacet, atrazine, prometryn, nitenpyram, bensulfuron-methyl, and pyrazosulfuron-ethyl) was improved upon employing redox mediator syringaldehyde [97]. The obtained results signaled successful pesticide adsorptions in soil and environmental wastewater samples. They reported the successful removal of over 65.9 and 54.5 % of pesticides using wheat straw immobilized laccase and peanut shell immobilized laccase for 3 days. The dosage of immobilized laccase biosorbent used was 25 g/L. However, the treatment of soil contaminated with pesticide compounds was conducted using wheat straw immobilized laccase and peanut shell immobilized laccase within 7 days. The biosorbent dose was 50 g/kg (soil). The maximum degradation rates were reported to range from 14.7 to 92.0 and 20.9 to 92.9 % respectively. Hence, it was concluded that biosorption coupled with laccase degradation presents an effective way of pesticide removal from wastewater especially when the laccase is immobilized on biomass materials.

Generally, practical applications of biomass are limited by some derelictions which include the biomass low rate of adsorption rate due to the adsorption process very reliant on the pH.

### 2.5 Carbon and graphene-based adsorbents

A study was conducted on magnetic and graphitic carbon nanostructures for the elimination of 2,4-D pesticide [52]. The magnetic nanoparticles prepared from filter paper (GCN-P) and cotton (GCN-C) were revealed to have higher BET surface area for GCN-P than GCN-C. The equilibrium data was best explained by the Redlich–Peterson isotherm with Elovich and M-exponential models explaining the kinetic data for GCN-P and GCN-C respectively, hinting at heterogeneous surface being provided by both adsorbents for the 2,4-D adsorption [52]. Magnetic property is another advantage credited to the nanostructures prepared from magnetic and graphitic carbon with the magnet favoring easy separation from the solution.

Fifteen different types of pesticides were used in contaminated water, the treatment was conducted using six various types of adsorbent which were treated and untreated rice straw biochar, corn stover biochar, and charcoal [98]. The researchers further studied the effects of some factors which include solution pH, water/adsorbent ratio, and pesticide concentration in the rice straw biochar that was not treated. Greater total pore volumes and larger surface areas were observed for corn stover biochars and untreated rice straw upon comparison to untreated charcoal with phosphoric acid treatment strongly influencing the surface functional groups and aromatization with respect to all the treated adsorbents. A study by Wanjeri et al. [55] reported the potential of graphene oxide-based silica-coated magnetic nanoparticles (Fe3O4@SiO2@GO) functionalized with 2-phenylethylamine (PEA) in the adsorption of some organophosphorus pesticides (OPPs) namely chlorpyrifos, parathion, and malathion [55]. The optimum adsorption conditions were reported to be 15 min contact time, 15 mg adsorbent dosage, and the solution concentration of 1 μg/mL with a negligible disparity in the pH condition, hinting at the suitability of using the material on various samples. The equilibrium and kinetic data of all the three pesticides were best described by the non-linear Sips and pseudo-second-order kinetic models respectively. After 10 cycles, there was a very low recovery of the OPPs from aqueous solution but after testing the adsorbent real wastewater samples from the Vaal River and Dam (South Africa), a recovery greater than 86.9 % was reported. The results confirmed the efficiency of the synthesized Fe3O4@SiO2@GO–PEA as a good adsorbent for the adsorption of pesticides.

### 2.6 Clay adsorbents

Other widely employed adsorbents applied to rid wastewater from varieties of pollutants such as pesticides are clay materials. An extensive adsorption-desorption study of endosulfan was reported on various Indian soils which are clayey soil (CL—lean clay with sand), red soil (GM—silty gravel with sand), sandy soil (SM—silty sand with gravel), and composted soil (PT—peat) based on the accepted standards set by ASTM (American Society for Testing and Materials) [99]. Their adsorption-desorption rate values were established to vary for alpha and beta endosulfan, relying on the type of soil used. The maximum specific adsorption capacity \( q_{\text{max}} \) values for the different soils varied from 0.1 to 0.45 mg/g for alpha endosulfan and 0.0942 to 0.2722 mg/g for beta endosulfan.
The maximum adsorption follows the order clay soil > composted soil > red soil > sand with functional groups effect more pronounced in clayey soil. There was a decreased endosulfan adsorption in clay soil at lower pH with higher desorption reported at both acidic and alkaline pH ranges when likened to neutral pH. The results further indicated alpha endosulfan to be more mobile than beta endosulfan [99]. It is more advisable to immobilize endosulfan in clay soil with biological and/or chemical process more suited to the effective remediation of other soil types.

Another investigation revealed how two distinct organohydrotalcites (OHTs): one intercalated with dodecane dioate (HT-DSS) and the other one with tetradecane dioate (HT-TDD) anions, prepared by the co precipitation method influenced the removal of non-ionic pesticide S-Metolachlor by adsorption [100]. The adsorption of S-Metolachlor pesticide was reported to be higher on the HT-TDD than HT-DDS, but lower desorption. Increase in temperature was also reported to enhance the adsorption of S-Metolachlor onto HT-TDD with the pesticide desorption process suggesting higher reversibility of S-Metolachlor adsorption from HT-DDS compared to HT-TDD. The results hinted at the possible role organohydrotalcites can play in removing S-Metolachlor pesticide from polluted water. In another development, Rodríguez-Liébana and co-workers evaluated a total of nine natural clay samples from South of Spain and the role they may play in the retention of metalaxyl and fludioxonil (two popularly used non-ionic fungicides) [101]. Different granulometry and mineralogical composition, high Ca content, and medium–low cation exchange capacity as well as specific surface area and low organic carbon content (≤ 0.8 %) were reported for the various clay samples. The Freundlich and pseudo-second-order models best explained the equilibrium and kinetic data generated with respect to metalaxyl adsorption, with both Freundlich and Langmuir best suited to the fludioxonil. Electrostatic attractions played a greater role in explaining why there was a better retention of metalaxyl (a more polar fungicide) than fludioxonil.

A novel functional material was synthesized and characterized by Gámiz and co-workers where they employed a cationic polymer hexadimethrine (SA-HEXAD) for the modification of SAz-1 montmorillonite which was compared with the more popular hexadecyl trimethyl ammonium-modified SAz-1 montmorillonite (SA-HDTMA) [56]. Potential of the new nanocomposite in decontaminating wastewater from pesticides was explored with the characterization and adsorption experiments revealing the extent of pesticide adsorption to strongly rely on the structure and features of the surface of each organo-clay as well as the nature of the considered pesticide. High affinity for anionic pesticides was noticed to be stronger with respect to SA-HEXAD which was presumably stimulated by electrostatic attraction on positively charged ammonium groups of the polymer but not by direct interaction with the clay. However, hydrophobic interactions were revealed to have big influence on SA-HDTMA showing greater adsorption of both uncharged and anionic pesticides. The success of their work involved providing new information about the surface properties of a novel organic–inorganic nanohybrid material (SA-HEXAD) as well as it being a promising adsorbent in the adsorptive removal of anionic organic pollutants from aqueous solutions.

Shattar et al. also investigated how the natural montmorillonite can be utilized in the ametryn removal by adsorption [59]. They reported an upsurge in the ametryn adsorption upon raising the initial concentration as well as operating temperature, with basic medium derail the adsorption process, producing maximum monolayer adsorption capacity of 188.81 mg/g. Major contribution from the work include revealing the practicability of montmorillonite as a feasible answer in the search for secondary herbicide on-site treatment.

2.7 Zeolites
Zeolites are very important materials where conductive polymers are incorporated because of their large specific surface area, well-ordered porosity, and negatively charge-balanced exchangeable cations [102]. Zeolites like many other materials have their limitations which include abysmal adsorption performance of anions and organics. To address such limitations, modification methods are crucial with the popular among them being acid/base treatment and surfactant impregnation which alter the hydrophilic/hydrophobic nature in order for the adsorption capacity to be improved. Another limitation associated to zeolites is poor desorption with respect to various contaminants but that was compensated by the relatively low price. Various researchers reported the potentials of zeolites and various zeolite materials as adsorbents for the removal of pesticides with special focus dedicated to the coupling of zeolites with polyaniline (PANI) composites. Properties such as simple synthesis, low production cost, and high conductivity among others qualify PANI to be among the most crucial and well-studied conducting polymers [102]. The nature of PANI composite systems help in aiding the successful elimination of a wide range of toxic and ecotoxic substances [103–105].

Bajuk-Bogdanović and co. synthesized tungstophosphoric acid and BEA (HPW/BEA) zeolite composites by employing wetness impregnation method which was followed by ultrasonication and calcination [106]. Upon evaluating how efficient the prepared composites can be
on the adsorptive removal of nicosulfuron pesticide in comparison to the parent zeolite, they revealed all the composites to be very good adsorbents with adsorption capacity of 12.1–25.8 mg of nicosulfuron per gram. Something very important from their findings is that the entire prepared composite performed far better than the parent BEA zeolite in the nicosulfuron adsorption, and the results compared very well with activated carbon which was reported from literature as the most effective adsorbent for various processes.

2.8 Metal organic frameworks (MOFs)

Another class of crystalline organic–inorganic hybrid solids with the potentials of being an excellent adsorbent for wastewater treatment are metal organic frameworks (MOFs), applied in the removal of several hazardous pollutants from wastewater due to their large surface area and high porosity. Even though MOF-type materials are rated very high as promising adsorbent materials, there have been few reports on the use of MOFs as pesticide adsorbents. A simple solvothermal synthetic method was proposed by Yang et al. which lead to the fabrication of metal organic framework–graphene oxide hybrid nanocomposite (UiO-67/GO), applied as an adsorbent for the removal of glyphosate pesticide from a polluted water [107]. They reported the adsorption process to take place in acidic medium at optimum pH of 4, leading to the glyphosate adsorption capacity value of 482.69 mg/g with pseudo-second-order and Langmuir models as the best fit for the kinetic and equilibrium data respectively. Another important finding from the work is the dominant mechanisms of the adsorption process which was revealed to be in the form of surface/inner-complexation with functional groups of UiO-67/GO. Additionally, the work further suggested UiO-67/GO composite to show great potential as the next-generation adsorbent for wastewater treatment as well as opening the door for other MOF/GO composite materials to be fabricated for effective organic pollutant removal. In another development, a new magnetic MOF (M-MOF) was also synthesized by Liu et al. thereby by employing Fe₃O₄–graphene oxide–β-cyclodextrin (Fe₃O₄–GO–β–CD) nanocomposite as the magnetic core which was used for the rapid adsorption and removal of neonicotinoid insecticides in tap water samples [60]. The obtained M-MOF has large surface area which resulted into adsorbent with high adsorption capacity for neonicotinoid insecticides. Upon applying the M-MOF adsorbent into spiked tap water samples for the neonicotinoid insecticide removal, the results suggested the developed M-MOF to be simple and effective potential adsorbent.

Successful attempt was also made in the removal of 2, 4-D molecules onto CeO₂ nanofibers derived from Ce-BTC metal organic frameworks [108]. Hydrothermal method was applied in the adsorbent preparation. They calcinated the Ce-BTC nanoparticles at 650 °C for 3 h with the obtained CeO₂ nanofibers used for 2,4-D adsorption from water. Based on the adsorption results, the optimum adsorbent dose and contact time were 2.5 mg and 100 min respectively revealing three isotherm models (Langmuir, Freundlich, and Sips) to agree well with the experimental data. The 2,4-D maximum adsorption capacity values reported were 86.16, 95.78, and 84.29 mg/g at 298, 308, and 318 K respectively.

In another development, other researchers established an easy and dependable method of determining nine pesticide residues in tobacco using GC–MS coupled with magnetic solid phase extraction thereby synthesizing a novel magnetic Zr-MOF nanocomposite based on graphene with large surface area value of 178 m²/g as well as possessing high thermal stability and good magnetic response which was established to be well suited for the fast enrichment of multi-pesticides in tobacco matrix [61]. Various extraction conditions such as adsorbent dose, time of adsorption, eluting solvent, and desorption time were investigated with the whole pretreatment being accomplished within 10 min. Acceptable recoveries in the range of 57.9 to 126.3 % were obtained for the tobacco samples. Though the method shows low limit of detection, good reproducibility (relative standard deviations < 12.7 %) and wide linear range were very encouraging.

Some limitations associated with the MOFs include high cost coupled with complicated synthesis process; based on that, researchers are advised to seek for alternative routes which may lead to a relatively reduced cost and short synthesis time while producing MOFs in large scales.

2.9 Equilibrium, kinetic modeling, and thermodynamic studies

For every adsorption process, information derived from the isotherms, kinetic, and thermodynamic data are very crucial for the development of a design model that is accurate and effective in the removal of organic contaminants from aqueous media and/or synthetic wastewater. In order to effectively predict adsorbent performance in wastewater treatment, data generated from isotherm studies are very vital. Different isotherm models are reported to be useful but the most popular two-parameter isotherm models are the Langmuir and Freundlich models describing monolayer formation by chemisorptions as well as multilayer physical adsorption through weak van der Waals forces respectively [109]. The limitations of Langmuir and Freundlich models were highlighted to be their inability in fitting the generated equilibrium data over a wide range of concentration by their single set of constants, and hence proposed three-
parameter isotherm equations (Redlich–Peterson, Sips, Toth models) to be more suitable since they encompassed additional parameters (pH, temperature) and other interactions in the adsorption mechanism [110]. Two parameter isotherms were reported to be the most popular and widely used models in the majority of pesticide adsorption processes as compiled in Table 3, with most of the processes described by monolayer formation on the adsorbent surfaces as described by the Langmuir isotherm model.

Kinetic studies and modeling are also very crucial in describing and predicting the optimum adsorption conditions [111] as well as providing vital information about mechanisms of adsorption and also the presume rate-controlling steps [112]. Pseudo-first- and pseudo-second-order kinetic models are the most popular and commonly applied in the pesticide adsorption studies. Despite their popularity, the models are handicapped such that they cannot recognize adsorption mechanisms. To address that drawback, other models such as Elovich and Weber-Morris were established and recommended [110]. In almost all the studied pesticide adsorption processes, only pseudo-first and pseudo-second-order models were employed by the researchers in explaining their generated kinetic data with lack of mechanism explanation using other aforementioned models well pronounced. As collated in Table 3, the best kinetic model that better interpreted pesticide adsorption processes was pseudo-second-order models.

Important thermodynamic parameters such as Gibbs free energy ($\Delta G^\circ$), enthalpy change ($\Delta H^\circ$), and entropy change ($\Delta S^\circ$) are also very useful in describing adsorption processes, thereby providing crucial information about the process spontaneity, endo- or exothermicity of an adsorption phenomenon, and randomness of the process. The adsorption mechanism can also be predicted from the thermodynamic parameters, for example, the predominant adsorption process mechanism can be said to be physisorption if $\Delta G^\circ$ ranges from $-20$ and $0 \text{kJ/mol}$, or chemisorptions if the values are in the range of $-80$ to $-400 \text{kJ/mol}$.

### 2.10 Economic consideration

It is very uncommon to find adsorbent cost estimation in literature despite being the most important aspect to be considered in real-life application of adsorption processes. The estimated average price of zeolites and Fuller’s earth were reported to be US$ 0.03–0.12 and US$ 0.04/kg respectively [113, 114]. While the market value of activated carbon was reported in literature by [115] to be in the range of US$ 2.0–2.2/kg. The advantages of the low-cost adsorbents are their prices, because their usage, treatment, and the processes of regeneration are not economically friendly. In our own view, local availability, transportation, treatment process, recycling, and the lifetime of the adsorbents are fundamental factors to be considered when choosing an adsorbent [116, 117].

Treatment of an exhausted adsorbent is important but cumbersome, which has not been considered seriously. The sorption selectivity and capacity of adsorbents can be improved through some treatments as suggested in the literature [118]. Heat energy and large quantity of solvent are being consumed during the regeneration process of an adsorbent. All these modifications will acquire additional cost as well as that of transportation but there are few articles in literature that discuss on the subsequent cost of mentioned treatments. A high price adsorbent with the capabilities of multiple usages, cheap and simple regeneration process is considered an economical and promising material for adsorption processes. Therefore, the actual application involves appraising the adsorbent cost from its entire life cycle [119]. Some materials such as chitosan, cyclodextrin coupled with their composites show some distinguished outputs despite their limited practical applications which was linked to high cost and complex synthesis; for that, critical assessment of those materials is highly recommended especially those covering the whole life cycle.

### 3 Conclusions

A productive wastewater treatment is very important; therefore, it is necessary to find simple, cheap, and efficient advanced wastewater treatment techniques. These lead to good practices of water management and waste elimination, availability of clean water, increase in environmental nexus, and growth of the economy. There were different methods mentioned in literature, but adsorption has become more prominent in eliminating pesticide from wastewater as it is easy to handle and toxic free. Agricultural wastes, bio-sorbents, nano materials, inorganic wastes, and activated carbon were among many other adsorbents that were successfully applied with aim of eliminating pesticides from wastewater. The abovementioned adsorbents show good adsorptive properties in different examined tools. However, there are some important points that should be considered to have a good understanding of these adsorbent’s adsorptive characteristics. Some studies focus on the determination of maximum adsorption capacities of synthetic pesticide solution in batch mode. Although the efficiency of an adsorbent does not depend only on their properties, it also relies on the adsorbent matrix characteristics as well as chemical revamping which can enhance the adsorption capacities due to having good adsorptive characteristics more than that of unmodified. This also leads to additional treatment cost of the chemical modification as well as creating secondary pollution from
Table 3 List of experimental conditions, isotherm, kinetic models, and maximum adsorption capacities for the removal of pesticides on different adsorbent materials

| Adsorbents                        | Pesticides                                      | Experimental conditions | Isotherm model | Kinetic model | Maximum adsorption capacity (mg/g) | References |
|-----------------------------------|-------------------------------------------------|-------------------------|----------------|---------------|------------------------------------|------------|
| Activated carbon-cloth            | Dinoseb, ametryn, diuron, aldicarb              | T = 25 °C, t = 125 min, \( C_0 = 6.5 \times 10^{-5} \) mol/L | F              | Ps1 or Ps2    | 301.84 (Dinoseb); 354.61 (ametryn); 213.06 (diuron); 421.58 (aldicarb) | [89]       |
| Borassus aethiopum shells-based activated carbon | Carbofuran                                      | Adsorbent dose = 0.15 g, pH = 2–12, T = 30 °C, t = 18 h, \( C_0 = 30–200 \) mg/L | L              | Ps2           | 160                                | [17]       |
| Granular activated carbon (GAC F300) | Carbofuran and 2,4-D                             | Adsorbent dose = 0.20 g, pH = 6.35 and 3.5, T = 30 °C, t = 26 h (carbofuran) and 8 h (2,4-D), \( C_0 = 50–225 \) mg/L (carbofuran) and 50–300 mg/L (2,4-D) | L              | Ps2           | 96.15 (Carbofuran); 181.82 (2,4-D) | [38]       |
| Date seed activated carbon        | Bentazon and carbofuran                         | Adsorbent dose = 0.20 g, pH = 2–12, T = 30 °C, t = 0–36 h, \( C_0 = 25–250 \) mg/L | F              | Ps2           | 86.26 (bentazon); 137.04 (carbofuran) | [40]       |
| Mesoporous activated carbon from starch (ACS) | Atrazine, pymetrozine, acetamiprid, diuron, thiacloprid, imazalil, difenoconazole, azoxystrobin, pyraclostrobin, trifloxystrobin, and chlorantraniliprole | Adsorbent dose = 5 to 120 mg, pH = 1–11, T = 25 °C, t = 0–4 h, \( C_0 = 0.5–2 \) mg/L | L              | Ps2           | 66.2 (pyraclostrobin) | [42]       |
| Waste rubber tire activated carbon | Methoxychlor, atrazine and methyl parathion     | Adsorbent dose = 0.02–0.14 g/L, pH = 2–12, T = 25–45 °C, t = 0–150 min, \( C_0 = 2–12 \) mg/L | L              | Ps1           | 112.0 (methoxychlor); 104.9 (atrazine); 88.9 (methyl parathion) | [43]       |
| Mesoporous activated carbon from coconut frond | Carbofuran                                      | Adsorbent dose = 0.20 g, pH = 2–12, T = 30–50 °C, t = 0–16 h, \( C_0 = 25–250 \) mg/L | F              | Ps2           | 198.4 (30 °C); 193.1 (40 °C); 205.0 (50 °C) | [48]       |
| Activated carbon from waste hemp  | Acetamiprid, dimethoate, nicosulfuron, carbofuran, and atrazine | Adsorbent dose = 0.20 g, T = 25 °C, t = 0–200 min, \( C_0 = 10–50 \) mg/L | F              | –             | 12.20 (acetamiprid); 11.80 (dimethoate); 19.50 (nicosulfuron); 15.40 (carbofuran); 15.50 (atrazine) | [49]       |
| Coconut shell activated carbon    | Malathion                                       | Adsorbent dose = 1.0 g | L              | –             | 909.1                              | [50]       |
| Adsorbents | Pesticides | Experimental conditions | Isotherm model | Kinetic model | Maximum adsorption capacity (mg/g) | References |
|------------|------------|-------------------------|----------------|--------------|----------------------------------|------------|
| NH₄Cl-induced activated carbon | Diazinon | pH = 2–10  
T = 25–40 °C  
t = 0–6 h  
C₀ = 2–10 mg/L  
NAC concentration (0.1–0.3 g/L) | L | Ps2 | 250.00 | [51] |
| Treated watermelon peels | Methyl parathion | Adsorbent dose = 0.05–1 g  
pH = 1–10  
T = 10–50 °C  
t = 10–100 min  
C₀ = 0.38–3.8 × 10⁻⁴ mol/L |  | Ps1 | 24.3 ± 1.6 μmol/g | [90] |
| Chestnut shells | Imidacloprid, acetamiprid, and thiamethoxam | Adsorbent dose = 7.2 g  
pH = acidic  
T = 25 °C  
t = 48 h  
C₀ = 5 mg/L |  | Ps2 | 8.5070 (imidacloprid); 4.6984 (acetamiprid); 14.310 (thiamethoxam) | [91] |
| Fungus *Pleurotus mutitus* | Metribuzin | Adsorbent dose = 1–4 g  
pH = 2–8  
T = 25 °C  
t = 0–25 min  
C₀ = 100–400 mg/L  
Particle size = 0–625 μm |  | – | 3.3 | [96] |
| Graphitic carbon nanostructures from filter paper | 2,4-D | Adsorbent dose = 2 mg  
pH = 2–10  
T = 30 °C  
t = 0–24 h  
C₀ = 0–300 mg/L |  | E and M-e | 77.13 | [52] |
| Graphitic carbon nanostructures from cotton | 2,4-D | Adsorbent dose = 2 mg  
pH = 2–10  
T = 30 °C  
t = 0–24 h  
C₀ = 0–300 mg/L |  | E and M-e | 26.93 | [52] |
| Phenyl-modified magnetic graphene/mesoporous silica | Avermectin, imidacloprid, pyridabens, dichlorvos, acetamiprid, dursban, isocarbophos, and phoxim | Adsorbent dose = 100 mg  
pH = 2–12  
T = 25–35 °C  
t = 0–2 h  
C₀ = 391–48430 μg/L |  | Ps1 | 9.208 (Avermectin); 6.404 (imidacloprid); 12.72 (Pyridaben); 47.78 (Dichlorvos); 5.108 (acetamiprid); 8.010 (dursban); 2.877 (isocarbophos); 8.233 (Phoxim) | [53] |
| Mesoporous carbon derived from a biopolymer and a clay | Dicamba Pestanal | Adsorbent dose = 30 mg  
pH = 2–11  
T = 25–55 °C | L | Ps2 | 251.9 | [54] |
| Adsorbents | Pesticides | Experimental conditions | Isotherm model | Kinetic model | Maximum adsorption capacity (mg/g) | References |
|------------|------------|-------------------------|----------------|---------------|-----------------------------------|------------|
| Graphene oxide-based silica-coated magnetic nanoparticles functionalized with 2-phenylethylamine | Chlorpyrifos, parathion, and malathion | $t = 0.3–2\text{ h}$, $C_0 = 25–1000\text{ mg/L}$ | sips | Ps2 | 25.6 (chlorpyrifos); 135 (parathion); 61.9 (malathion) | [55] |
| Four Indian soils | α-endosulfan | $t = 0.25–24\text{ h}$, $C_0 = 0.15–100\text{ mg/L}$ | L | – | 0.10–0.45 (α-endosulfan); 0.094–0.272 (β-endosulfan) | [99] |
| Natural montmorillonite | Ametryn | $t = 0.20\text{ g}$, $pH = 2–12\text{; } T = 30–50\text{ °C}$, $t = 0–7\text{ h}$, $C_0 = 25–150\text{ mg/L}$ | L | Ps2 | 18.4–25.4 (Protonated PANI/BEA composites); 18.2 (pristine BEA zeolite); 29.8 (PANIs) | [102] |
| Polyaniline/BEA zeolite composites | Nicosulfuron | $t = 20\text{ mg}$, $pH = 2–5\text{; } T = 23\text{ °C}$, $t = 0–40\text{ h}$, $C_0 = 10–100\text{ mg/L}$ | L-F | – | 0.558 (thiamethoxam); 0.363 (imidacloprid); 0.362 (acetamiprid); 0.639 (nitenpyram); 0.533 (dinotefuran); 0.412 (clothianidin), and 0.275 (thiacloprid) | [60] |
| Magnetic graphene oxide–cyclodextrin | Thiamethoxam, imidacloprid, acetamiprid, nitenpyram, dinotefuran, clothianidin, and thiacloprid | $t = 5\text{ mg}$, $pH = 2–11\text{; } T = 0–120\text{ min}$, $C_0 = 0.5–100\text{ mg/L}$ | F | Ps2 | 0.558 (thiamethoxam); 0.363 (imidacloprid); 0.362 (acetamiprid); 0.639 (nitenpyram); 0.533 (dinotefuran); 0.412 (clothianidin), and 0.275 (thiacloprid) | [60] |
| LaFe$_{0.9}$Co$_{0.1}$O$_3$ | Vitavax | $t = 1–3\text{ g/L}$, $T = 15–45\text{ °C}$, $t = 5–40\text{ min}$, $C_0 = 200–800\text{ mg/L}$ | L | Ps1 | 166.67 | [64] |
| LaFe$_{0.1}$Co$_{0.9}$O$_3$ | Vitavax | $t = 1–3\text{ g/L}$, $T = 15–45\text{ °C}$, $t = 5–40\text{ min}$, $C_0 = 200–800\text{ mg/L}$ | L | Ps1 | 142.86 | [64] |
| Multi-walled carbon nanotubes | Diazinon | $t = 0.1$ and 0.3 g/L, $pH = 4$ and 7, $T = 24\text{ °C}$, $t = 1–15\text{ min}$, $C_0 = 0–100\text{ mg/L}$ | – | – | – | [62] |
| Modified chitosan | Pentachlorophenol | Adsorbent dose = 0.1 and 0.3 g/L, $pH = 4$ and 7, $T = 24\text{ °C}$, $t = 1–15\text{ min}$, $C_0 = 0–100\text{ mg/L}$ | R-P | Ps2 | 36.85 (20 °C); 32.19 (30 °C); 22.35 | [63] |
leaching of chemicals during modification treatments. There is need for extensive review on the secondary pollution caused during the modification of adsorbents which is rarely reported by the articles gathered in this review. Two parameter isotherms such as Freundlich and Langmuir are recommended to be examined alongside with three parameter models such as Sips and Toth in equilibrium modeling as this will give a comprehensive understanding of adsorption pathway. In the kinetic studies, Elovich and Weber and Morris kinetic models need to be studied to comprehend and investigate the in-depth adsorption pathways. This is vital because adsorption mechanism cannot be identified correctly by only the pseudo-first-order and pseudo-second-order models. The thermodynamic parameters that are temperature dependent should be examined with caution due the observation of an enthalpy–entropy compensation.

The disposal of pesticide-loaded wastes from adsorption processes demands urgent attention. The ability of an adsorbent to be reused is an important element in cost effectiveness. The reuse and regeneration of adsorbents are discussed in some studies while some do not, so detailed assessment of the regeneration of adsorbents are highly recommended for the adsorption process to be economically achievable. Cost analysis on the adsorbents practical application is also very crucial and should be incorporated in further researches that involve pesticide removal from wastewater using adsorption method.

## Abbreviations
OCPs: Organochlorine pesticides; SPs: Synthetic pyrethroids; OPPs: Organophosphorus pesticides; PMOCS: Persistent and mobile organic compounds; HCH: Hexachlorocyclohexane; BP: Bromopropylate; DSAC: Date seed activated carbon; ACS: Activated carbon from starch; GCB: Graphitized carbon black; MP: Methyl parathion; CoDa: Compositional data analysis; GCN-C: Magnetic nanoparticles prepared from cotton; PEA: 2-Phenylethylamine; OHTs: Organohydrotalcites; HT-DDS: Intercalated with dodecylsulfate; HT-TDD: Intercalated with tetradecanedioate; PANI: Polyaniline coupled with zeolites; MOFs: Metal organic frameworks; 2,4,5-T: 2,4,5-Trichlorophenoxy acetic acid; 2,4-D: 2,4-Dichlorophenoxyacetic acid; 4-CPA: 4-Chlorophenoxyacetic acid; CFA: 2-(4-Chlorophenoxy)-2-methylpropionic acid, Ps1: Pseudo-first-order model, Ps2: Pseudo-second-order model, E Elovich, L Langmuir; R-P Redlich–Peterson, M-e M-exponential; PANIs polyanilines, PEI polyethyleneimine, J Jossens, Pur Pal colloidal solution of Fe3O4 with a 1% mass dispersion of purified palygorskite, FeO Pal: non-hydrothermally treated magnetic FeO Pal nanoparticles, FeO Pal2: hydrothermally treated magnetic FeO Pal nanoparticles

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