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Grigorios Kyriakopoulos[a]; Danae Doulia[a]
[a] School of Chemical Engineering, National Technical University of Athens, Athens, Greece

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Adsorption of Pesticides on Carbonaceous and Polymeric Materials from Aqueous Solutions: A Review

Grigorios Kyriakopoulos and Danae Doulia
School of Chemical Engineering, National Technical University of Athens, Athens, Greece

Abstract: Carbonaceous and polymeric materials have been extensively used in adsorption processes for the removal of pesticides from aqueous solutions. The aim of this review is the systematic and comparative presentation of the possibilities of the above adsorbents, arising from the data reported in the literature for the period 1990–2004. A brief description of each article is given in tables. The data is divided into two groups, based on the chemical structure of adsorbent (carbonaceous or polymeric material) and is given in tables. In each table information on the type of adsorbent (powder, granular, fibers, cloths, resins, cartridges etc), pesticide structure, experimental conditions, aim and results of each work, is reported. In addition, data is included concerning single pesticides adsorption, competitive adsorption, parameters of adsorption isotherms (Langmuir, Freundlich, Dubinin–Radushkevich) and kinetic model's parameters (homogeneous surface diffusion model-HSDM, equivalent background compound-EBC, Peel model), such as surface diffusion coefficients and mass transfer coefficients. Information on adsorption yields, effect of various factors on adsorption effectiveness, static or continuous operation, laboratory, pilot or industrial scale process and combination of adsorption with other methods, is also included.

Keywords: Activated carbon, adsorption, equilibrium model's parameters, kinetic model's parameters, pesticides, polymeric adsorbents

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Address correspondence to Danae Doulia, School of Chemical Engineering, National Technical University of Athens, Zografou Campus, Athens GR-157 80, Greece. E-mail: ddoulia@chemeng.ntua.gr

INTRODUCTION

Serious environmental impacts in soil, air and water have been observed from the extensive agricultural use of pesticides. Pesticides protect mainly crops from pest organism including insects, plants, fungi, rodents, and nematodes. Pesticides may appear as pollutants in water sources, having undesirable impacts to human health because of their toxicity, carcinogenicity and mutagenicity or causing aesthetic problems such as taste and odors (1, 2). Environmental regulations in developed countries have become very strict for drinking water treatment over the last few years, especially regarding pesticide compounds (levels decreased to only 0.1 μg/l) (3).

So far, numerous research studies have been reported on pesticides removal from aqueous solutions, aiming at the purification of process streams and/or the recovery of valuable compounds (4–6). There are many methods available to treat raw water for the separation of possible harmful organics before offering it to the public use. Conventional treatment technologies including chemical coagulation, sedimentation, filtration, clarification, disinfection, have been widely used but they were not always successful. Pesticides which are insoluble in water, such as DDT, or are easily decomposed, such as carbamate insecticides, generally can be removed effectively by the conventional methods. However, conventional treatment has often been proved ineffective for the separation of the majority of pesticides or their metabolites. Therefore, a number of innovative water treatment methods have been developed to create more efficient systems, particularly for the hydrophilic organic compounds (7). The applied methods are classified in two categories. The first category, which includes adsorption and membrane technology methods, is based on the removal of toxic organic substances (8). The second category of methods, such as oxidation, ozonation, voltammetry, photocatalysis is based on pesticides decomposition (9, 10). Adsorption is one of the most frequently applied methods because of its efficiency, capacity and applicability on a large scale. This process has been also widely used to remove pesticides from drinking water. The more common adsorbents are: carbon, polymers, agricultural products and soils. In the present review we compile and discuss the data related to the adsorption of pesticides on carbonaceous and polymeric materials from aqueous solutions.

EQUILIBRIUM MODELS

Intensive investigation of the adsorption of solids has led to the development of a large number of empirical isotherm equations. Their main advantage has been a good afterwork representation of experimental data. Theoretical

studies tried to find a link between empirical isotherms and heterogeneity of the surfaces. These equations correspond to distribution of adsorption energy, which are characteristic of the majority of the systems used in practice. The main adsorption isotherms applied in adsorption systems are:

- Langmuir isotherms

  The well-known Langmuir equation describes localized, monolayer adsorption on homogeneous adsorbent when attractive interactions between adsorbed molecules are neglected:

$$C_{ad} = v_m b C_{eq}/(1 + bC_{eq}) \tag{1}$$

  where C_{ad} is the adsorbed amount on the support at concentration C_{eq} in the bulk, $v_m b$ is the Henry's law constant for the Langmuir equation. v_m (mol/g or mol/m^2) is the maximum amount of solute adsorbed per unit weight of adsorbent (surface saturation) and b (l/mol) is related to the heat of adsorption. For testing the applicability of Langmuir equation, three transformed equations are used (11). Adsorption occurs in a flat surface and either: the solute is chemisorbed on a set of distinct localized adsorption sites, all of them releasing the same adsorption energy, or mobile physical adsorption occurs until only a relatively low coverage degree is reached.
- Freundlich Isotherm

  The Freundlich equation, unlike the Langmuir one, does not become linear at low concentration and does not show a saturation or limited value:

$$C_{ad} = K_F C_{eq}^{1/n} \tag{2}$$

  where the constants K_F and n can be obtained from a plot of log C_{ad} versus log C_{eq}. The intercept log K_F gives a measure of the adsorbent and the slope $1/n$ of the intensity of adsorption. Basically, the equation is an empirical one limited in its usefulness to its ability to fit data. This isotherm corresponds to a decreasing exponential distribution function. The surface is mainly considered heterogeneous.
- Dubinin–Radushkevich (DR) Isotherm

  For the D-R isotherm, physical adsorption occurs through a pore volume-filling mechanism, the adsorption energy (E) decreasing as the occupied volume increases. The adsorption energy for a given equilibrium concentration c_e is estimated from the Polanyi adsorption potential theory as RT ln (c_s/c_e) where c_s is the solubility (12).

$$C_{ad} = v_m \exp\left[-\left(\frac{RT}{E}\ln\left(\frac{c_s}{c_e}\right)\right)^2\right] \tag{3}$$

KINETIC MODELS

Many empirical models employed in the literature to describe the mechanisms of adsorption of more complicated systems. Models with theoretical basis are a better tool to design and study the system considering a wide range of conditions and to reduce the time spent in expensive pilot-plant studies. In addition, they allow the correlation of the model parameters to the physical and chemical properties of the system, leading to a better understanding of the process.

Drinking water companies have to deal with pesticides with very different properties and large concentration fluctuations. It is necessary to predict the lifetime of adsorbent i.e. Granular activated carbon (GAC). The performance of an adsorbent depends on the properties of pesticide and of natural organic matter (NOM) such as humic and fulvic acids in water. The concentration of NOM is typically 1000 times higher than the concentration of pesticide and differs in composition and level in natural waters. Two types of laboratory experiments are used to predict full–scale breakthrough curves: bottle experiments (equilibrium experiments) and rapid small–scale column tests (RSSCT). The principal problem lies in translating the outcome of laboratory experiments to full scale. The main difficulties are reported by Heijman and Hopman (13). The removal of pesticides is considered that it is generally negatively influenced by the presence of NOM.

The evaluation of equilibrium experiments is based on the equivalent background concentration model (EBC method) (13). Adsorption isotherms are constructed for NOM in competition with the pesticide using powdered activated carbon (PAC). The EBC characteristics, i.e., the Freundlich equation of the fictive adsorption isotherm, are calculated using the ideal adsorbed solution theory (IAST) for two competing components (13, 14). The IAST equations are derived from the Gibbs equation. The contribution of each adsorbed component to the spreading pressure in a multi-component system is related to the amount of each component adsorbed. The drawbacks of EBC method are the rather rough approach of NOM by a fictive single component the use of powdered adsorbent and the prediction is limited to only equilibrium conditions. The validity of this approach is therefore limited (13).

The rapid small-scale column test (RSSCT) was introduced by Crittenden et al. (in 13). A full-scale column process can be scaled down to a small-column experiment if some dimensionless groups (Peclet, Stanton and pore-diffusion modulus) are kept constant. If smaller grains are used, the duration of the experiment decreases by a factor of about ten. The dimensions and the process variables of the small column are calculated using the homogenous surface diffusion model (HSDM) (13, 14). In this model, the following mechanisms are considered:

1. Axial dispersion of the pesticide in the bulk fluid of the column, caused by diffusion or random fluid movement around the adsorbent particles.

2. External mass-transfer resistance or film transfer caused by the diffusion of the adsorbate from the bulk solution to the adsorbent surface.
3. Internal mass-transfer resistance of pore and surface diffusion.
4. Adsorption on activated carbon and the competition with NOM.

To simulate a full-scale column, the amount of spreading in the breakthrough curve must be identical to the small column. If the competition between pesticide and NOM is the same in both small-scale and full-scale, the passed volume in the small column per unit of activated carbon is directly related to the passed volume in a full-scale column. In this way, the competitive binding and kinetic aspects are combined in one experiment, and extensive isotherm or kinetic studies are not required to obtain a full-scale breakthrough prediction from RSSCT. The major shortcomings in this approach are mentioned by Heijman and Hopman (13).

In order to achieve a complete characterization of PAC slurry at different ages, kinetic tests are fitted using the HSDM (15, 16). HSDM allows the determination of two kinetic parameters: the superficial diffusivity coefficient D_s and the liquid film mass transfer coefficient k_f.

Advanced models (like Peel model) take into account the structural heterogeneity of activated carbon by assuming a bidisperse structure (12). In Peel model, the carbon particle is partitioned into two regions: macropores, in which an initial rapid uptake occurs; and micropores, in which restricted diffusion takes place and the remaining capacity to equilibrium is utilized. As micropores branch off macropores, mass transfer proceeds through three different steps coupled in series: (i) mass transfer from fluid phase to particle surface, (ii) diffusion in the macropore region and (iii) diffusion in the micropore region. However, a different approach is proposed to define the fraction of macropore region. In the model of Peel et al., the following parameters are calculated: f (fraction of macropore region), k_L (external mass transfer coefficient, cm/s), D_p (effective macropore diffusivity, cm^2/s), D_s (effective surface diffusivity, cm^2/s^{-1}). D_p and D_s are linked through a relationship developed by Neretnieks (12).

ADSORPTION ON CARBONACEOUS MATERIALS

The most commonly used adsorbent in adsorption processes is activated carbon (2–5,17). Generally, carbonaceous materials have a special place among the main adsorbents, as they are known, for a long time, to be capable of adsorbing various organic compounds. Activated carbon is a versatile material that can be applied in many technological processes. However, the operation cost in large-scale plants is high due to carbon loss during the regeneration process (thermal desorption or combustion of toxic substances) (18). A variety of activated carbon materials have been used, such as, granular activated carbon (GAC), powdered activated carbon

(PAC), carbon cloth, fibers, felts or carbon cloth electrodes, black carbon from wheat residues (WC), carbon black and commercial activated carbon (AC). The forms GAC and PAC are the most used since they are considered very capable and effective materials for the adsorption of a variety of pesticides. The chemical and technical characteristics of an activated carbon depend on both the precursor used and the experimental conditions of each manufacturing process (19, 20). The raw materials used for activated carbon production are wood, carbon or bones after combustion. The activation process includes the treatment with carbon dioxide and high temperature steam (900–1100°C) or air, in order carbon with pore structure and high internal surface to be produced (21).

The main characteristics of GAC and PAC are the following: Granular activated carbon (GAC) has been used in many processes for the treatment of drinking water supplies and industrial wastewaters (12, 22). It has been, primarily, applied in fixed-bed column adsorbers. GAC is characterized by relatively lower amount required in water treatment processes, easier handling and possibility for regeneration reducing, therefore, the production cost of drinking water. However, the GAC fixed-beds require an appreciable investment in equipment, except of high cost for operation and maintenance (5). The main difficulty in the design and operation of GAC adsorbers focuses on the modeling of the effects of natural organic matter (NOM) or coagulants on the adsorption of synthetic organic chemicals (SOCs). The design and operation of a GAC adsorber remains complicated. This is probably due to the natural organic matter adsorption, or NOM fouling, which affects the effectiveness of GAC adsorption by decreasing both the adsorption capability and the adsorption rate of SOCs traces (23, 24). There is a considerable amount of information available in the literature, concerning adsorption of pesticides onto GAC. Despite this, there is still much to learn about the mechanisms of adsorption of these compounds, which is reflected in the empirical nature of many models employed, to describe these systems (5, 12, 22).

The powdered activated carbon adsorption process has been used as an effective method, in temporal and emergent practice, to remove residual pesticide and other hazardous chemicals in raw water during drinking water treatment (25). PAC is commonly applied at water treatment plants, mainly for taste and odor control. It offers certain advantages over GAC, such as the low capital cost and flexibility of operation, as it can be applied only when needed. However, in most central wastewater treatment units, GAC has been used instead of PAC, whose adsorption capacity is difficult to be fully utilized (5). Also, an additional filtration procedure is required for PAC recovery and reuse (12, 22). At pesticide concentration in the range of 0.20–0.50 μg/l, 2–50 mg/l (200 ppt–50 ppm) PAC are required for the achievement of the upper permitted detection limit (0.1 μg/l or ppb). The adsorption of pesticides (neutrals or ionogenics) onto PAC is dependent on their physico-chemical properties. Efforts have been made for establishing

PAC dosage strategy in water treatment plants and for this purpose the octanol–water partition coefficient has been introduced (25). Recently, particular interest has been focused on mathematical models for pesticides adsorption on PAC (26). Pesticides removal from water is negatively affected by the presence of problematic and undesirable fractions of NOM, such as humic acids due to the competitive adsorption between pesticides and NOM. Indeed, the molecules of this matter adsorbing into the pores of activated carbon, reduce the available pesticides adsorption surface (13). In this case, the addition of coagulants, such as polyaluminium chloride, was applied successfully before the PAC addition (27). So, a high quantity of humic acid, prohibiting adsorption, is retained by the coagulants.

The use of by-products or residues of agricultural production (e.g., olive waste cake) as precursors for the production of cheap and effective activated carbon has been reported in the literature. Indeed, these activated carbons have been proved more effective to adsorb pollutants contained in drinking water, than commercial activated carbon. Generally, the activation method consists of two steps: a carbonization step under inert atmosphere, followed by an activation step under high temperature in the presence of an activated agent such as carbon dioxide, steam or air (20, 28).

The need to remove specific pollutants from water led manufacturers to produce more efficient activated carbon materials, such as carbon cloth, fibers, felts or carbon cloth electrodes. Many studies on purification of water by adsorption of impurities on the carbon cloth have been appearing in the literature during the last few years (3). More attractive carbon materials are now available, with large specific areas in the range of 2000–2500 m^2g^{-1} (8). These new carbonaceous materials have better technical characteristics in comparison with those of the conventional active carbon adsorbents, namely:

- High adsorption efficiency and effectiveness, adsorption capability and functionality for the accumulation of larger amount of useful organic compounds or impurities
- Large specific areas
- Good mechanical and structural integrity
- Minimization of the diffusion limitation to adsorption since these materials behave as quasi–three–dimensional
- High selectivity and improved pesticides adsorption behaviour in the presence of NOM (3).

Due to the abundant studies on pesticides adsorption onto carbonaceous materials from aqueous solutions, a systematic presentation of the relative information is given for easier approach and comparison. So, in Table 1, the research activities have been compiled and the relative data concerning the type of activated carbon, type of pesticide, experimental conditions

Table 1. Pesticides adsorption on carbonaceous materials

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
1	Ayranci and Hoda 2004a (8)	Bentazon and propanil	High area activated prewetted carbon cloth (ACF, specific area 2500 m^2/g)	The adsorption of single and bisolute solutions of pesticides was examined at pH natural, T = 25°C, time 125 min using a special V-shaped cell and UV/Vis spectrometer. Simulation of experimental adsorption isotherm data to Langmuir and Freundlich equations was used. The percent coverage at the carbon cloth surface was 0.023–0.024.
2	Ayranci and Hoda 2004b (31)	Metribuzin, bromacil, 2,4-D and atrazine	High area activated carbon cloth (specific area 2500 m^2/g)	The removal of pesticides from single and bisolute solutions was examined at pH natural, T = 25°C, time 125 min using a special V-shaped cell and UV/Vis spectrometer. The order of the extent of adsorption was: metribuzin < 2,4-D < bromacil < atrazine and the adsorption process was found to follow a first-order kinetic. The percent coverage at the carbon cloth surface was 0.026–0.66.
3	Baudu et al. 2004 (32)	Atrazine and diuron	Four types of activated carbon	Examination of the Ideal Adsorbed Solution Theory (IAST) for the prediction of competitive adsorption among the pesticides and various kinds of natural organic matter upon four types of activated carbon.
4	Yang et al. 2004 (28)	Diuron, bromoxynil and ametryne	Wheat residue derived black carbon (WC) and commercial activated carbon (AC)	Adsorption was studied at T = 25°C, time 24 h using HPLC analysis. The density of oxygen-containing functional groups on WC resulted in 30–50% pesticide adsorption decrease of that by AC, due to the blockage of WC surface by the water molecules

				associated with the functional groups. Generally, pH increase (2.2–6.6) led to adsorption decrease on WC due to deprotonation and development of repulsion electrostatic forces between the functional groups of pesticides and the adsorbent. The kinetics was studied
5	Gerard and Barthelemy 2003 (33)	Diuron, chloridazon, atrazine and MCPA	Granular activated carbon (GAC) (specific area 1100 m^2/g)	The adsorption capability of GAC (as filling material in column) for the removal of pesticides from drinking water was investigated. The adsorption efficiency of GAC, regarding to the type of pesticide was: MCPA< chloridazon and atrazine< diuron. It was observed that the weakly adsorbed pesticides of drinking water caused a decrease in lifetime of activated carbon bed.
6	Gerard et al. 2003 (34)	Diuron	Activated carbon	The combination of adsorption with ozonation for the industrial pretreatment of drinking water containing herbicides, such as diuron, was investigated. The use of 1.3 mg ozone/l caused significant alterations in the structure of humic and fulvic acids and increased the adsorption capability of the herbicide upon the activated carbon.
7	Kabsch-Korbutowicz and Majewska-Nowak 2003 (35)	Atrazine	Activated carbon	Coagulation followed by adsorption of the pesticide from its aqueous solutions on activated carbon bed, was studied. The coagulatives were alumina and ferrum. The effect of Natural Organic Matter (NOM) on the pesticide adsorption was evaluated. It was

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
				proved that coagulation, with or without the use of polyelectrolytes, was inappropriate method at removing the pesticide from its aqueous solutions.
8	Bacaoui et al. 2002 (20)	2,4-Dichlorophenoxy-acetic acid, 2,4-D and MCPA	Seven types of activated carbon	The performance of a series of seven activated carbons by steam-activation of olive-waste cakes was studied. These activated carbons showed higher adsorption capacity values than that of a commercial activated carbon used for drinking water treatment.
9	Banerjee and Kumar 2002 (36)	Acephate	Granular activated carbon (GAC)	The adsorption capability of GAC (as filling material in column) for the removal of the pesticide from pesticide industrial wastewaters was studied. The applied optimal quantity of carbon was 85 g/l at initial pesticide concentration of 2.9 mg/l and an almost 100% pesticide removal was achieved. The contact time of the static adsorption experiments was 80 min. The adsorption kinetics followed the Langmuir isotherm.
10	Baup et al. 2002 (37)	Atrazine, bromoxynil and diuron	Two types of granular and powdered activated carbon	The adsorption capability of granular and powdered activated carbon and the kinetics of adsorption experiments using Freundlich isotherms and the Homogeneous Surface Diffusion Model (HSDM), respectively was estimated. In the first experiment, it was observed that the crushing of granular to powdered activated carbon improved the accessibility of the free adsorbent sites. In the second experiment, the adsorption was carried out in granular

				carbon column and the possibility of pesticides adsorption, combined with the surface diffusion coefficients and the contact time between pesticide–adsorbent, was estimated.
11	Matsui et al. 2002 2002b (24)	Simazine and asulam	Granular activated carbon (GAC)	The adsorption capability of granular activated carbon (as filling material of microcolumn) for the removal of a polar (asulam) and non polar (simazine) herbicide was investigated. Experiments were carried out in three aqueous solutions containing Natural Organic Matter (NOM) with different molecular weight (MW) distributions. The low–MW molecules competed directly with strongly adsorbing pesticides, such as simazine, for adsorption sites. Asulam adsorbed weaker on the carbon and its direct competition for adsorption sites originated from both the strongly adsorbing, low–MW NOM and the more weakly adsorbing, higher-MW NOM.
12	Sakakibara et al. 2002 (38)	Isoprothiolane	Granular activated carbon (GAC)	The simultaneous removal of nitrates and the pesticide using hybridic biofilm reactor was examined. The reactor consisted of the outer cylindrical cathode where the denitrated biofilm was fitted and the inner anode compartment, which contained the granular activated carbon. Effective simultaneous removal of NO_3 and the pesticide was achieved in the anode. The experimental data were fitted to Langmuir isotherms and to simple models of adsorption kinetics.

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
				The theoretical model and the experimental values were in good agreement to each other.
13	Sotelo et al. 2002 (12)	Lindane and Alachlor, MPCB and TPCB	Granular activated carbon (GAC–F 400)	The application of activated carbon for the removal of four organochlorine compounds from water was studied. Static adsorption experiments were carried out and the kinetic parameters of adsorption isotherms were estimated. TPCB showed lowered capability of saturation and decreased capability of internal movement among the examined compounds. This phenomenon could be attributed to the chemisorption mechanism of TPCB–phenomenon that was reinforced by its very low solubility.
14	Martín-Gullón and Font 2001 (3)	Atrazine	Activated carbon fibers (three types) with surface area (m^2/g) 1061, 1570, 1665 and commercial activated carbon (one type) with surface area (m^2/g) 1062	The activated carbons were the filling material of microculmns in which the aqueous solutions of pesticides–originated from underground waters–passed through. The highly activated carbon fibers were seven times more effective comparing to the commercial carbon, while the latter was more effective than the average activated carbon fibers. This behaviour of high activated carbon was attributed to the porosity of the material and the acceptable distribution of small size mesopores, resulting in the selective adsorption of the micro-pollutants instead of Natural Organic Matter (NOM).

15	Pelekani and Snoeyink 2001 (39)	Atrazine	Four microporous phenolic resin-based activated carbon fibers (ACFs) with twilled–weave fabrics) and surface area (BET, m^2/g) 877, 1518, 1615, 1918 and mesoporous ACF with surface area (BET, m^2/g) 2999 m^2/g	The effect of different micropore size distribution of fibers on the mechanism of competitive adsorption, between the pesticide and Congo Red dye (a compound of higher size than atrazine) was investigated. The impact of increasing the size of the competing compound on the competitive adsorption mechanism in different size pores was evaluated by a series of batch kinetic and equilibrium experiments.
16	Baup et al. 2000 (17)	Atrazine, bromoxynil and diuron	Granular activated carbon (GAC–Chemviron F 400)	Experimental and theoretical estimation of the adsorption kinetics of pesticides on carbon were performed. The theoretical simulation achieved using the Homogeneous Surface Diffusion Model (HSDM), while the experimental calculation was achieved using a differential column batch reactor (DCBR). The calculated diffusion coefficient values (Ds) were higher compared to perfectly mixed contactors. Moreover, the computed Ds values were more accurate because of the better assessment of the external mass transfer coefficient (k_f) for fixed beds.
17	Gerard et al. 2000 (40)	Atrazine and MCPA	Granular activated carbon (GAC–Chemviron F 400)	The adsorption capability of granular activated carbon for the removal of pesticides from drinking water was estimated. The limiting factor of coexistence of humic and fulvic acids in the aqueous solution was

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
				investigated. The presence of acids was considered a competitive factor of the pesticides adsorption capability upon carbon. This impeding effect was increased primarily due to humic and secondly due to fulvic acids.
18	Pelekani and Snoeyink 2000 (41)	Atrazine	Four microporous phenolic resin-based activated carbon fibers(ACFs) with twilled–weave fabrics) and surface area (BET, m^2/g) 877, 1518, 1615, 1918 and mesoporous ACF with surface area (BET, m^2/g) 2999 m^2/g	The effectiveness of pore size distribution on the nature of adsorption competition mechanism between the pesticide and methylene blue (MB) dye (a compound of similar size to atrazine) was investigated. The role of pore size, pore size distribution, size of the target compound and size competing species were evaluated for a better understanding of adsorption mechanisms, useful for designing and selecting adsorbents for a particular application. Also, single atrazine adsorption results were given at initial low concentrations up to 100 $\mu g/l$ and higher concentration 8200 $\mu g/l$. Atrazine-MB adsorption was examined under simultaneous and MB or atrazine preloading conditions.
19	Campos et al. 2000 (42)	Atrazine	Powdered activated carbon (PAC)	The effectiveness of upflow floc blanket reactor (FBR) to remove the pesticide and other organic compounds—present in drinking water sources—was investigated. The experiments were carried out in laboratory-scale and the operating parameters were carbon dose of and hydraulic loading rate.
20	Campos et al. 1999 (2)			

21	Abu-El-Sha'r et al. 1999 (43)	Cypermethrin and malathion	Granular and powdered activated carbon (GAC and PAC)	The adsorption capability of granular and powdered carbon, derived from the process of olive oil production, at removing pesticides, bacteriums, viruses and metals such as Cr(III), Ni(II), Pb(II), Cd(II) and Zn(II), was investigated. The applied technology was simple and economical for industrial wastewater treatment.
22	Dessouki et al. 1999 (44)	Ametryn, applaud, aldrin and chlorothalonil	Granular activated carbon (GAC)	The effectiveness of a number of processes including GAC adsorption, γ radiation and N, O addition for the removal of pesticides from their aqueous solutions was studied. Radiation in combination with adsorption, resulted in effective removal of toxic pesticides and led to pesticide acceptable concentration in solution, according to international standards. The above method was proved more effective than the application of conventional techniques.
23	Frimmel et al. 1999 (7)	2-Aminonaphthalene-1-sulfonate, diuron and 1-naphthol	AC F-300 (1000 m^2/g)	The adsorbability of the pesticides and Natural Organic Matter (NOM) onto the organic polymeric resin and onto activated carbon was investigated by determining the relative isotherms. The breakthrough behaviour of the compounds in filter columns and in a laboratory plant was investigated.
24	Lebeau et al. 1999 (14)	Atrazine	Powdered activated carbon (PAC)	The effect of Natural Organic Matter (NOM) loading and calcium carbonate with regard to pesticide adsorption on PAC, was investigated. The samples were collected from Seine river. The adsorption

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
				capacity was measured by the classical method of Freundlich isotherm. Estimation of the optimal experimental conditions for the removal of specific pesticide concentration was made.
25	Pelekani and Snoeyink 1999 (45)	Atrazine	Microporous activated carbon fibers (ACFs) with narrow and broad pore size distributions. The porous structure of ACFs was phenolic resin-based (mean pore size was 6 and 13,4 Å)	The impact of pore size distribution on competition mechanisms between Natural Organic Matter (NOM) in natural waters and the micropollutant atrazine was assessed using activated carbon fibers (ACFs). The use of adsorbents with heterogeneous micropore size distributions can reduce the level of pore blockage by NOM (dominant competition mechanism when pores are large enough for micropollutants but not for NOM) and minimize its effect on trace compound adsorption. When the pores are large both for micropollutants and NOM, the competition mechanism becomes important.
26	van Leeuwen et al. 1999 (46)	Endosulfan 1 and 2, diazinon, malathion, atrazine, simazine and chlorpyrifos	Granular activated carbon (GAC)	The effectiveness of various processes such as ozonation, GAC adsorption, biofilter and chemical coagulation combined with microfiltration for the treatment of two starch industrial wastes with increased COD loading was examined. The use of biofilter, biological activated carbon and coagulation–followed by microfiltration–resulted in 99% approximately removal of the majority of pesticides.

				The main quantity of pesticides were separated during biological treatment process.
27	Xiao-yun and Ming 1999 (47)	Triazophos	Activated carbon	The effectiveness of powdered activated carbon treatment in an activated sludge system (PACT-AS) combined with the Rhodopseudomonas capsulatus material in batch flow reactor for the removal of the pesticide, was investigated. The kinetic modeling of the PACT-AS system is fundamental for toxic wastes treatment in industrial scale.
28	Ashley et al. 1998 (48)	Atrazine with its metabolites deethylatrazine and deisopropylatrazine	Granular and powdered activated carbon (GAC and PAC)	The experimental parameters of this work were the solution pH (7 and 9) and the adsorbent materials (GAC and PAC). Reversed Phase High Performance Liquid Chromatography (RP-HPLC) was used for the analysis of pesticides. Significant differences in the adsorption of the three pesticides under the examined experimental conditions were recorded. The experimental data were fitted to Freundlich model.
29	Ayele et al. 1998 (49)	Atrazine and diuron	Three types of granular activated carbon (GAC)	Three types of GAC were compared for the removal of two pesticides. The experimental data were fitted to kinetic isotherm models of adsorption. Best adsorbent material was proved carbon F-400. The experimental data were fitted to Langmuir model. The use of the other models indicated that the pesticide adsorption was an exothermic phenomenon.

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
30	Gerard et al. 1998 (50)	Bentazon, chloridazon, lenacil and diuron	Granular and powdered activated carbon (GAC and PAC)	Batch and continuous adsorption experiments were carried out for the estimation of Freundlich parameters from pesticides solutions. Ultrapure water or water samples from Meuse river were used. The competitive function of organic matter particles was estimated. GAC was used in batch while PAC was used in continuous adsorption experiments.
31	Hllgardt et al. 1998 (51)	Atrazine	Activated carbon (Chemviron F-400)	The adsorption capability of carbon and Ni for the pesticide removal was investigated. Carbon was characterized with spectroscopic and microporous analyses. Pesticides removal up to 99.8% was achieved.
32	Horner et al. 1998 (52)	Atrazine	Activated carbon (Chemviron F-400)	Comparative evaluation of the adsorption capability of activated carbon and three types of carbonaceous polymeric resins for pesticide removal was made. Carbon regeneration using methanol and ethanol solvents in-situ techniques was examined.
33	Hu et al. 1998 (25)	MCPB, imazalil, bentazone, MCPP, dinoseb, PCP, imidacloprid and linuron	Powdered activated carbon (PAC)	The adsorptive characteristics of ionogenic pesticides on PAC were described. The effects of pH on the adsorbabilities of acidic and basic pesticides on PAC were evaluated by correlating 1-octanol-water partition coefficients (log Pow) with the Freundlich adsorption constant (log k) over a pH range of 3–9. The aim of this study was the development of a

				simplified method for determining PAC dosage in drinking water treatment.
34	Kouras et al. 1998 (5)	Lindane	Powdered activated carbon (PAC)	The adsorption of the insecticide on PAC from aqueous solutions with and without the simultaneous presence of coagulants, was studied. Ferric chloride and basic polyaluminium chlorosulfate were examined as coagulants with the addition, in certain cases, of polyacrylamide. The effect of solution pH, position of coagulant addition, as well as, type of coagulant and carbon concentration on PAC adsorption efficiency was investigated. Solution pH did not highly affect PAC effectiveness, while coagulant dosages were found to reduce the adsorption capability of PAC. Therefore, it was necessary to double PAC concentration for the removal of the pesticide in equivalent level without the use of coagulants.
35	Paune et al. 1998 (53)	Terbuthylazine and molinate	Commercial granular activated carbon (GAC) in columns	A screening study was carried out using aqueous samples from Llobregat river (Barcelona–Spain), in order to establish an improved treatment for the removal of pesticides and other organic pollutants. The organic compounds removed effectively by using GAC, were estimating. The analysis was conducted with Gas Chromatography/Mass Spectrometry (GC/MS).

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
36	Gicquel et al. 1997 (54)	Atrazine	Four types of powdered activated carbon (PAC)	The coexistence of organic matter, trace metals and pesticides in drinking water treatment industry was examined for the removal of the pesticide by adsorption upon PAC. Five types of natural waters (which were pretreated using a variety of methods) were examined. The actions of pesticide and Natural Organic Matter were competitive to each other in the adsorption process. The complexity of the developed mechanisms was determined by the synergistic effect of the following factors: the carbon nature, the presence of organic matter and metal elements as well as the initial quantity of the pesticide.
37	Hu et al. 1997 (55)	Hymexazol, methomyl, imidacloprid, thiophanatemethyl, carbaryl, linuron and thiobencarb	Powdered activated carbon (PAC)	The adsorption coefficient was compared with the coefficients of octanol-water (logPow) in a binary system. The Freundlich model was applied for the determination of adsorption parameters. The analysis by using Reversed Phase High Performance Liquid Chromatography (RP-HPLC) was carried out. The highly polar pesticides (low logPow values) could not be removed easily by using GAC adsorption.
38	Hussein et al. 1997 (56)	Cyanox, actellic, danitol and cyfluthrin	Powdered activated carbon (PAC)	Adsorption of simple pesticides solutions from their mixtures on GAC adsorbent was investigated. The experimental data were fitted to the Freundlich model. For the analysis Gas Chromatography with Electron Capture Detector (GC-ECD) was used. The

				chemical pesticide structure and their solubility on adsorption performance, was examined.
39	Lambert et al. 1997 (57)	Pentachlorophenol and propetamphos	Activated carbon	Activated carbon and three inorganic adsorbed materials (active bauxite, diatom earth and synthetic clay) were evaluated for the removal of selected industrial pollutants in fabric industries (such as the examined pesticides). Activated carbon was proved more effective in comparison with the three inorganic adsorbents. The latter were almost ineffective for pesticides separation.
40	Orlandini et al. 1997 (58)	Atrazine	Granular activated carbon (GAC)	Pesticide adsorption in the presence of Basic Organic Matter (BOM) upon GAC was examined. The experiments were carried out in small fixed bed. The presence of BOM reduced the external and internal mass transfer coefficient of the pesticide upon the carbon surface. When ozonation was applied prior to adsorption, a reduction of the adsorbed quantity was observed.
41	Thacker et al. 1997 (59)	γ-HCH, p, p'-DDT and p, p'-DDE	Granular activated carbon (GAC)	GAC adsorption capacity for pesticides removal was estimated. The experiments were carried out in continuous stirring and fixed bed reactors. According to the outcoming results, a drinking water treatment unit was developed for domestic purposes.

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
42	Yang et al. 1997 (9)	Phenoxy acids (MCPA, MCPP, MCPB)	Granular activated carbon (GAC–Filtrasorb 400) with particle size 0.85–1.2 mm and apparent density 0.48 g/cm^3)	A thermal detection technique, which is based on monitoring the effects of partial desorption of adsorbed material, was used after the pesticides adsorption on a carbon packed column. The adsorption results showed that this approach allowed effective prediction adsorption of single or multiple-sensor arrays, using a modified neural network for signal interpretation. GAC was proved effective for all the examined pesticides adsorption.
43	Adams and Watson 1996 (60)	Metabolites of s-triazines deethylatrazine, deethylsimazine and deethylcyanazine	Powdered activated carbon (PAC–bituminous coal carbon)	The adsorption of atrazine, simazine and cyanazine metabolites upon PAC was effective but lower than that of atrazine, resulting in higher estimated carbon costs. The Langmuir and Freundlich adsorption isotherms were estimated.
44	Bernazeau et al. 1996 (61)	Atrazine	Activated carbon	The effect of coexistence of the pesticide and Dissolved Organic Carbon (DOC) on the competitive adsorption on activated carbon was studied. The kinetics and adsorption isotherms parameters were incorporated in a prediction model of DOC adsorption.
45	Hopman et al. 1996 (62)	Pesticides	Activated carbon fibers (ACFs)	ACFs were used as an alternative to GAC adsorbent for pesticide removal. Adsorption capacity of ACFs was much higher than that of GAC (for diuron it varies between a factor 3 to 8). However, the costs of ACFs were relatively high compared to GAC and the possibilities of reactivation of ACFs were not clear.

				The effect of polarity of pesticides and the presence of Natural Organic Matter (NOM) on adsorption was studied. Pilot-plant research to confirm laboratory results was scheduled.
46	Knappe et al. 1996 (63)	Atrazine	Granular activated carbon (GAC)	The adsorption capability of the GAC filter for the pesticide removal was estimated. An exponential decrease of adsorption capability with loading time was observed. Furthermore, the powdered form of GAC was used in column for the treatment of Seine river water samples. For the evaluation of the column performance, the Homogeneous Surface Diffusion Model (HSDM) was applied based on adsorption isotherms.
47	Orlandini et al. 1996 (64)	Atrazine	Activated carbon	The Ideal Adsorbed Solution Theory (IAST) for the competitive adsorption prediction between the pesticide and the Basic Organic Matter (BOM) upon activated carbon was investigated. Ozonation resulted in reduction of BOM adsorption and increase (approximately double) of pesticide adsorption. In the contrary, the continuous ozone treatment did not affect the total equilibrium pesticide concentration.
48	Snoeyink and Knappe 1996 (65)	Atrazine	Powdered activated carbon (PAC)	The Equivalent Background Compound (EBC) model was applied for the competitive adsorption prediction between the pesticide and organic matter. Static adsorption experiments were carried out and the parameters of adsorption kinetics were calculated. As

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
				optimization factors were selected the adsorption time and the required quantity of carbon for a defined pesticide removal.
49	Hopman et al. 1995 (66)	Pesticides	Activated carbon fibers (ACFs)	The use of ACFs as an alternative adsorbent for pesticide removal from water was studied. The adsorption capacity of ACF for diuron removal was higher by a factor of 10 to 20 than the adsorption capacity of GAC. Natural Organic Matter (NOM) preloading did only slightly decrease the ACFs life. However, the costs of ACFs were relatively high as compared to GAC and the possibilities of reactivation of ACF were not clear.
50	Knappe et al. 1995 (67)	Atrazine	Granular activated carbon (GAC)	GAC in microcolumns was applied for pesticide removal from spring waters or from byproducts of water treatment. The lifetime of carbon columns was estimated for effective pesticide removal.
51	Kouras et al. 1995 (27)	Dodine	Powdered activated carbon (PAC)	Fungicide removal by the simultaneous action of PAC, coagulants and polyelectrolytes was investigated. The efficiency of fungicide removal was estimated with respect to the type and dose of coagulant and polyelectrolyte, the PAC amount and pH value. The investigation included the determination of optimal conditions for fungicide removal.

52	Ronday et al. 1995 (68)	Bitertanol, chloridazon, dimethoate, mcpa, mcpp, nitrothalisopropyl, propoxur, thiofanate-methyl and thiram	Activated carbon	The Carbo-Flo process effectiveness was studied. This process included flocculation, filtration through a sand/gravel filter and adsorption on activated carbon of wastewater contaminated with agricultural pesticides. The analysis by using High Performance Liquid Chromatography (HPLC) was carried out. Chemical and toxicological analyses showed that a high degree of purification was possible (more than 99.56% for pesticides tested).
53	Hopman et al. 1994 (69)	Polar and non-polar pesticides	Granular activated carbon (GAC)	The effectiveness of filters, with filling material GAC, for pesticides removal from drinking water was estimated. The coexistence of Natural Organic Matter (NOM) and polar or non polar pesticides was investigated and the adsorption kinetics using GAC was studied. Pretreatment of carbon with NaOH solution resulted in adsorption increase up to 50%. Furthermore, filtration of aqueous stream on membrane, prior to adsorption on carbon, resulted in fortifying the carbon lifetime for atrazine removal. Additionally, the increase of the microcolumn length increased the carbon lifetime for simazine by a factor of 10.
54	Edell et al. 1993 (70)	Atrazine, cyanazine, dichlorprop, MCPA, mecoprop and bentazone	Activated carbon	The effect of coexistence of pesticides and Dissolved Organic Matter (DOC) on their separation by using Solid Phase Extraction (SPE) was estimated. High Performance Liquid Chromatography (HPLC) was

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
				applied for the analysis. The outcoming results of coagulation (using aluminium), filtration on activated carbon and ozonation on full scale were compared and evaluated. The competitive action between DOC, atrazine and MCPA based on adsorption isotherms was studied.
55	Haist-Gulde et al. 1993 (71)	Pesticides on drinking water treatment unit	Granular and powdered activated carbon (GAC and PAC)	A variety of physico-chemical methods for pesticides removal present in drinking water was evaluated. Ozonation resulted in initial pesticide reduction up to 50% by altering ozone dosage, reaction time and molecular structure of pesticides. GAC and PAC adsorption were proved the most efficient processes in comparison with the rest applied methods. The initial pesticide and Natural Organic Matter (NOM) concentrations were the selected factors in the above study.
56	Najm et al. 1993 (26)	TCP	Powdered activated carbon (PAC)	The PAC effectiveness to upflow floc blanket reactors for the adsorption of natural and synthetic organic chemicals was evaluated. The adsorption isotherms were estimated and the results were compared under laboratory and field conditions.
57	Donati et al. 1992 (72)	Atrazine, aldrin, lindane and bromophosethyl	Carbon black (soot)	The adsorption capability of carbon black and calcinated sludge for the removal of pesticides and the metals Ni^{2+}, Pb^{2+}, NO^{3-}, HPO_4^{2-} from their aqueous

				solutions, was estimated. Both materials showed similar adsorption behavior.
58	Hall et al. 1992 (73)	Atrazine, alachlor and permethrin	Carbon fibers	The Carbo-Flo process effectiveness was studied. This process included flocculation, filtration through a sand/gravel filter and adsorption on activated carbon of wastewater contaminated with agricultural pesticides. Filtration through a type of grit gravel and two types of fined grained carbon was applied. Analysis was carried out by using Gas Chromatography. Higher than 99.9% removal of pesticides was achieved. The treated aqueous stream was reused or disposed, the solid phase could be incinerated and the carbon could be regenerated. The highest performance of the process was achieved with sufficient dilution of the initial wastewater.
59	Davis 1991 (74)	Ethylene dibromide (EDB)	Granular activated carbon (GAC)	The adsorption effectiveness of GAC for pesticide removal from their aqueous solution was studied. The effect of variation in the concentration of Natural Organic Matter (NOM) in pesticides solutions on the competitive adsorption yield, was investigated. Static and dynamic Freundlich adsorption isotherms were derived. GAC treatment was proved the best available technology in natural systems for the control of toxic chemical compounds, including in ground and drinking waters.

(*continued*)

Table 1. Continued

Ref. item #	Reference	Pesticide	C Adsorbent	Aim–experimental–results
60	Lafrance et al. 1991 (75)	aldicarb, lindane and pentachlorophenol	Activated carbon	The competitive adsorption of pesticides and dissolved humic and fulvic acids on activated carbon was studied. Experiments were carried out in binary systems. The apparent interactions and the sorption kinetics of the above compounds were affected by their water solubility and the aromatic nature of their molecules. Improvement of simultaneous adsorption of humic and fulvic compounds and the pesticides on activated carbon can be achieved when the appropriate interactions among the adsorbed compounds can be developed.
61	Longley et al. 1991 (76)	1,2-dibromo-3-chloropropane (DBCP), ethylene dibromide (EDB) and 1,2-dichloropropane	Granular activated carbon (GAC)	Static and dynamic adsorption experiments were carried out for the estimation of GAC capacity for pesticides removal. The relevant Freundlich adsorption isotherms were calculated. Field tests under mild environmental conditions and strong fluctuations of the quality of natural waters were performed. Static adsorption experiments were proved more simple and economical. Competitive adsorption between carbon and bacteria associated metabolic products probably could occur.

62	Pirbazari et al. 1991 (77)	Alachlor and heptachlor	Granular activated carbon (GAC)	The GAC capacity for the pesticides and their metabolites removal in environmental and economical terms was studied. Homogeneous Surface Diffusion Model (HSDM) was applied for the prediction of the dynamic behaviour of carbon in fixed-bed microcolumns. The presence of humic acids resulted in significant decrease of the pesticides adsorption. The capital cost of heptachlor metabolite removal was 30% higher than that of alachlor.
63	Speth and Miltner 1990 (78)	Insecticides	Granular activated carbon (GAC)	Adsorption isotherms of 58 organic compounds, which were dissolved in distilled water, filtrated river water and filtrated ground water, were constructed. The examined compounds included volatile compounds and insecticides. These compounds had already been or planned to be accepted for legislative approval by USEPA.

(static or continuous operation, laboratory, pilot or industrial scale), aim and results of each work, are reported for the period 1990–2004. In Table 2, specific data on adsorbent capacity in single pesticides adsorption and competitive adsorption, effect of various factors on adsorption effectiveness, isotherm parameters (Langmuir, Freundlich, Dubinin–Radushkevich), kinetic model parameters (HSDM, EBC, Peel etc) including surface diffusion coefficients, mass transfer coefficients are included.

ADSORPTION ON POLYMERIC MATERIALS

The use of synthetic adsorbent polymers, particularly in drinking water treatment, has been investigated by several authors. During the last few years, attempts have been made to improve these adsorption polymers, which originally were developed on the basis of ion-exchange resins, possessing a specific surface of $200-800\ m^2/g$. The development in polymer science technology allowed the production of highly porous polymers of $800-1500\ m^2/g$, which is similar to the surface of activated carbon. An example is a styrene-divinyl benzene copolymer, Lewatit EP 63, which has been used for the eliminitation of substances with molecular weight less than $200\ g/mol$ and of chlorinated hydrocarbons. In addition, the above copolymer has been applied in water analysis for the selective enrichment of organic trace pollutants. Polymeric materials are characterized with lower energy demands and, consequently, lower costs for regeneration or renewal of the adsorbents in comparison with carbonaceous materials (7).

A category of polymeric resins, which have been widely investigated for the removal of organic compounds, pharmaceuticals and pesticides from aqueous solutions, is amberlite adsorbents. These resins are either styrene-divinyl benzene copolymers or polymers of acrylic esters (such as XAD-2, XAD-4 and XAD-7 resins). Polymers (synthetic or natural) (29), have become popular and been used more and more frequently in HPLC practice for the separation and quantitative determination of commercial pesticides (30).

The research studies on polymeric adsorbents related to pesticide removal and analysis for the period 1990–2004, are concentrated in Table 3. So, the research activities have been compiled and the relative data concerning the: type of activated carbon, type of pesticide, experimental conditions (static or continuous operation, laboratory, pilot or industrial scale), aim and results of each work, are reported. In Table 4, specific data on adsorbent capacity in single pesticides adsorption and competitive adsorption, effect of various factors on adsorption effectiveness, isotherm parameters (Langmuir, Freundlich) are included. The chemical structure and useage of pesticides examined on all carbonaceous and polymeric materials are presented in Table 5.

Table 2. Carbon capacities, equilibrium and kinetic parameters in adsorption of pesticides on carbonaceous materials

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Acephate	GAC (325 mesh)	2.9 mg/l	43.0 mg/g	L p $v_m = 32.6$ mg/g b = 0.049 l/mg		(9)
Actellic	PAC (325 mesh)	10 mg/l	142–327 mg/g	F p $(mg/g)(l/\mu g)^{1/n}$ K = 0.106, 1/n = 0.679		(38)
Alachlor	GAC (1070 m^2/g)	240 mg/l	317–409 mg/g		Peel model p $k_L \times 10^3$ (cms^{-1}) = 5.1–6.1 f = 0.18–0.45 Dp $\times 10^4$ (cm^2s^{-1}) = 2.04	(13)
Alachlor	Carbon fibers	795 mg/l	Removal >99.9%			(58)
Alachlor	GAC (Filtrasorb 400, Calgon Corporation) 100/230 mesh	863 μg/l	100 mg/g	F p, K = 41.27 $(\mu g/mg)(l/\mu g)^{1/n}$ 1/n = 0.15	HSDM p D $\times 10^{11}$ (cm^2s^{-1}) = 6.80 $k_f \times 10^3$ (cms^{-1}) = 8.40	(62)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Alachlor–humic acid	GAC (Filtrasorb 400, Calgon Co.) 100/230 mesh	850 μg/l 5 mg as TOC/l	70 mg/g	F p, K = 28.50 $(\mu g/mg)(l/\mu g)^{1/n}$ 1/n = 0.13	HSDM p D × 10^{11} (cm^2s^{-1}) = 2.30 $k_f \times 10^3$ (cms^{-1}) = 7.00	(62)
Alachlor	GAC 50 × 200 mesh		230–430 mg/g	F p K = 81.7 $(\mu g/g)(l/\mu g)^{1/n}$ 1/n = 0.257		(63)
Alachlor–NOM	GAC 50 × 200 mesh	TOC 2.0–2.6 mg/l		F p, K = 10.8–61.6 $(\mu g/g)(l/\mu g)^{1/n}$ 1/n = 0.331–0.376		(63)
Aldicarb	PAC (Darco G-60, Aldrich) 0–15 mm	23.75–237.50 μg/l	150 nmol/g			(60)
Aldicarb–humic acid	PAC (Darco G-60, Aldrich) 0–15 mm	23.75–237.50 μg/l 25 mg/l	135 nmol/g			(60)
Aldicarb	GAC 50 × 200 mesh			F p, K = 8.27 $(\mu g/g)(l/\mu g)^{1/n}$ 1/n = 0.402		(63)

Aldicarb–NOM	GAC 50 × 200 mesh	TOC 2.0 mg/l		F p, K = 4.16 $(\mu g/g)(l/\mu g)^{1/n}$ 1/n = 0.414	(63)
Aldrin	GAC (BACM) (1100 m^2/g)	3–7 mg/l	14 mg/g		(22)
Aldrin	Active carbon (F 100) Clay carbon GAC (burned clay and carbon black) (1–10 mm) (61 m^2/g)	100 ppb	Removal 86% 91%		(57)
Ametryne	AC (776 m^2/g)	42.8 mg/l	0.18 mg/m^2 (pH 2.24) 0.25 mg/m^2 (pH 3.94) 0.27 mg/m^2 (pH 6.07)		(4)
Ametryne	WC (310 m^2/g)	42.8 mg/l	0.093 mg/m^2 (pH 2.42) 0.12 mg/m^2 (pH 4.05) 0.092 mg/m^2 (pH 5.96)		(4)
Ametryne	GAC (BACM) (1100 m^2/g)	3–7 mg/l	12 mg/g		(22)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Applaud	GAC (BACM) (1100 m^2/g)	3–7 mg/l	24 mg/g			(22)
Asulam	GAC (22–26 μm)					(11)
Atrazine	Carbon cloth (2500 m^2/g)	4.69×10^{-5} mol/l	1.98 mol/m^2 C-cloth		First-order rate constant $k = 0.024$ min^{-1}	(2)
Atrazine	PAC A (coal) (1200 m^2/g, 0.68 mm)	250 μg/l	79,000 μg/g	F p, K(μg/g)(l/μg)$^{1/n}$ K = 40420 1/n = 0.27		(3)
	PAC B (coal) (983 m^2/g, 0.75 mm)			K = 30570 1/n = 0.25		
	PAC C (wood) (770 m^2/g, 1.21 mm)		85,000 μg/g	K = 45206 1/n = 0.24		
	PAC D (coconuts shell) (1153 m^2/g, 0.87 mm)		79,433 μg/g	K = 42550 1/n = 0.21		

Atrazine–NOM	PAC A (coal) ($1200\ m^2/g$, 0.68 mm)	250 μg/l	30,000 μg/g	F p, $K(\mu g/g)(l/\mu g)^{1/n}$ $K = 12624$ $1/n = 0.32$		(3)
	PAC B (coal) ($983\ m^2/g$, 0.75 mm)		30,000–60,000 μg/g	$K = 12223$ $1/n = 0.35$		
	PAC C (wood) ($770\ m^2/g$, 1.21 mm)		200,000 μg/g	$K = 17322$ $1/n = 0.29$		
	PAC D (coconuts shell) ($1153\ m^2/g$, 0.87 mm)			$K = 20356$ $1/n = 0.26$		
Atrazine	AC ($1100\ m^2/g$)	500 μg/l	42.7 mg/g			(5)
Atrazine–humic acid	GAC (Filtrasorb 300–Chemviron Carbon) ($1000\ m^2/g$)	0.1–1.0 mg/l 10–50 mg/l	Pesticide removal 20–100%			(7)
Atrazine	GAC A ($1200\ m^2/g$) 9.2 Å	500 μg/l	750 μmol/g	F p, $K(\mu mol/g)(l/\mu mol)^{1/n}$ $K = 610$, $n = 3.38$	Differential column batch reactor (DCBR) $k\ (cms^{-1}) = 2.75 \times 10^{-2}\ D \times 10^{10}$ $(cm^2s^{-1}) = 5.0$	(10)
	GAC B ($1153\ m^2/g$) 6.6 Å	500 μg/l		$K = 720$, $n = 3.60$	$D \times 10^{10}$ $(cm^2s^{-1}) = 0.32$	

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Atrazine	ACF commercial pitch–based CF(Donacarbo)	2.5 μg/l	Very poor Very poor			(14)
	ACF-48 (1061 m^2/g)		0.7 mg/g			
	ACF-58 (1570 m^2/g)		0.1 mg/g			
	ACF-68 (1665 m^2/g)					
	Commerc. GAC (1062 m^2/g)					
Atrazine–NOM	ACF-68 (1665 m^2/g)	Atrazine 2.5 μg/l	0.2 mg/g			(14)
	Commerc. GAC (1062 m^2/g)	NOM 1.5 mg/l	Very poor			
Atrazine	ACF Phenolic resin–based (Nippon Kynol, Japan)	Atrazine 100 μg/l				(15)
	ACF-10 (877 m^2/g)		2.76 mg/g			
	ACF-15 (1518 m^2/g)		2.13 mg/g			
	ACF-20 (1615 m^2/g)		2.43 mg/g			
	ACF-25 (1918 m^2/g)		3.09 mg/g			
	MESO (2999 m^2/g)		1.47 mg/g			

Atrazine–congo red (CR)	ACF Phenolic resin–based (Nippon Kynol, Japan)	Atrazine				(15)
	ACF-10 (877 m^2/g)	50 μg/l	0.15 mg/g			
	ACF-15 (1518 m^2/g)	CR	1.00 mg/g			
	ACF-25 (1918 m^2/g)	5.2 mg/l	2.00 mg/g			
	MESO (2999 m^2/g)		1.00 mg/g			
Atrazine	GAC (Filtrasorb 400–Chemviron Carbon) (1.00–1.25 mm)	259.0–498.8 μg/l	147.3 mg/g	F p, K(μmol/g) $(l/\mu mol)^{1/n}$ $K = 607.2$ $n = 3.38$	HSDM p, Ds × 10^{10} $(cm^2s^{-1}) = 5.0$ $k_f \times 10^2$ (cms^{-1}) $= 2.75$	(16)
Atrazine	PAC (Filtrasorb 400–Chemviron Carbon) (1100 m^2/g)	400 μg/l, water mineral reconstituted	60 mg/g	F p, K(mg/g)$(l/mg)^{1/n}$ $K = 49$ $1/n = 1.07$		(17)
Atrazine–humic acids	PAC (Filtrasorb 400–Chemviron Carbon) (1100 m^2/g)	400 μg/l 0.09–0.55 μg/l water mineral reconstituted	40–60 mg/g	F p, K(mg/g)$(l/mg)^{1/n}$ $K = 7.76–19.9$ $1/n = 0.87–1.03$		(17)
Atrazine–eulvic acids	PAC (Filtrasorb 400–Chemviron Carbon) (1100 m^2/g)	400 μg/l 0.34 mg/l, water mineral reconstituted	60 mg/g	F p, K(mg/g)$(l/mg)^{1/n}$ $K = 22.9$ $1/n = 0.91$		(17)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Atrazine	ACF, Phenolic resin–based (Nippon Kynol)	Atrazine 100 μg/l				(18, 25)
	ACF-10 (877 m^2/g)		2.76 mg/g			
	ACF-15 (1518 m^2/g)		2.13 mg/g			
	ACF-20 (1615 m^2/g)		2.43 mg/g			
	ACF-25 (1918 m^2/g)		3.09 mg/g			
	MESO (2999 m^2/g)		1.47 mg/g			
Atrazine–methylene blue (MB)	ACF, Phenolic resin–based (Nippon Kynol)	Atrazine 50 μg/l MB				(18)
	ACF-10 (877 m^2/g)	2.3 mg/l	0.15 mg/g			
	ACF-15 (1518 m^2/g)		1.00 mg/g			
	ACF-20 (1615 m^2/g)		1.50 mg/g			
	ACF-25 (1918 m^2/g)		1.00 mg/g			
	MESO (2999 m^2/g)		1.00 mg/g			
Atrazine	PAC (Calgon Co) (10 μm)	Atrazine 515.8 μg/l	4 mg/g	F p, K (mmol/g) $(l/mmol)^{1/n}$ K = 238.2, 1/n = 0.44	D × 10^{11} (cm^2min^{-1}) = 2.0	(19)
Atrazine–NOM	PAC (Calgon Co) (10 μm)	Atrazine 40.3 μg/l groundwater DOC 2.1 mg/l	5 mg/g		D × 10^{11} (cm^2min^{-1}) = 0.7	(19)

Atrazine–NOM	PAC (Filtrasorb 400–Chemviron Carbon) (1100 m^2/g)	2.0 μg/l DOC 2.1 mg/l	0.21–0.38 mg/g 10 mg/g			(20)
Atrazine	PAC (PICA) (14 μm, 1630 m^2/g)	0.1–10 μg/l (deionized water)	3.3–16.5 mg/g	F p, K(mgl/g)(l/μg)$^{1/n}$ K = 7.4, 1/n = 0.35		(24)
Atrazine–NOM	PAC (PICA) (14 μm) 1630 m^2/g	Atrazine 2–5 μg/l NOM 0.94 μg/l	0.16–0.3 mg/g	IAST p, K = 1.06 (mmol/g)(l/mmol)$^{1/n}$ 1/n = 0.94	HSDM p, D × 10^{15} (m^2s^{-1}) = 1.33 $k_f \times 10^{10}$ (ms^{-1}) > 1.6	(24)
Atrazine–NOM	ACF, Phenolic resin–based (Nippon Kynol)	46–305 μg/l				(25)
	ACF-10 (885 m^2/g)		0.3–0.9 mg/g			
	ACF-25 (2312 m^2/g)		0.5 mg/g			
Atrazine and its metabolites	GAC (F 400, Calgon)			Freundlich parameters (μg/g)(l/μg)$^{1/n}$	38,000	(28)
			75 mg/g	K = 38,000, 1/n =0.22 (pH 7) K = 193,000, 1/n = 0.57 (pH 9)		
Deethylatrazine			60 mg/g	K = 15,500, 1/n =0.26 (pH 7) K = 15,400, 1/n =0.29 (pH 9)		

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Deisopropyla-trazine			50 mg/g	K = 5040, 1/n =0.80 (pH 7) K = 7550, 1/n = 0.60 (pH 9)		
Atrazine and its metabolite deethylatrazine	PAC (WPL, Calgon)		45 mg/g (deethylatrazine)	F p, K(μg/g)(l/μg)$^{1/n}$ K = 15,400, 1/n =0.59 (pH 7) K = 18,100, 1/n =0.18 (pH 7) K2 = 16,700, 1/n = 0.25 (pH 9)		(28)
Deisopropyla-trazine				K = 7750, 1/n =0.48 (pH 7) K = 8390, 1/n =0.42 (pH 9)		
Atrazine	PAC	50 μmol/l	Max pesticide removal (%)	Fp, Kmmol/g) (l/mmol)$^{1/n}$	Adams and Bohart model *ka* (l/min/mmol)	(29)

	(F-400, Chemviron Carbon) ($1490\ m^2/g$)		90 (1.2 mmol/g)	K = 1.2, n = 4.0	*ka* = 19.4	
	Picazine (Pica) ($1235\ m^2/g$)		65 (1.1 mmol/g)	K = 0.6, n = 3.8	*ka* = 11.9	
	Acticarbone (Ceca) ($915\ m^2/g$)		48–55 (0.7 mmol/g)	K = 0.6, n = 10.5	*ka* = 2.3–3.2	
Atrazine	GAC (Filtrasorb 400, Chemviron Carbon) ($1100\ m^2/g$)		Removal 99.8%			(31)
Atrazine	Activated carbon (F 400, Chemviron Carbon) ($950\ m^2/g$)	1–10 mg/l	230 mg/g	F p, K $(mg/g)(l/mg)^{1/n}$ K = 208.8 1/n = 0.209		(32)
Atrazine	PAC A (wood) ($1235\ m^2/g$, 0.6 mm)	5–250 μg/l	60,000 μg/g	Fp, K $(\mu g/g)(l/\mu g)^{1/n}$ K = 5668, 1/n = 0.41		(36)
	PAC B ($1430\ m^2/g$, 0.7 mm)		130,000 μg/g	K = 20,925, 1/n = 0.30		
	PAC C ($1490\ m^2/g$, 0.6 mm)		60,000 μg/g	K = 29,261, 1/n = 0.13		
	PAC D ($1400\ m^2/g$, 1.0 mm)		150,000 μg/g	K = 110,60,1/n = 0.43		

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Atrazine–NOM	PAC A (wood) (1235 m^2/g, 0.6 mm)	5–250 μg/l	20,000–36,000 μg/g	F p, K(μg/g)(l/μg)$^{1/n}$ K = 3713–6063 1/n = 0.33–0.43		(36)
	PAC B (1430 m^2/g, 0.7 mm)		27,000–49,000 μg/g	K = 9565–16336 1/n = 0.21–0.38		
	PAC C (1490 m^2/g, 0.6 mm)		25,000–45,000 μg/g	K = 8651–19099 1/n = 0.18–0.37		
	PAC D (1400 m^2/g, 1.0 mm)		29,000–55,000 μg/g	K = 6630–12970 1/n = 0.25–0.46		
Atrazine	GAC (NORIT ROW 0.8 S) (<75 μm)	4.37 μg/l	Virgin GAC 7 mg/g	F p, K (mg/g)(l/μg)$^{1/n}$ K = 7.14, n = 0.18	HSDM p Ds × 10^{13} (cm^2s^{-1}) = 9.6 $k_f \times 10^4$ (cms^{-1}) = 15.0	(40)
		2.70 μg/l	GAC + ozonation 5–6 mg/g	K = 4.34–4.84 n = 0.25–0.36	Ds × 10^{13} (cm^2s^{-1}) = 6.6–9.1 $k_f \times 10^4$ (cms^{-1}) = 8.8–10.0	

Atrazine	PAC (Calgon water powdered low Activity)	50 μg/l	20–70 mg/g (pH 6.0–8.0)	L p v_m = 90.5 –43.9 mg/g b = 226–103 l/mg F p, K(mg/g)(l/mg)$^{1/n}$ K = 467–278 1/n = 0.44–0.56	(43)
Atrazine metabolites deethylatrazine	PAC (Calgon water powdered low activity)	50 μg/l	22 mg/g (pH 6.0)	L p v_m = 44.6 mg/g b = 122 l/mg F p, K(mg/g)(l/mg)$^{1/n}$ K = 163 1/n = 0.43	(43)
Deisopropylatrazine			20 mg/g (pH 6.0)	L p v_m = 54 mg/g, b = 75 l/mg F p, K (mg/g) (l/mg)$^{1/n}$ K = 462 1/n = 0.65	
Atrazine–NOM (natural water)	GAC, F-400	1.5–2.0 μg/l DOC	0.2– 0.6 mg/g		(44)
	CECA TE	1–8 mg/l	0–0.25 mg/g		
Atrazine–NOM	ACF (1400–2500 m^2/g)	2 μg/l	75.6–150.6 mg/g	Freundlich parameters (mg/g)(l/μg)$^{1/n}$ K = 75.6–105.6 n = 0.416–0.516	(45)
		DOC 1.5 mgC/l	29.7 mg/g	K = 29.7, n = 0.5	
	GAC (1000 m^2/g)				

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Atrazine	GAC (PICA B) (52 μm)	5 mg/l	40 mg/g	Fp, K(mg/g)(l/μg)$^{1/n}$ K = 5.02, 1/n = 0.543		(46)
Atrazine–NOM	GAC (PICA B) (52 μm)	34 μg/l	3–4 mg/g	F p, K (mg/g)(l/μg)$^{1/n}$	HSDM p Ds × 10^{11} (cm^2s^{-1}) = 5.39–6.78	(46)
		172 μg/l	10–13 mg/g	K = 0.665–0.898 1/n = 0.582–0.587	$k_f \times 10^4$ (cms^{-1}) = 5.68–7.39	
Atrazine–NOM	PAC (NORIT ROW 0.8 S) (75 μm)	3–300 μg/l DOC 2.1 mg/l	No ozonation 2–68 mg/g	Fp, K (mg/g)(l/μg)$^{1/n}$		(47)
			Raw water–no ozone 0.13–2.70 mg/g	K = 7, n = 0.5 K = 39.5, n = 0.46		
			Raw water–ozone (4.8 mg O_3/l) 0.13–5.00 mg/g	K = 0.05, n = 1.35		
Atrazine	PAC (Hydrodarco B, Norit)	86,212 μg/l	43 mg/g			(48)
Atrazine–NOM	PAC (Hydrodarco B, Norit)	26–212 μg/l TOC 4.2 mg/l	14–30 mg/g		HSDM p, Ds × 10^{11} (cm^2min^{-1}) = 3.59 $k_f \times 10^9$ ($cmmin^{-1}$) = 4.04	(48)

Atrazine	AC	100 μg/l	Removal 95%			(54)
Atrazine	HKW activated carbon		100 mg/g	Fp, K $(mg/g)(l/mg)^{1/n}$ K = 208, n = 0.24		(55)
Atrazine–NOM	GW activated carbon	3 μg/l DOC 3.6 mg/l	0.2–1.0 mg/g			(55)
Atrazine	Active carbon (F 100)	100 ppb	Removal 97%			(57)
	Clay carbon GAC (burned clay and carbon black) (1–10 mm, 61 m^2/g)		82%			
Atrazine	Carbon fibers	5100 mg/l	Removal > 99.9%			(58)
Atrazine	GAC 50 × 200 mesh			F p, K $(\mu g/g)(l/\mu g)^{1/n}$ K = 38.7, 1/n = 0.291		(63)
Atrazine–NOM	GAC 50 × 200 mesh	TOC 2.6 mg/l		F p, K $(\mu g/g)(l/\mu g)^{1/n}$ K = 25.1, 1/n = 0.356		(63)
Bentazon	Carbon cloth (2500 m^2/g)	4.5×10^{-5} mol/l	1.49×10^{-8} mol/m^2 C-cloth	F p, K(mg/g) K = 53, 1/n = 0.558 L p vm = 151 mg/g, b = 0.574 l/mg	First-order rate constant $k = 0.011$ min^{-1}	(1)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Bentazon–propanil	Carbon cloth (2500 m^2/g)	4.5×10^{-5} mol/l 4.5×10^{-5} mol/l	1.62×10^{-8}–1.59×10^{-8} mol/m^2 C-cloth	F p, K(mg/g) K = 53, 1/n = 0.558 L p vm = 151 mg/g, b = 0.574 l/mg	First-order rate constant $k = 0.011\ min^{-1}$	(1)
Bentazon	PAC (F-400, Chemviron Carbon) (45 μm)	5–100 μg/l	Removal 99.7%			(30)
Bentazon–NOM	PAC (F-400, Chemviron Carbon) (45 μm)	5–100 μg/l TOC 2.49 mg/l	Removal 43.8% 55.9 %	F p K = 0.5, n = 0.82		(30)
Bentazon	PAC (300 mesh)	500 μg/l	40 μmol/g	F p, K(μmol/g)(l/g)$^{1/n}$ K = 41.7, n = 10 (pH 7.0)		(33)
Bentazon–NOM	ACF (1400–2500 m^2/g) GAC (1000 m^2/g)	2 μg/l DOC 1.5 mgC/l	19.1–24.7 mg/g 12.2 mg/g	F p, K (mg/g)(l/μg)$^{1/n}$ K = 19.1–24.7 n = 0.272–0.289 K = 12.2, n = 0.342		(45)
Bentazon	GAC (ROW 0,8 S)	0.85 μg/l	47 mg/g			(53)
Bentazon–NOM	GAC (ROW 0,8 S)	0.85 μg/l	32 mg/g			(53)
Bromacil	Carbon cloth (2500 m^2/g)	4.69×10^{-5} mol/l	1.91 mol/m^2 C-cloth		First-order rate constant $k = 0.020\ min^{-1}$	(2)

Bromacil–metribuzin	Carbon cloth ($2500\ m^2/g$)		1.44×10^5(mol/l) 1.44×10^5(mol/l)	4.41–5.88 mol/m^2 C-cloth		(2)
Bromophosethyl	Active carbon (F 100) Clay carbon GAC (burned clay and carbon black) (1–10 mm) ($61\ m^2/g$)	100 ppb	Removal 92% 77%			(57)
Bromoxynil	AC ($776\ m^2/g$)	35.6 mg/l	0.62 mg/m^2 (pH 2.47) 0.45 mg/m^2 (pH 4.53) 0.28 mg/m^2 (pH 6.58)			(4)
Bromoxynil	WC ($310\ m^2/g$)	35.6 mg/l	0.21 mg/m^2 (pH 2.53) 0.16 mg/m^2 (pH 4.26) 0.086 mg/m^2 (pH 6.42)			(4)
Bromoxynil	GAC A ($1200\ m^2/g$) 9.2 Å	500 μg/l		F p, K(μmol/g) $(l/\mu mol)^{1/n}$ K = 575, n = 5.42 K = 1060, n = 4.29	Differential column batch reactor (DCBR) $D \times 10^{10}$ (cm^2s^{-1}) = 4.0	(10)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
	GAC B (1153 m^2/g) 6.6 Å	500 μg/l	1240 μmol/g		$k(cms^{-1}) = 2.60 \times 10^{-2}$ $D \times 10^{10}$ $(cm^2s^{-1}) = 0.8$	
Bromoxynil	GAC (Filtrasorb 400–Chemviron Carbon) (1.00–1.25 mm)	454.8–817.5 μg/l	198.8 mg/g	Fp, K(μmol/g) $(l/\mu mol)^{1/n}$ $K = 573.0$, $n = 5.42$	HSDM p, Ds $\times 10^{10}$ $(cm^2s^{-1}) = 4.0$ $k_f \times 10^2$ $(cms^{-1}) = 2.60$	(16)
Carbaryl	PAC (1000–1400 m^2/g) (300 mesh)	500 μg/l	500 μmol/g	F p, K $(mg/g)(l/mg)^{1/n}$ $K = 11.041$, $1/n = 0.35$		(37)
Carbofuran	GAC 50 × 200 mesh			F p, K$(\mu g/g)(l/\mu g)^{1/n}$ $K = 16.4$, $1/n = 0.408$		(63)
Carbofuran–NOM	GAC 50 × 200 mesh	TOC 2.0 mg/l		F p, K$(\mu g/g)(l/\mu g)^{1/n}$ $K = 7.69–13.1$ $1/n = 0.355–0.423$		(63)
Chloridazon	AC (1100 m^2/g)	500 μg/l	75.6 mg/g			(5)
Chlorothalonil	GAC (BACM) (1100 m^2/g)	3–7 mg/l	20 mg/g			(22)
Chlorotoluron–NOM	Minicolumn test ACF (1400–2000 m^2/g) GAC (1000 m^2/g)	2 μg/l DOC 1.5 mgC/l	3.3–3.9 mg/g 0.9 mg/g			(49)

Cyanazine metabolite deethylcyanazine	PAC (Calgon water powdered low activity)	50 μg/l	7 mg/g (pH 6.0)	L p $v_m = 12.6$ mg/g b = 624 l/mg Fp, K $(mg/g)(l/mg)^{1/n}$ K = 54, 1/n = 0.33	(43)
Cyanazine metabolite deethylcyanazine	GAC (F 400, Calgon)			Fp, K $(\mu g/g)(l/\mu g)^{1/n}$ K = 3610, 1/n =0.64 (pH 7)	(28)
Cyanazine metabolite deethylcyanazine	PAC (WPL, Calgon)			F p, K$(\mu g/g)(l/\mu g)^{1/n}$ K = 4740, 1/n =0.59 (pH 7)	(28)
Cyanox	PAC (325 mesh)	10 mg/l	133–273 mg/g	F p, K (mg/g) $(l/\mu g)^{1/n}$ K = 0.069, 1/n = 0.667	(38)
Cyanox–actellic	PAC (325 mesh)	10 mg/l	125–247 mg/g	F p, K$(mg/g)(l/\mu g)^{1/n}$ K = 0.065, 1/n =0.720	(38)
		10 mg/l	133–273 mg/g	K = 0.087, 1/n =0.641	
Cyanox–danitol	PAC (325 mesh)	10 mg/l	133–267 mg/g	F p, K$(mg/g)(l/\mu g)^{1/n}$	(38)
		10 mg/l	143–333 mg/g	K = 0.085,1/n =0.618 K = 0.114,1/n =0.663	
Cyfluthrin	PAC (325 mesh)	10 mg/l	150–393 mg/g	F p, K $(mg/g)(l/\mu g)^{1/n}$ K = 0.133,1/n =0.664	(38)
Cypermethrin	GAC from solid residue of olive mill products (JEFT)			F p, $K = 3.16 \times 10^{-65}$ n = 15.73	(21)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
2,4-D	Carbon cloth ($2500\ m^2/g$)	4.69×10^{-5} (mol/l)	$1.81\ mol/m^2$ C-cloth	0.027	First-order rate constant $k = 0.016\ min^{-1}$	(2)
2,4-D	AC (from olive–waste cakes, steam activated) ($623, 826\ m^2/g$) Commercial AC ($650\ m^2/g$)	10–1500 mg/l	2.17, 2.41 mmol/g 1.65 mmol/g			(8)
2,4-D	GAC (F 300)		70 mg/g	F p,K $(mg/g)(l/mg)^{1/n}$ K = 70, n = 0.13		(55)
Dalapon	GAC 50 × 200 mesh			F p, K $(\mu g/g)(l/\mu g)^{1/n}$ K = 4.92, 1/n = 0.224		(63)
Danitol	PAC (325 mesh)	10 mg/l	146–363 mg/g	F p, K $(mg/g)(l/\mu g)^{1/n}$ K = 0.127, 1/n =0.686		(38)
Danitol–cyfluthrin	PAC (325 mesh)	10 mg/l	142–300 mg/g	F p, K $(mg/g)(l/\mu g)^{1/n}$ K = 0.110, 1/n =0.571		(38)
		10 mg/l	150–333 mg/g	K = 0.146, 1/n =0.486		
DDT–NOM	GAC I ($70.5\ m^2/g$) GAC II ($65\ m^2/g$) GAC III ($574\ m^2/g$) GAC IV ($452\ m^2/g$)	5, 10 μg/l TOC 9 mg/l	Removal 60–90% (TOC) 99%			(41)
Dikegulac	GAC (ROW 0,8 S)		12 mg/g			(53)

Dicamba	GAC 50 × 200 mesh			F p, $K(\mu g/g)(l/\mu g)^{1/n}$ $K = 33.1$, $1/n = 0.147$	(63)
Dimethylatrazine	GAC (F 300)		100 mg/g	F p, K $(mg/g)(l/mg)^{1/n}$ $K = 161$, $n = 0.29$	(55)
Dinoseb	PAC (300 mesh)	500 μg/l	230 μmol/g	F p, K $(\mu mol/g)(l/g)^{1/n}$ $K = 218.8$, $n = 3.8$ (pH 7.0)	(33)
Dinoseb	GAC (ROW 0,8 S)		58 mg/g		(53)
Diuron	PAC A (coal) (1200 m^2/g, 0.68 mm)	250 μg/l	140,000 μg/g	F p, $K(\mu g/g)(l/\mu g)^{1/n}$ $K = 81{,}452$, $1/n = 0.24$ $K = 60{,}757$, $1/n = 0.21$	(3)
	PAC B (coal) (983 m^2/g, 0.75 mm)				
	PAC C (wood) (770 m^2/g, 1.21 mm)		150,000 μg/g	$K = 101{,}018$, $1/n = 0.19$	
	PAC D (coconuts shell) (1153 m^2/g, 0.87 mm)		100,000 μg/g	$K = 86{,}836$, $1/n = 0.16$	

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Diuron–NOM	PAC A (coal) (1200 m^2/g, 0.68 mm)	250 μg/l	100,000 μg/g	F p, $K(\mu g/g)(l/\mu g)^{1/n}$ $K = 41{,}118$, $1/n = 0.32$		(3)
	PAC B (coal) (983 m^2/g, 0.75 mm)		80,000–125,000 μg/g	$K = 28{,}307$, $1/n = 0.31$		
	PAC C (wood) (770 m^2/g, 1.21 mm)		200,000 μg/g	$K = 30{,}374$, $1/n = 0.30$		
	PAC D (coconuts shell) (1153 m^2/g, 0.87 mm)			$K = 37{,}662$, $1/n = 0.30$		
Diuron	AC (776 m^2/g)	120 mg/l	0.36 mg/m^2 (pH 2.51)			(4)
			0.36 mg/m^2 (pH 5.43)			
	WC (310 m^2/g)	120 mg/l	0.13 mg/m^2 (pH 2.42)			(4)
			0.11 mg/m^2 (pH 5.30)			
Diuron	AC (1100 m^2/g)	100, 500 μg/l	106.8 mg/g			(5)

Diuron	GAC (Filtrasorb 400–Chemviron Carbon) ($1100\ m^2/g$)	1–100 μg/l		F p, $K(mg/g)(l/\mu g)^{1/n}$ K = 758.6, 1/n = 1.52	(6)
Diuron–humic acids	GAC (Filtrasorb 400–Chemviron Carbon) ($1100\ m^2/g$)	1–100 μg/l 0.08–0.90 mg/l	50 mg/g	F p, $K(mg/g)(l/\mu g)^{1/n}$ (no ozone) K = 16.2–46.8 1/n = 1.29–1.57 (ozonation 1.0–1.5 mg/l) K = 17.4–70.8 1/n = 0.95–1.23	(6)
Diuron–fulvic acids	GAC (Filtrasorb 400–Chemviron Carbon) ($1100\ m^2/g$)	1–100 μg/l 0.08–0.90 mg/l	50 mg/g	F p, $K(mg/g)(l/\mu g)^{1/n}$ (no ozone) K = 75.8–251.2 1/n = 1.11–1.58 (ozonation 1.0–1.5 mg/l) K = 91.2–251.2 1/n = 0.94–1.25	(6)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Diuron	GAC A (1200 m^2/g) 9.2 Å	500 μg/l		F p, K(μmol/g) $(l/\mu mol)^{1/n}$ K = 875, n = 4.63	DCBR D × 10^{10} (cm^2s^{-1}) = 0.65 $k(cms^{-1}) = 2.70 \times 10^{-2}$	(10)
	GAC B (1153 m^2/g) 6.6 Å	500 μg/l	1290 μmol/g	K = 1230, n = 6.45	D × 10^{10} (cm^2s^{-1}) = 0.25	
Diuron	GAC (Filtrasorb 400–Chemviron Carbon) (1.00–1.25 mm)	261.1–558.1 μg/l	219.7 mg/g	F p, K(μmol/g) $(l/\mu mol)^{1/n}$ K = 875.2, n = 4.63	HSDM p Ds × 10^{10} (cm^2s^{-1}) = 0.65 $k_f \times 10^2$ (cms^{-1}) = 2.70	(16)
Diuron–NOM	AC F-300 (1000 m^2/g)	0.1– 5.0 mg/l DOC 0.11 mg/l	50 mg/g	F p, K(mg/g)$(l/mg)^{1/n}$ K = 310, n = 7.69		(23)
Diuron	AC F-300 (1000 m^2/g)	0.09 –1.00 mg/l	32–320 mg/g			(23)
Diuron	PAC (F-400, Chemviron Carbon) (1490 m^2/g)	50 μmol/l	Removal (%) 82 (1.4 mmol/g)	F p, K(mmol/g) $(l/mmol)^{1/n}$ K = 0.7, n = 4.2 K = 1.1, n = 9.6	Adams and Bohart model *ka* (l/min/mmol) *ka* = 1.2–2.0	(29)
	Picazine (Pica) (1235 m^2/g)		65–70 (1.4 mmol/g)	K = 1.2, n = 3.3	*ka* = 1.6	
	Acticarbone (Ceca) (915 m^2/g)		40 (1.2 mmol/g)		*ka* = 1.6–1.8	

Diuron	PAC (F-400, Chemviron Carbon) (45 μm)	5–100 μg/l	Removal 99.7%		(30)
Diuron–NOM	PAC (F-400, Chemviron Carbon) (45 μm)	5–100 μg/l TOC 2.49 mg/l	96.8	F p K = 20.89, n = 0.58	(30)
Diuron–NOM	ACF (1400–2500 m^2/g) GAC (1000 m^2/g)	2 μg/l DOC 1.5 mgC/l	127.4–200.3 mg/g 35.7 mg/g	F p, K $(mg/g)(l/\mu g)^{1/n}$ K = 133.9–258.8 n = 0.387–0.539 K = 28.1, n = 0.884	(45)
Diuron–NOM	ACF (1400–2000 m^2/g) GAC (1000 m^2/g)	5000 μg/l DOC 1.5 mgC/l	75–613 mg/g 4–116 mg/g		(49)
Dodine	PAC (Chemviron, 318 W) 40–50% > 40 μm	250 μg/l	2.45 mg/g (pH 5.0–8.0)		(51)
Hymexazol	PAC (1000–1400 m^2/g) (300 mesh)	500 μg/l	60 μmol/g	F p, $K(mg/g)(l/mg)^{1/n}$ K = 0.015, 1/n = 0.96	(37)
Imazalil	PAC (300 mesh)	500 μg/l	690 μmol/g (pH = 3.0–8.6)	F p, $K(\mu mol/g)(l/g)^{1/n}$ K = 154.9–602.6 n = 3.6–5.0	(33)
Imidacloprid	PAC (300 mesh)	500 μg/l	330 μmol/g (pH = 7.0)	F p, $K(\mu mol/g)(l/g)^{1/n}$ K = 288.4, n = 2.9	(33)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Imidacloprid	PAC (1000–1400 m^2/g) (300 mesh)	500 μg/l	400 μmol/g	F p, K $(mg/g)(l/mg)^{1/n}$ K = 7.120, 1/n = 0.44		(37)
Isoprothiolane (IPT)–nitrates	GAC (Hybrid biofilm electrode reactor, BER)	2–2000 μg/l	Removal 96.0–96.8%			(12)
Lenacil	PAC (Chemviron Carbon, F-400) 45 μm	5–100 μg/l	Removal 99.7%			(30)
Lenacil–NOM	PAC (Chemviron Carbon, F-400) 45 μm	5–100 μg/l TOC 2.49 mg/l	Removal 73.4% 26.3%	F p, K = 1.94, n = 0.91		(30)
Lindane	GAC (1070 m^2/g)	10 mg/l	516–772 mg/g		Peel model p $k_L \times 10^3$ (cms^{-1}) = 4.4 –6.5 f = 0.22–0.50 Dp $\times 10^4$ (cm^2s^{-1}) = 2.45	(13)

Lindane	PAC (313 W, Chemviron) (800 m^2/g)	4.3–21.3 μg/l	365 mg/g	F p, K(mg/g)(l/g)$^{1/n}$ K = 181–255 1/n = 0.41–0.57 L p, v_m = 412–855 mg/g b = 1–0.45 l/mg	K apparent relative adsorption rate constant = 0.030–0.156 (μg/mg/min)$^{1/2}$ linear adsorption kinetic model	(34)
Lindane–NOM	GAC I (70.5 m^2/g) GAC II (65 m^2/g)	5, 10 μg/l	Removal 60–90%			(41)
	GAC III (574 m^2/g) GAC IV (452 m^2/g)	TOC 9 mg/l	(TOC) 99%			
Lindane	Active carbon (F 100)	100 ppb	Removal 95%			(57)
	Clay carbon GAC (burned clay and carbon black) (1–10 mm) (61 m^2/g)		70%			
Lindane–humic acid	PAC (Filtrasorb 400–Chemviron Carbon) < 50 μm	1 mg/l	7.5 mg/g			(60)
		10 mg/l	75 mg/g			
Lindane–fulvic acid	PAC (Filtrasorb 400–Chemviron Carbon) < 50 μm	1 mg/l	0.78 mg/g			(60)
		10 mg/l	7.8 mg/g			

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Heptachlor hydrolysis product 1 hydroxy-chlordene	GAC (Filtrasorb 400, Calgon Co) 100/230 mesh	48 μg/l	40 mg/g	F p, K(μg/mg)(l/μg)$^{1/n}$ K = 8.35, 1/n = 0.47	HSDM p D × 10^{11} (cm^2s^{-1}) = 6.00 $k_f \times 10^3$ (cms^{-1}) = 4.0	(62)
Heptachlor hydrolysis product 1 hydroxy-chlordene–humic acid	GAC (Filtrasorb 400, Calgon Co) 100/230 mesh	38 μg/l	20 mg/g 5 mg as TOC/l	F p, K (μg/mg)(l/μg)$^{1/n}$ K = 5.97, 1/n = 0.35	HSDM p D × 10^{11} (cm^2s^{-1}) = 4.50 $k_f \times 10^3$ (cms^{-1}) = 3.20	(62)
Linuron	PAC (300 mesh)	500 μg/l	600 μmol/g (pH = 7.0)	F p, K (μmol/g)(l/g)$^{1/n}$ K = 537.0, n = 3.8		(33)
Linuron	PAC (1000–1400 m^2/g) (300 mesh)	500 μg/l	600 μmol/g	F p, K (mg/g)(l/mg)$^{1/n}$ K = 16.315, 1/n = 0.35		(37)
Malathion	GAC from solid residue of olive mill products (JEFT)			F p K = 6.30 × 10^{-80} n = 19.33		(21)
MCPA	AC (1100 m^2/g)		25.1 mg/g			(5)

MCPA	AC (from olive–waste cakes, steam activated) (623, 826 m^2/g)	10–1500 mg/l	2.07, 2.34 mmol/g		(8)
	Commercial AC (650 m^2/g)		1.62 mmol/g		
MCPA	PAC (Filtrasorb 400–Chemviron Carbon) (1100 m^2/g)	500 μg/l mineral water reconstituted	46 mg/g	F p, K(mg/g)(l/mg)$^{1/n}$ K = 17.4 1/n = 0.82	(17)
MCPA–humic acids	PAC (Filtrasorb 400–Chemviron Carbon) (1100 m^2/g)	500 μg/l 0.19–0.46 mg/l mineral water reconstituted	39–43 mg/g	F p, K (mg/g)(l/mg)$^{1/n}$ K = 6.61–9.12 1/n = 0.79–0.88	(17)
MCPA –fulvic acids	PAC (Filtrasorb 400–Chemviron Carbon) (1100 m^2/g)	500 μg/l 0.34–1.34 mg/l mineral water reconstituted	46–50 mg/g	F p, K(mg/g)(l/mg)$^{1/n}$ K = 6.76–13.18 1/n = 0.62–0.74	(17)
MCPA	GAC (0.85–1.20 mm) (Filtrasorb 400–Chemviron Carbon)		390 mg/g	L p v_m = 388 mg/g b = 0.09 l/mg	(42)
MCPA–phenol	GAC (0.85–1.20 mm) (Filtrasorb 400–Chemviron Carbon)	0.016–0.021 mg/ml (phenol)	125–170 mg/g		(42)
MCPA	AC	100 μg/l	Removal 95%		(54)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
MCPB	GAC (1070 m^2/g)	5.9 mg/l	316–387 mg/g		Peel model p $k_L \times 10^3$ (cms^{-1}) = 4.7–6.5 f = 0.23–1.00 Dp $\times 10^4$ (cm^2sec^{-1}) = 9.03	(13)
MCPB	PAC (300 mesh)	500 μg/l	270 μmol/g (pH = 3.0–8.7)	F p, K (μmol/g)$(l/g)^{1/n}$ K = 99.3–532.0, n = 3.6–4.1		(33)
MCPB	GAC (0.85–1.20 mm) (Filtrasorb 400–Chemviron Carbon)		410 mg/g	L p v_m = 457 mg/g b = 0.23 l/mg		(42)
MCPP	PAC (300 mesh)	500 μg/l	60 μmol/g (pH = 7.0)	F p, K(μmol/g)$(l/g)^{1/n}$ K = 60.3, n = 10.0		(33)
MCPP	GAC (0.85–1.20 mm) (Filtrasorb 400–Chemviron Carbon)		400 mg/g	L p v_m = 394 mg/g b = 0.24 l/mg		(42)
Methomyl	PAC (1000–1400 m^2/g) (300 mesh)	500 μg/l	130 μmol/g	F p, K (mg/g)$(l/mg)^{1/n}$ K = 1.964, 1/n = 0.41		(37)

Metazachlor	GAC (F 300)	200 μg/l	120 mg/g			(55)
Metazachlor–NOM	GW activated carbon	200 μg/l DOC 1.3 mg/l	7.0 mg/g			(55)
Metolachlor	GAC (ROW 0,8 S)		126 mg/g			(53)
Metolachlor–NOM	GAC (ROW 0,8 S)	DOC 0.1–0.82 μg/l	100 mg/g			(53)
Metolachlor	GAC (F 300)		190 mg/g	F p, K(mg/g)(l/mg)$^{1/n}$ K = 256, n = 0.35		(55)
Metribuzin	Carbon cloth (2500 m^2/g)	4.69×10^{-5} (mol/l)	1.76 mol/m^2 C-cloth		First-order rate constant $k = 0.015\ min^{-1}$	(2)
PCP	PAC (300 mesh)	500 μg/l	300 μmol/g (pH 7.0)	F p, K (μmol/g)(l/g)$^{1/n}$ K = 309.0, n = 3.2		(33)
PCP	PAC (Picactif CNB 100/EWN, Pica Carbons) (1938 m^2/g)	150 μg/l	31.6–7.9 mg/g (pH 5.5–8.5)			(39)
PCP	PAC (Filtrasorb 400–Chemviron Carbon) <50 μm	5 mg/l	100 mg/g			(60)
PCP –fulvic acid	PAC (Filtrasorb 400–Chemviron Carbon) <50 μm	5 mg/l 20 mg/l	95 mg/g			(60)
Permethrin	Carbon fibers	237.5 mg/l	Removal 99.9%			(58)

(*continued*)

Table 2. Continued

Pesticide	C Adsorbent	Co	Cmax., exp.	Isotherm model parameters	Kinetic characteristics	Ref item # in Table 1
Propanil	Carbon cloth ($2500\ m^2/g$)	$4.5\ 10^{-5}$(mol/l)	1.58×10^{-8} mol/m^2 C-cloth	F p, K(mg/g) K = 73, 1/n = 0.301 L p $v_m = 114$ mg/g, b = 0.317 l/mg	First order rate constant $k = 0.012\ min^{-1}$	(1)
Propetamphos	PAC (Picactif CNB 100/EWN, Pica Carbons) ($1938\ m^2/g$)	150 μg/l	50.1 mg/g (pH 5.5–8.5)			(39)
Simazine	GAC ($1070\ m^2/g$) (22–26 μm)					(11)
Simazine	GAC (F 400, Calgon)		pH 7 pH 9	F p, K $(\mu g/g)(l/\mu g)^{1/n}$ K = 13100, 1/n =0.22 K = 6330, 1/n =0.41		(28)
Simazine	PAC (WPL, Calgon)		pH 9	F p, K $(\mu g/g)(l/\mu g)^{1/n}$ K = 13300, 1/n =0.25		(28)
Simazine	GAC (ROW 0,8 S)		36 mg/g			(53)
Simazine	GAC (F 300)		90 mg/g	F p, K $(mg/g)(l/mg)^{1/n}$ K = 171, n = 0.31		(55)
TCP (2,4,6)	PAC (coal based, Calgon Carbon) (5.28–37.30 μm, 325 mesh)	21–415 μg/l	8–70 mg/g (groundwater) 100 mg/g (distilled water)	F p, K$(mg/g)(l/\mu g)^{1/n}$ (Co = 34–109 μg/l) K = 2.08–3.24 1/n = 0.53–0.47	HSDM p (Co = 34–109 μg/l) Ds $\times 10^{10}$ ($cm^2 min^{-1}$) = 0.44–3.10	(57)

Terbuthylazine	GAC (bituminous coal) (1000–1100 m^2/g)	0.14–1.07 μg/l	1000 mg/g			(35)
Terbutryn	GAC (F 300)		230 mg/g	F p, K $(mg/g)(l/mg)^{1/n}$ K = 343, n = 0.29		(55)
Thiobencarb	PAC (1000–1400 m^2/g) (300 mesh)	500 μg/l	900 μmol/g	F p, $K(mg/g)(l/mg)^{1/n}$ K = 14.458, 1/n = 0.46		(37)
Thiophanatemetyl	PAC (1000–1400 m^2/g) (300 mesh)	500 μg/l	430 μmol/g	F p, $K(mg/g)(l/mg)^{1/n}$ K = 25.492, 1/n = 0.33		(37)
TPCB	GAC (1070 m^2/g)	0.046 mg/l	10 mg/g		Peel model p $k_L \times 10^3$ $(cms^{-1}) = 4.7$ f = 1.00 Dp $\times 10^4$ $(cm^2sec^{-1}) =$ 0.032	(13)
Mixtures						
Pesticide manufacturing wastewater	GAC (activated carbon pellets) Pre-treatment (ozone 20 g/l)	Total concentration 1.6 g/l Endosulphan 1 Endosulphan 2 Diazinon Chlorpyrifos Dicamba	Removal 100%			(26)

Table 3. Pesticides adsorption on polymeric materials

Ref. item #	Reference	Pesticide	Polymeric material	Aim–experimental–results
1	Kyriakopoulos et al. 2003 (11)	Alachlor and amitrole	Polymeric resins, amberlites XAD-4 and XAD-7	The adsorption capability of the polymeric resins for the pesticides removal was investigated. The effect of solution pH and the resins structure on adsorption effectiveness was examined. The experimental data were applied to Freundlich and Langmuir adsorption isotherm models.
2	Trochimczuk et al. 2003 (79)	Atrazine, imazapyr and 2,4-dichlor-ophenoxyacetic acid	Copolymers Acrylonitrile (AN)/ divinylbenzene (DVB) and methylacrilonitrile (MAN)/ divinylbenzene (DVB) (six types) and styrene/divinyl-benzene resins (three types)	The adsorption capability of various types of polymers for pesticides removal was studied. The experiments were carried out using inert solvents. The effect of the type of specific area of the adsorbents and the presence of polar groups in their molecules was investigated. Atrazine adsorption was much higher than that of imazapyr and 2,4-dichlorophenoxyacetic acid in all cases.
3	Yoshizuka et al. 2000 (29)	Methyl parathion (MP)	Two types of chitosan micropar-ticles [β-(1-4)-2-amino-2-deoxy-D-glucose] which are hydrolyzed products of chitin (polysaccharide) (CMs) and their silver-complexes (SCMs)	Two types of chitosan polymers and their silver-complexes were prepared using the crosslinking agents glutaraldehyde and epichlorohydrin. The selected factors for adsorption–desorption experiments were the solution pH and the concentration of silver and pesticide. Furthermore, from the iteration of adsorption and release experiments of MP, glutaraldehyde–cross-linked SCM provided good reusability for MP removal.

4	Dessouki et al. 1999 (44)	Ametryn, applaud, aldrin and chlorothalonil	MERCK II, weak anion exchanger (polystyrene with aliphatic amino groups) and MERCK III, strong anion exchanger (polystyrene with anchored quaternary ammonium groups)	The effectiveness of a number of processes including adsorption on the two types of polymers for the removal of pesticides from their aqueous solutions was studied. Radiation in combination with adsorption, resulted in effective removal of toxic pesticides and led to pesticide acceptable concentration in solution, according to international standards. The above method was proved more effective than the application of conventional techniques.
5	Frimmel et al. 1999 (7)	2-Aminonaphthalene-1-sulfonate, diuron and 1-naphthol	Polymeric resins LiChrolut EN and Lewatit EP 63 (styrene-divinyl benzene copolymers)	The adsorbability of the pesticides and Natural Organic Matter (NOM) onto the organic polymeric resin and onto activated carbon was investigated by determining the relative isotherms. The breakthrough behavior of the compounds in filter columns and in a laboratory plant was investigated. Finally, the regenerability of the polymer resin with isopropanol was tested. A recovery of 92–96% of the substances was reached.
6	Koskinen et al. 1999 (80)	Alachlor, atrazine, imidacloprid, isofenphos, nicosulfuron and triadimefon	Polyvinylbenzene lysimeters (PVC)	The suitability of the polymer for underground water sampling was investigated. Among the tested pesticides, only isofenphos showed low and high adsorption rate (at about 9% of applied quantity) as well as desorption difficulty using as solvents methanol and water. Optimization of the method could be achieved by estimating the probable interactions determing by the chemical structure of the pesticide and the properties of the lysimeter material.

(*continued*)

Table 3. Continued

Ref. item #	Reference	Pesticide	Polymeric material	Aim–experimental–results
7	Horner et al. 1998 (52)	Atrazine	Activated carbon (carbonized polymer from lignin)	Comparative evaluation of the adsorption capability of activated carbon and three types of carbonaceous polymeric resins for pesticide removal was made. Carbon regeneration using methanol and ethanol solvents in-situ techniques was examined.
8	Streat et al. 1998a (81)	Simazine, chlorotoluron, isoproturon, atrazine and diuron	Hypersol-Macronet MN-200 polymer	The regeneration of the crosslinked polymer and activated carbon, on the surface of which pesticides were adsorbed, was investigated. The solvents, ethanol, ethanol azeotrope, acetone, methanol and 1-propanol were used for the regeneration. The regeneration of the polymer was carried out in micro-columns. Activated carbon (Chemviron F-400) regeneration was not effective. The advantages of the polymeric adsorbents were investigated.
9	Streat et al. 1998b (82)	Simazine, chlorotoluron, isoproturon, atrazine and diuron	Hypersol-Macronet polymers	The pesticides adsorption on the crosslinked polymers and activated carbon in microcolumns was evaluated. The order of the extent of adsorption was: isoproturon > diuron > atrazine > chlorotoluron. The overall effect of the hydrophobic interactions and the hydrogen bonding developed on the polymeric matrix was examined. The presence of fulvic acid resulted in slight adsorption capability reduction of the polymers and strong adsorption capability reduction of the activated carbon (Chemviron F-400). This effect was attributed to the physico-chemical properties of the adsorbent materials.

10	Streat and Sweetland 1998 (83)	Simazine, chlorotoluron, isoproturon, atrazine and diuron	Hypersol-Macronet polymers	The adsorption capability of the polymers for the removal of single pesticides and their mixtures, from their aqueous solutions, was studied. The retention mechanisms included the hydrophobic interactions and the hydrogen bonding. The adsorption parameters were estimated using the Freundlich model. The adsorption energy of the pesticides on the polymeric materials was lower than that of activated carbon.
11	Doulia et al. 1997 (84)	Atrazine	XAD-2, XAD-4 and XAD-7 polymeric resins	The adsorption capability of the polymers for the pesticide removal from its aqueous solutions was investigated. Analysis was performed using High Performance Liquid Chromatography (HPLC). The adsorption isotherms were fitted to the Freundlich and Langmuir models. The effect of the pesticide polarity, solution pH and ionic strength as well as the chemical structure of the polymers was examined. At high pH values, the adsorption effectiveness of the polymers was ranked thus: XAD-7 > XAD-4 > XAD-2, while at low pH values: XAD-4 > XAD-7 > XAD-2.
12	Streat and Sweetland 1997 (85)	Atrazine	Two types of Hypersol-Macronet polymers: MN-100 and MN-200	The adsorption capability of the polymers for the pesticides removal from drinking water was evaluated. The experiments were conducted using microcolumns and the adsorption isotherms were studied. IR radiation provided information on the chemical functionality of the molecules.

Table 4. Polymer capacities, equilibrium parameters in adsorption of pesticides on polymeric materials

Pesticide	Polymer adsorbent	Co	Cmax., exp.	Isotherm model parameters	Ref. Item # in Table 3
Alachlor	Styrene–divinylbenzene–copolymer (XAD-4, Rohm & Haas, 750 m^2/g)	100–800 mg/l	2.0 mol/g (pH 6.5) 3.0 mol/g (pH 5) 4.0 mol/g (pH 3)	F p, K $(mol/g)(l/g)^{1/n}$ $K = 0.14–4.73 \times 10^{-3}$ n = 4.07–1.81 (pH-3–6.5)	1
	Polyacrilic ester (XAD-7 Rohm & Haas, 450 m^2/g)		2.6 mol/g (pH 6.5) 2.3 mol/g (pH 5) 1.4 mol/g (pH 3)	$K = 8.26–3.38 \times 10^{-5}$ n = 6.39–7.50 (pH-3–6.5)	
Aldrin	MERCK II, weak anion exchanger (polystyrene with aliphatic amino groups) (0.4–0.5 mesh)	3–7 mg/l	10 mg/g		4
	MERCK III, strong anion exchanger (polystyrene with anchored quaternary ammonium groups) (0.3–0.6 mesh)		8 mg/g		
Ametryne	MERCK II weak anion exchanger (polystyrene with aliphatic amino groups) (0.4–0.5 mesh)	3–7 mg/l	9 mg/g		4

	MERCK III strong anion exchanger (polystyrene with anchored quaternary ammonium groups) (0.3–0.6 mesh)		7 mg/g		
Amitrole	Styrene–divinylbenzene–copolymer (XAD-4, Rohm & Haas, 750 m^2/g)	100–800 mg/l	2.0 mol/g (pH 6.5) 2.5 mol/g (pH 5) 12.0 mol/g (pH 3)	F p, K(mol/g)(l/g)$^{1/n}$ K = 0.62–1.40 × 10^{-3} n = 1.45–1.57 (pH = 3.0–6.5)	1
	Polyacrilic ester (XAD-7 Rohm & Haas, 450 m^2/g)		7.0 mol/g (pH 6.5) 7.5 mol/g (pH 5) 11.0 mol/g (pH 3)	K = 7.01–1.19 × 10^{-3} n = 1.12–2.30 (pH-3.0–6.5)	
Applaud	MERCK II weak anion exchanger (polystyrene with aliphatic amino groups) (0.4–0.5 mesh)	3–7 mg/l	14 mg/g		4
	MERCK III strong anion exchanger (polystyrene with anchored quaternary ammonium groups) (0.3–0.6 mesh)		12 mg/g		
Atrazine	Activated carbon (carbonized polymer from lignin)	1–10 mg/l		F p, K (mg/g)(l/mg)$^{1/n}$	7
	LF 1 (1331 m^2/g)		330 mg/g	K = 218, 1/n = 0.295	
	LF 2 (1762 m^2/g)		530 mg/g	K = 355.8, 1/n = 0.295	

(*continued*)

Table 4. Continued

Pesticide	Polymer adsorbent	Co	Cmax., exp.	Isotherm model parameters	Ref. Item # in Table 3
Atrazine	MN–100	1–100 μg/l	19,500 μg/g	F p, (μmol/g)(l/μmol) 1/n (MN-200)	8
	MN–150				
	MN–200			K = 2073, 1/n = 0.718	
				Fp, K $(\mu mol/g)(l/\mu mol)^{1/n}$	
Atrazine (A) – Chlorotoluron (C) – Diuron (D) – Isoproturon (I) – Simazine (S)	MN–100	1–100 μg/l	17.0 μmol/g	$K_A = 4410$, $1/n_A = 0.899$	8
			12.0 μmol/g	$K_C = 826$, $1/n_C = 0.746$	
			10.2 μmol/g	$K_D = 1852$, $1/n_D = 0.823$	
			15.0 μmol/g	$K_I = 2641$, $1/n_I = 0.825$	
			11.0 μmol/g	$K_S = 478$, $1/n_S = 0.724$	
	MN–150		20.5 μmol/g	$K_A = 3300$, $1/n_A = 0.869$	
			19.0 μmol/g	$K_C = 1150$, $1/n_C = 0.783$	
			11.0 μmol/g	$K_D = 2339$, $1/n_D = 0.844$	
			19.0 μmol/g	$K_I = 3288$, $1/n_I = 0.874$	
			17.0 μmol/g	$K_S = 550$, $1/n_S = 0.718$	
	MN–200		20.5 μmol/g	$K_A = 3023$, $1/n_A = 0.825$	
			15.0 μmol/g	$K_C = 1273$, $1/n_C = 0.758$	
			11.0 μmol/g	$K_D = 2374$, $1/n_D = 0.814$	
			15.0 μmol/g	$K_I = 6421$, $1/n_I = 0.893$	
			14.0 μmol/g	$K_S = 440$, $1/n_S = 0.697$	

Atrazine (A) – Chlorotoluron (C) – Diuron (D) – Isoproturon (I) – Simazine (S) – Fulvic acid	MN–200	20 μg/l each pesticide 20 mg/l	10.5–10.8 μmol/g		9
Atrazine	Styrene–divinylbenzene–copolymers (XAD-2, Rohm & Haas, 300 m^2/g)	30–500 mg/l	10.0–12.0 mg/g (pH 2–11)	F p, K $(mg/g)(l/mg)^{1/n}$ $K \times 10^{-4} = 11.02$ $n = 2.95$ (pH 2) $K \times 10^{-4} = 15.60$ $n = 2.63$ (pH 5) $K \times 10^{-4} = 21.63$ $n = 2.31$ (pH 11)	11
	(XAD-4, Rohm & Haas, 750 m^2/g)		13.0–16.0 mg/g (pH 2–11)	$K \times 10^{-4} = 13.84$ $n = 3.17$ (pH 2) $K \times 10^{-4} = 21.63$ $n = 2.72$ (pH 5) $K \times 10^{-4} = 22.91$ $n = 2.49$ (pH 11)	
	Polyacrilic ester (XAD-7 Rohm & Haas, 450 m^2/g)		12.0–24.0 mg/g (pH 2–11)	$K \times 10^{-4} = 10.59$ $n = 3.01$ (pH 2) $K \times 10^{-4} = 16.00$ $n = 3.04$ (pH 5) $K \times 10^{-4} = 20.90$ $n = 2.92$ (pH 11)	

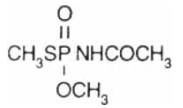
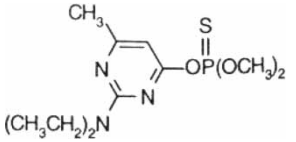
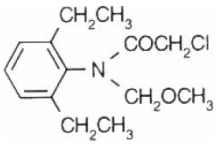
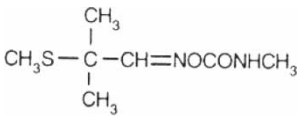
(*continued*)

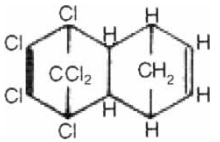
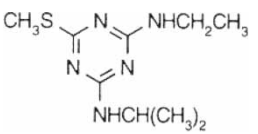
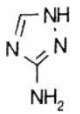
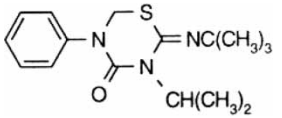
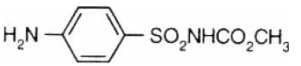
Table 4. Continued

Pesticide	Polymer adsorbent	Co	Cmax., exp.	Isotherm model parameters	Ref. Item # in Table 3
Atrazine – NOM	MN 100 (weak base anion Macronet) (8–30 μm)	0.1 μg/l	26 μmol/g	F p, K $(\mu mol/g)(l/\mu mol)^{1/n}$ $K = 83$, $1/n = 0.883$	12
	MN 200 (no added functionality) (8–30 μm)	TOC 3 ppb	50 μmol/g	$K = 241$, $1/n = 0.937$	
Chlorothalonil	MERCK II weak anion exchanger (polystyrene with aliphatic amino groups) (0.4–0.5 mesh)	3–7 mg/l	11 mg/g		4
	MERCK III strong anion exchanger (polystyrene with anchored quaternary ammonium groups) (0.3–0.6 mesh)		9 mg/g		
Chlorotoluron	MN–200	1–100 μg/l	80 μmol/g	F p, $K(\mu mol/g)(l/\mu mol)^{1/n}$ $K = 1520$, $1/n = 0.715$	8
Diuron	Styrene–divinylbenzene–copolymer (Lewatit EP63, Merck) (1000–1400 m^2/g)	0.09–1.00 mg/l	25–200 mg/g		5

Diuron–NOM	Styrene–divinylbenzene–copolymer (LiChrolut EN, Bayer) ($1200\ m^2/g$)	0.1–5.0 mg/l DOC 0.11 mg/l	50 mg/g	F p, $K(\mu mol/g)(l/\mu mol)^{1/n}$ K = 770–274, n = 1.25–2.38	5
Diuron	MN–200	1–100 μg/l	70 μmol/g	F p, $K(\mu mol/g)(l/\mu mol)^{1/n}$ K = 2073, 1/n = 0.718	8
Isoproturon	MN–200	1–100 μg/l	80 μmol/g	F p, $K(\mu mol/g)(l/\mu mol)^{1/n}$ K = 2323, 1/n = 0.706	8
Methyl parathion	Chitosan–glutaraldehyde copolymer (CM 1) Chitosan–epichlorohydrin copolymers (CM 2) Silver–complexes (SCM 1) (SCM 2)	20 μmol/l >2000 μmol/l	 1 μmol/g 0.1 μmol/g 180 μmol/g 60 μmol/g		3
Simazine	MN–200	1–100 μg/l	90 μmol/g	F p, $K(\mu mol/g)(l/\mu mol)^{1/n}$ K = 864, 1/n = 0.738	8

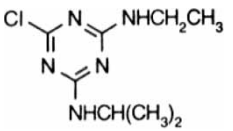
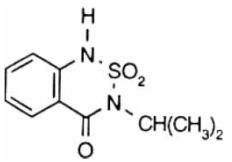
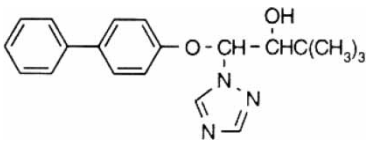
Table 5. Chemical structure and usage of pesticides examined on carbonaceous and polymeric materials

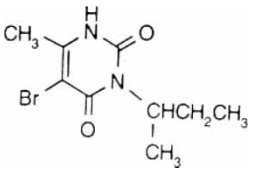
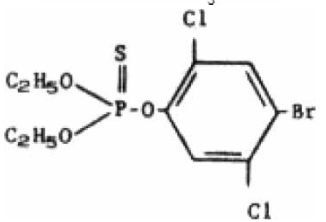
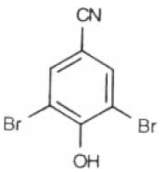
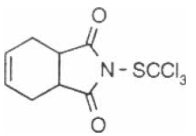
Pesticide	Molecular type	Category	pKa	Usage/Ref Table 1 (C*) Table 3 (P*)
Acephate		Organophosphorus	—	Insecticide (C9)
Actellic (or pirimiphos-methyl)		Organophosphorus	3.71	Insecticide, acaricide (C38)
Alachlor		Chloroacetanilide	—	Herbicide (C13, 62) (P1)
Aldicarb		Oxime carbamate	—	Insecticide, acaricide, nematicide (C60)

Aldrin			—	Insecticide (C57) (P4)
Ametryn		1,3,5–Triazine	4.10	Herbicide (C22) (P4)
Amitrole		Triazole	4.2 and 10.7	Herbicide (P1)
Applaud (or buprofezin)			—	Insecticide, acaricide (C22) (P4)
Asulam			4.82	Herbicide (C11)

(*continued*)

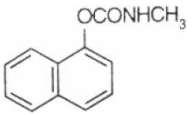
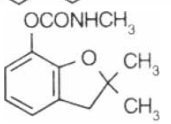
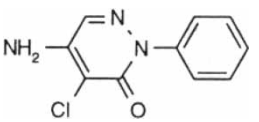
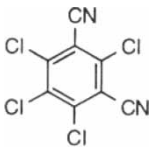
Table 5. Continued

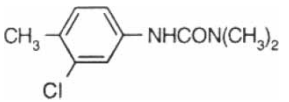
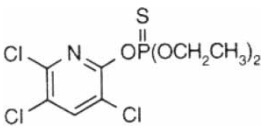
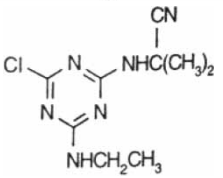
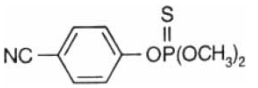
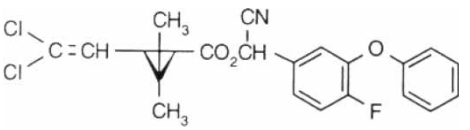
Pesticide	Molecular type	Category	pKa	Usage/Ref Table 1 (C*) Table 3 (P*)
Atrazine		1,3,5–Triazine	1.70	Herbicide (C2, 3, 5, 7, 10, 14 – 20, 24, 25, 28, 29, 31, 32, 36, 40, 43, 43 – 48, 54, 55, 57, 58, 63) (P7 – 9, 11, 12)
Bentazone			3.30	Herbicide (C1, 30, 33, 54)
Bitertanol		Azole	—	Fungicide (C52)

Bromacil		Uracil	9.27	Herbicide (C2)
Bromophosethyl			—	Insecticide (C61)
Bromoxynil		Hydroxybenzonitrile	3.86	Herbicide (C10, 16)
Captan		N-Trihalomethylthio	—	Fungicide (C52)

(*continued*)

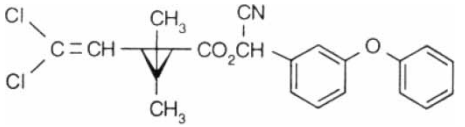
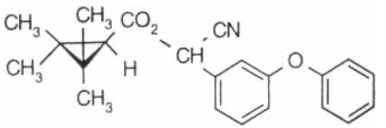
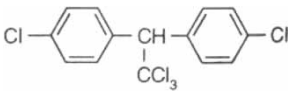
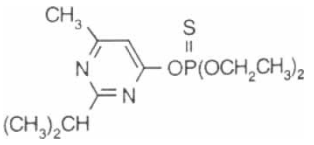
Table 5. Continued

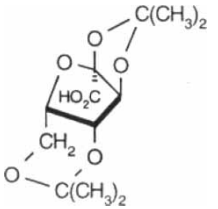
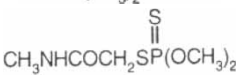
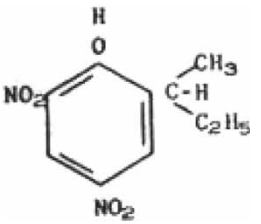
Pesticide	Molecular type	Category	pKa	Usage/Ref Table 1 (C*) Table 3 (P*)
Carbaryl		Carbamate	—	Insecticide, plant growth regulator (C37)
Carbofuran		Carbamate	—	Insecticide, nematicide (C63)
Chloridazon		Pyridazinone (PSII)	—	Herbicide (C5, 30, 52)
Chlorothalonil			—	Fungicide (C22) (P4)

Chlorotoluron		Urea	—	Herbicide (P8, 9, 30)
Chlorpyrifos		Organophosphorus	—	Insecticide (C26)
Cyanazine		1,3,5-Triazine	0.63	Herbicide (C43, 54)
Cyanophos (or cyanox)		Organophosphorus	—	Herbicide (C38)
Cyfluthrin		Pyrethroid	—	Insecticide (C38)

(*continued*)

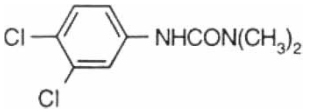
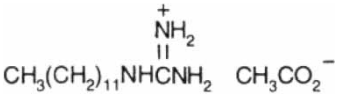
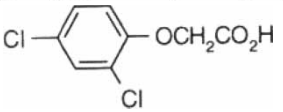
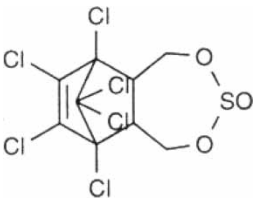
Table 5. Continued

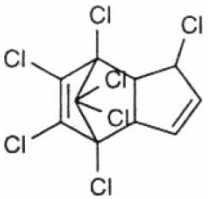
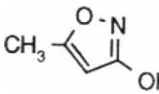
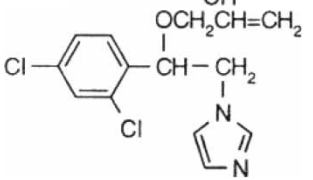
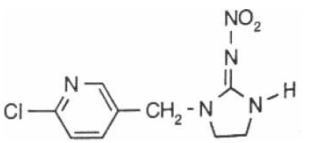
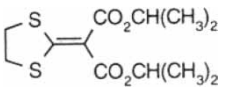
Pesticide	Molecular type	Category	pKa	Usage/Ref Table 1 (C*) Table 3 (P*)
Cypermethrin		Pyrethroid	—	Insecticide (C21)
Dalapon	$CH_3CCl_2CO_2H$	Halogenated propanoic acid	1.74–1.84	Herbicide (C63)
Danitol (or fenpropathrin)		Pyrethroid	—	Acaricide, insecticide (C38)
DDT (p,p′)		Organochlorine	—	Insecticide (C41)
Diazinon		Organophosphorus	—	Insecticide, acaricide (C26)

Dichlorprop			—	Nematicide (C54)
Dikegulac			—	Plant growth regulator (C53)
Dimethoate		Organophosphorus	—	Insecticide, acaricide (C52)
Dinoseb			4.62	Herbicide (C33)

(*continued*)

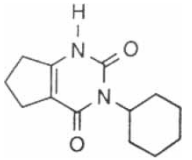
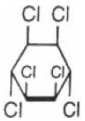
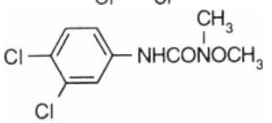
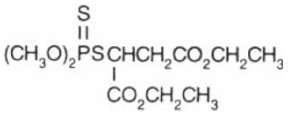
Table 5. Continued

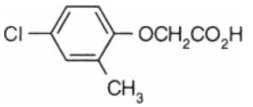
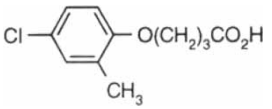
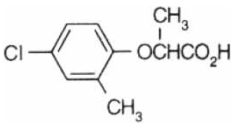
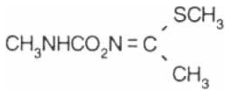
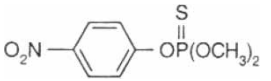
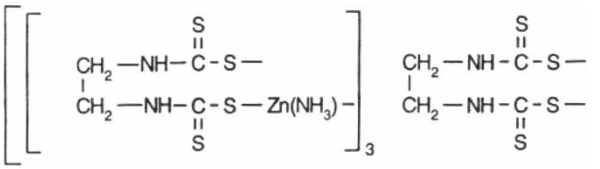
Pesticide	Molecular type	Category	pKa	Usage/Ref Table 1 (C*) Table 3 (P*)
Diuron		Urea	—	Herbicide (C3 – 6, 10, 16, 23, 29, 30, 45, 49) (P5, 8, 9)
Dodine		Guanidine	—	Fungicide (C51)
2,4-D (2,4 dichloro-phenoxyacetic acid)		Aryloxyalkanoic acid	2.73	Herbicide (C2, 8)
Endosulfan		Cyclodiene organochlorine	—	Insecticide, acaricide (C26)

Heptachlor		Cyclodiene organochlorine	—	Insecticide (C62)
Hymexazol			5.92	Fungicide (C37)
Imazalil		Azole	6.53	Fungicide (C33)
Imidacloprid			—	Insecticide (C33, 37)
Isoprothiolane			—	Fungicide (C12)

(*continued*)

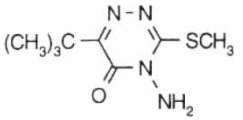
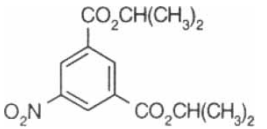
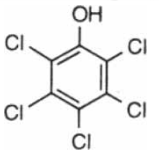
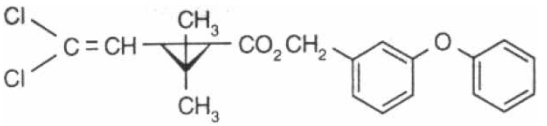
Table 5. Continued

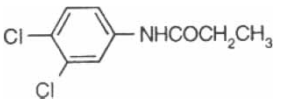
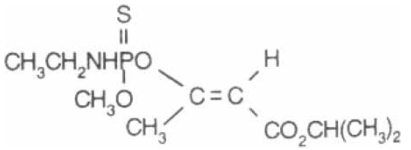
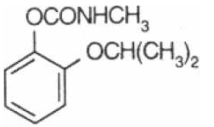
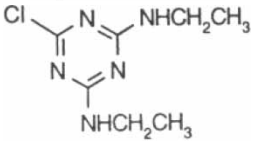
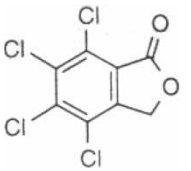
Pesticide	Molecular type	Category	pKa	Usage/Ref Table 1 (C*) Table 3 (P*)
Lenacil		Uracil	10.30	Herbicide (C30)
Lindane (or γ–HCH)		Organochlorine	—	Insecticide (C13, 34, 41, 57, 60)
Linuron		Urea	—	Herbicide (C33, 37)
Malathion		Organophosphorus	—	Insecticide, acaricide (C21, 26)

MCPA		Aryloxyalkanoic acid	3.07	Herbicide (C5, 8, 17, 42, 54)
MCPB		Aryloxyalkanoic acid	4.84	Herbicide (C13, 33, 42)
MCPP (or Mecoprop)		Aryloxyalkanoic acid	3.78	Herbicide (C33, 42)
Methomyl		Oxime carbamate		Insecticide, acaricide (C37)
Methyl parathion		Organophosphorus		Insecticide (P3)
Metiram		Alkylenebis (dithiocarbamate)	—	Fungicide (C52)

(*continued*)

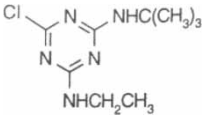
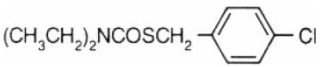
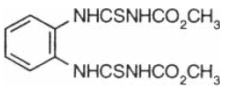
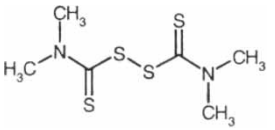
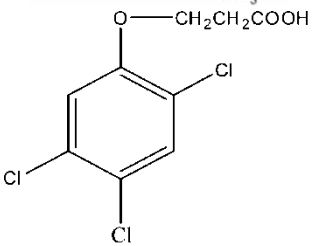
Table 5. Continued

Pesticide	Molecular type	Category	pKa	Usage/Ref Table 1 (C*) Table 3 (P*)
Metribuzin		1,2,4–Triazinone	—	Herbicide (C2)
Molinate		Thiocarbamate	—	Herbicide (C35)
Nitrothalisopropyl			—	Fungicide (C52)
Pentachlorophenol (or PCP)			4.71	Insecticide, fungicide, herbicide (C33, 39, 60)
Permethrin		Pyrethroid	—	Insecticide (C58)

Propanil		Anilide	—	Herbicide (C1)
Propetamphos		Organophosphorus	13.67	Insecticide, acaricide (C39)
Propoxur		Carbamate	—	Insecticide (C52)
Simazine		1,3,5-Triazine	1.62	Herbicide (C11, 26, 43) (P3)
TCP (phthalide)			—	Fungicide (C56)

(*continued*)

Table 5. Continued

Pesticide	Molecular type	Category	pKa	Usage/Ref Table 1 (C*) Table 3 (P*)
Terbuthylazine		1,3,5-Triazine	2.00	Herbicide (C35)
Thiobencarb		Thiocarbamate	—	Herbicide (C37)
Thiophamatemethyl		Benzimidazole precursor	7.28	Fungicide, wood protectant (C37, 52)
Thiram		Dimethyldithiocarbamate	—	Fungicide (C52)
TPCB (fenoprop)			—	Herbicide, plant growth regulator (C13)

CONCLUSIONS

It is obvious that data on adsorption using carbonaceous and polymeric materials are abundant, since a great variety of adsorbent materials are available connected with different processes. GAC and PAC are the more common adsorbents, which are frequently and mainly applied in conventional laboratory or industrial columns for treatment of drinking water and wastewaters. They are effective to separate primarily insoluble or easily decomposed pesticides. Innovative carbonaceous materials including carbon cloth, fibers, felts or carbon cloth electrodes, black carbon from wheat residues (WC), carbon black and commercial activated carbon (AC) are very promising adsorbents. They combine higher adsorption capability, extending to soluble organic pesticides, with regeneration and reuse efficiency.

Polymers (synthetic or natural) have been used, also, successfully in drinking water treatment for pesticide removal. The development in polymer science technology allowed the production of highly porous polymers, with similar adsorption capabilities to activated carbon. In addition, single or more sophisticated polymeric materials have become popular and been used more and more frequently in HPLC and GC/MS practices for the trace enrichment, separation and quantitative determination of commercial pesticides and residues in ranges below ng/g. Polymeric materials are characterized with lower energy demands and, consequently, lower costs for regeneration or renewal of the adsorbents, in comparison with carbonaceous materials. However, their investigation and application as adsorbent are very limited, in comparison to carbonaceous materials.

ABBREVIATIONS

AC	Activated Carbon
b	Langmuir parameter, (l/mol)
C^*	Reference number in Table 1
C_{ad}	Mol of adsorbate per unit weight (or surface) of adsorbent at equilibrium (mol/g or mol/m^2)
C_{eq}	Mol of adsorbate remained in the solution at equilibrium (mol/l)
c_s	Solubility (mol/l)
D_p	Effective macropore diffusivity, (cm^2/s)
DR	Dubinin–Radushkevich isotherm
D_s	Effective surface diffusivity coefficient, (cm^2/s)
E	Adsorption energy (kJ/mol)
EBC	Equivalent Background Compound
f	fraction of macropore region
Fp	Freundlich parameters
GAC	Granular Activated Carbon

HPLC	High Performance Liquid Chromatography
HSDM	Homogeneous Surface Diffusion Model
IAST	Ideal Adsorbed Solution Theory
K_F	Freundlich parameter, (μmol/g) (l/μmol)$^{1/n}$
k_f	liquid film mass transfer coefficient (cm/s)
k_L	external mass transfer coefficient (cm/s)
Lp	Langmuir parameters
n	Freundlich parameter, dimensionless
NOM	Natural Organic Matter
P*	Reference number in Table 3
PAC	Powdered Activated Carbon
R	Universal constant, l atm/(mol K)
Ref.	Reference item number in Table 1 or Table 3
RSSCT	Rapid Small Scale Column Test
T	Absolute temperature (K)
v_m	Langmuir parameter (mol/g or mol/m^2)
WC	Wheat residue Carbon

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