Review Article

Understanding the Degradation of Carbofuran in Agricultural Area: A Review of Fate, Metabolites, and Toxicity

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ABSTRACT

Pesticides are commonly applied in agriculture to manage pests, parasites, weeds, and other crop diseases to maximise product output value and minimise or reduce yield losses. Pesticides are widely and indiscriminately used in crop production in most countries. Carbofuran is a highly toxic insecticide commonly used to protect crops in agricultural areas. Exposure to carbofuran can cause harmful effects on both the ecological environment and human health, particularly on non-target species such as birds and aquatic organisms. Carbofuran continues to be used, although it has been banned in some countries. This review paper highlights carbofuran usage, its residue, toxicity, and mechanisms of degradation pathways in water, soil, and food, especially in agriculture. It has been shown that hydrolysis, photolysis, and microbial degradation are the main pathways for carbofuran degradation. Carbofuran phenol is significantly less toxic than all photo-metabolites, while 3-ketocarbofuran and 3-hydroxycarbofuran are practically as harmful as the parent compound. Hence, more study is needed on degradation pathways that may thoroughly minimise the toxicity of this deadly pesticide.

INTRODUCTION

Pesticides are compounds or a mix of chemicals designed to kill, prevent, or control pests (Cossi et al., 2020). According to the terminology used in the agricultural

industry, "synthetic pesticide" refers to any pesticide manufactured and not found naturally. Synthetic pesticides are generally produced through chemical synthesis and are designed to be more potent and persistent than their natural counterparts (Ahmadi, 2019). Organochlorines, organophosphates, carbamates, and pyrethroids are classes of synthetic pesticides. In contrast to synthetic pesticides, pesticides derived from natural sources, such as plants or microbes, are often called "biopesticides" or "organic pesticides". Biopesticides are derived from living organisms and their by-products, and they typically have low toxicity levels and little environmental impact (Ayilara et al., 2023).

Pesticides are used to control a wide range of pests, such as insects, plant pathogens, weeds, microbes, nematodes (roundworms), molluscs, mammals, birds, and fish, which cause massive losses in plantations and properties, spread infectious diseases, and act as disease vectors. Moreover, applying pesticides against pests and air-borne diseases improves the agricultural sector's economic output and boosts crop yields (Idayu et al., 2014; Okoli et al., 2017). Despite having significant benefits, there are serious concerns regarding the effects of pesticides, such as their potential toxicity toward humans and other animals (Daliya et al., 2020).

Malaysia is an agriculture-based country with vast areas reserved for plantations and farming. 70% of the cropland is devoted to oil palm and rubber plantations, which occupy more than 3.8 million hectares (Fatah et al., 2017). Given the massive demand for plantation produce in recent years, pesticides have been extensively used. It has been reported that applying pesticides leads to ground and surface water contamination and causes many undesirable effects and problems in tropical countries with heavy rainfall, high humidity, and high temperatures (Farahani et al., 2007; Ismail et al., 2004). In Japan, China, and the Republic of Korea, more than 10 kg/ha of pesticide are applied, while most Asian countries are below 1 kg/ha (Figure 1).

It represents an average annual growth rate of 1.6% in the net value of agricultural pesticides used during the past 15 years. Recently, about two million metric tonnes of pesticides have been used annually: herbicides (50%), insecticides (30%), fungicides (18%), rodenticides (9%), and nematicides (Sharma et al., 2019). Their transport, transfer, and transformation mechanisms determine pesticides' environmental fate. Herbicides in paddy fields, vegetable plantations in the Cameron Highlands, Pahang, Johor and tobacco-growing areas were studied (Boh & Yeang, 2002; Nashriyah & Azimahtol, 2002; Halimah et al., 2005; Ismail et al., 2015). It was also reported that surface and groundwater pollution due to pesticides had become a growing concern in tropical countries, including Malaysia (Sapari & Ismail, 2012).

Carbofuran is a highly hazardous pesticide that harms people, animals, and the environment. Due to its adverse effects, many countries, including Malaysia, have prohibited its use. However, as an alternative to chemical pesticides, there has been a recent
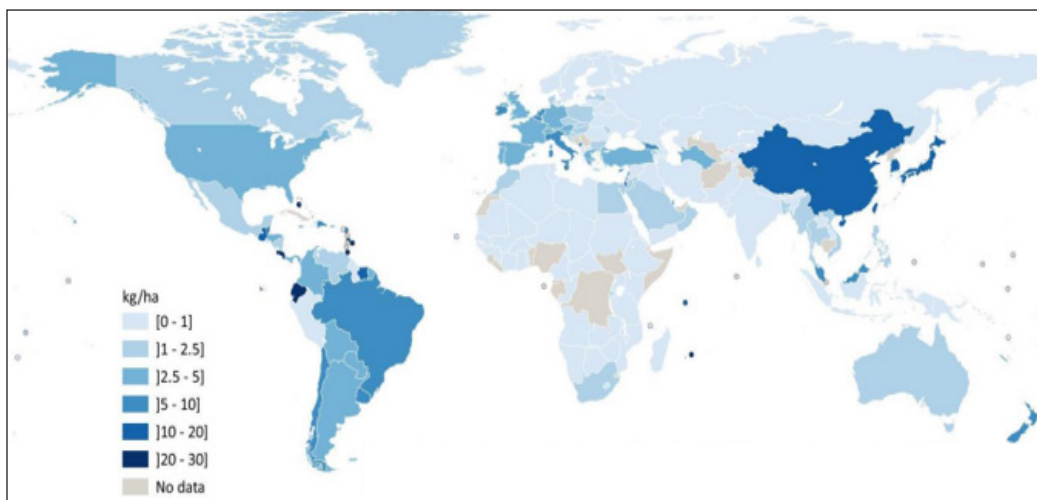
Figure 1. Pesticides use per cropland area, 2018 (FOA, 2020)

interest in using biological agents and natural pesticides. Natural pesticides are derived from natural sources such as plants, minerals, or microorganisms, whereas biological control agents are living organisms that feed on or parasitise pests (Yubak-Dhoj et al., 2021).

Biological control and natural pesticides are effective in pest control while posing the least risk to humans and the environment. They are frequently more specific and targeted than chemical pesticides, which can have unintended consequences for non-target organisms. Biological agents and natural pesticides are becoming more popular as safer and more sustainable alternatives to chemical pesticides such as carbofuran (Torres & Bueno, 2018).

In a study by Mustapha et al. (2019), 3-hydroxycarbofuran and 3-ketocarbofuran as carbofuran by-products are more polar but equally toxic to target and non-target organisms. Other known by-products of carbofuran include carbofuran phenol, 3-hydroxy-7-carbofuran phenol, and 3-keto-7-carbofuran phenol (through phenyl-ring oxidation/reduction and hydroxylation reactions), N-hydroxymethyl carbofuran, and 3-hydroxy-N-hydroxymethylcarbofuran (through methyl hydroxylation reactions). In plant tissue samples, 3-hydroxycarbofuran was higher and lasted longer than the parent compound (Ramasubramanian & Paramasivam, 2018; Ramesh et al., 2015).

The reaction pathways and breakdown of pesticides are crucial to determining the process involved, especially the nature of the reactive intermediates and their final products. In this way, proper management and control of the discharge of pesticides into the environment can be implemented (Fenner et al., 2013; Bose et al., 2021). For instance, water management is vital in rice production since the growth of the paddy field requires a large amount of water supply. Water from the main canal is channelled into each plot and retained for a certain period before being drained from the paddy field. Therefore,

the pesticides used in surface water would significantly affect the water quality and could threaten the lives of aquatic animals in the surrounding plantation.

This review aims to assess the reported concentrations of carbofuran residues and their effects on the environment and human health, as well as to discuss their insights on carbofuran usage, toxicity, and degradation, particularly in agriculture. Thus, we aim to emphasise the comprehensive mechanism of the carbofuran degradation pathway via hydrolysis, photolysis, and microbial degradation into its significant metabolites.

CARBOFURAN

Carbofuran (2,3-dihydro-2,2-dimethyl benzofuran-7-yl-N-methylcarbamate) is a broad-spectrum insecticide, acaricide, and nematicide. Carbofuran is classified under the general group of carbamate derivatives called furadan, curaterr, carbodan, carbosip, and chinufur, with its chemical structure shown in Figure 2 (Pyne, 2015; Mukaj et al., 2017).

It was during World War II that a lot of new methods were developed for dealing with pests. Many manufactured chemicals were tested for their insecticidal efficacy because of the pressing need to reduce human disease transmission by pests in tropical areas. Figure 3 displays a timeline of carbofuran usage throughout history. Carbamates, a third class of chemically synthesised insecticides, were identified by Swiss scientists in the 1940s. In the mid-1940s, the Geigy Chemical Company aimed to create an insect repellent and began working on carbofuran. A set of tests on carbamate compounds found that these compounds were ineffective insect repellents and poisonous to flies, mosquitoes, aphids, and other smaller pests. Geigy was prompted by this situation to explore the development of dimethyl carbamate insecticides instead of carbamate repellents (Mahindru, 2009).
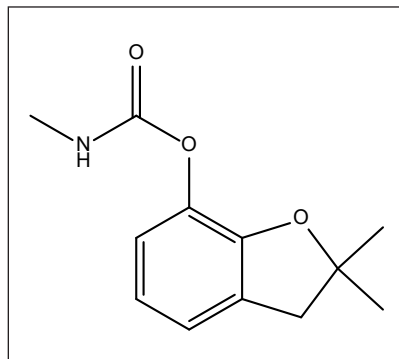

Figure 2. Carbofuran chemical structure
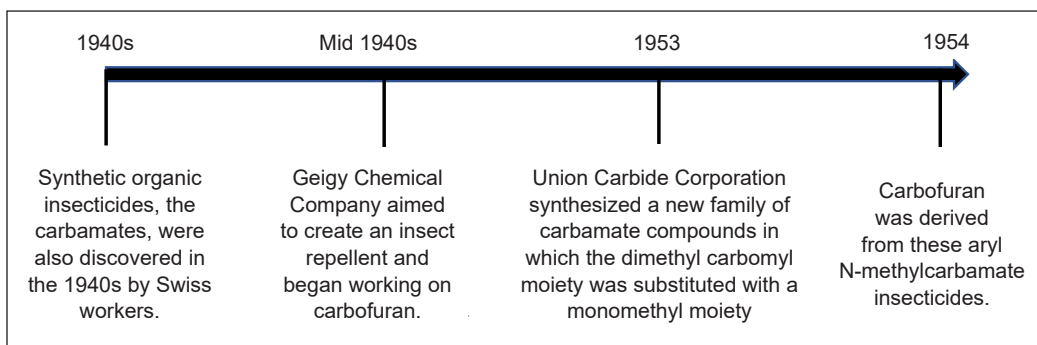
Figure 3. Timeline showing the history of the production of carbofuran

1940s	Mid 1940s	1953	1954
Synthetic organic insecticides, the carbamates, were also discovered in the 1940s by Swiss workers.	Geigy Chemical Company aimed to create an insect repellent and began working on carbofuran.	Union Carbide Corporation synthesized a new family of carbamate compounds in which the dimethyl carbomyl moiety was substituted with a monomethyl moiety	Carbofuran was derived from these aryl N-methylcarbamate insecticides.

In 1953, Union Carbide Corporation synthesised a new family of carbamate compounds in which the dimethyl carbamoyl moiety was substituted with a monomethyl moiety. Compared to dimethyl carbamic acids, the insecticidal properties of aryl N-methylcarbamate were superior (Park et al., 2013). Carbofuran was derived from these aryl N-methylcarbamate insecticides.

Carbofuran (2,3-dihydro-2,2-dimethyl-7-benzofuranyl-methylcarbamate) is a nematicide generally applied to soil or grassland. It is highly mobile and soluble in water (351 g/mL), posing a danger of environmental water pollution (Table 1) (Ćwieląg-Piasecka et al., 2021). The

Table 1
Carbofuran's physical and chemical characteristics (Otieno et al., 2010a)

Chemical formula	$C_{12} H_{15} NO_3$
Molecular weight	221.6 g/mol
Physical state	White crystalline solid
Flammability	Not flammable
Melting point	15 to 154°C
Density	1.180 (20 °C)
Vapour pressure	$2 \times 10\text{-}5$ mmHg (33°C) $1.1 \times 10\text{-}4$ mmHg (50°C)
Octanol/water partition coefficient	42.5
Water solubility	351 µg/ml (250°C)
K_{oc}	9–36 ml/g

pesticide has moderate sorption to soil, based on organic matter and clay mineral composition, though it is unclear which soil element has the strongest affinity (Cáceres et al., 2019; Khairatul et al., 2013). Carbofuran degrades faster in an alkaline medium but is relatively stable in neutral or acidic environments. It is hydrophilic at concentrations up to 700 mg/L, while its solubility decreases in organic solvents at less than 30 mg/L (Brasel et al., 2007).

As with carbofuran, it has a low solubility in water but a high solubility in acetone, acetonitrile, benzene, and cyclohexane. It degrades at temperatures above 130°C and stimulates combustion when ignited. The substance is available as a powder, granules, and flowable formulation in a solvent (USEPA, 2006). It has a shorter environmental half-life than chlorinated hydrocarbon insecticides, degrades faster, and is excreted by nontarget organisms. Carbofuran may reach the aquatic environment by runoff from treatment plantation fields, direct application or broadcasting of granular formulations, or drift from sprayable mixtures (Valente-Campos et al., 2019).

CARBOFURAN USAGE/RESIDUE IN AGRICULTURAL PRODUCTS

Carbofuran is a pesticide that is commonly used to repel pests and nematodes on a wide range of crops, including rice, potatoes, corn, and soybeans, because of its broad-spectrum biological action and comparatively low persistence compared to organochlorine pesticides (Kuswandi et al., 2017; Bedair et al., 2022).

In Asia, Australia, and South America, its use is widespread. Meanwhile, Canada, Kenya, Brazil, the United States, and the European Union are among the countries that

have banned or restricted the use of carbofuran. Canada banned carbofuran-containing pesticides in 2009 when Health Canada's Pest Management Regulatory Agency (PMRA) cancelled all carbofuran registrations (Health Canada, 2020). In 2010, Kenya prohibited carbofuran import, distribution, and sale. Carbofuran's registration in Brazil was suspended in 2011, effectively banning its use there. In 2008, the European Union banned the use of carbofuran in all its member countries. The United States Environmental Protection Agency (EPA) banned all carbofuran uses in the country in 2009, claiming risks to human health and the environment (U.S. EPA, 2009).

Aubergines and other vegetables in Malaysia are often treated with carbofuran (Sim et al., 2019). It is an approved insecticide until May 2023, when it will be banned in agriculture (Pesticides Act 1974, 2021). The Pesticides Board of Malaysia, which oversees controlling pesticides in Malaysia, has said that carbofuran will be banned on April 20, 2021. The ban was put in place because the chemical was harmful to people and the environment, as well as to wildlife and organisms that were not its intended target.

About 1% of the earth's surface is used to grow paddy rice (Oryza sativa) because it is grown on every continent except Antarctica. Over half of the world's population uses rice as its primary food, which ranks second to wheat in global cultivation (Kumar et al., 2020). Given that rice is the only food crop cultivated during the rainy season in the tropical areas of Asia, the region has contributed over 90% of the world's rice production. Malaysia's land area used for rice cultivation has remained consistent since the 1980s at roughly 0.7 million ha. Nevertheless, rice productivity increased yearly, from 2.1 t/ha in 1961 to 3.6 t/ha in 2008. Similarly, total rice production has increased yearly since 1985, with an average annual increase of 28,000 metric tons (Ibitoye et al., 2014).

Table 2 summarises the amounts of carbofuran residues in water from the different agricultural industries. Carbofuran is a pesticide that can leave residues in treated products and is subject to maximum residue limits (MRL). However, it is important to note that MRLs for carbofuran may vary by country or region and are subject to periodic updates. Carbofuran levels in Canadian freshwater ranged from 0.03 to 158.5 mg/L, which is high. Carbofuran was discovered once (at 3.0 µg/L) in 678 samples from 1971 to 1986 (Health Canada, 2020). As for the USA, 1 µg/L of carbofuran was detected in streams (Papadakis et al., 2015), and 1 to 30 µg/L was discovered in groundwater (Conway & Pretty, 2013). For example, carbofuran has been heavily used in Kenya, increasing environmental contamination. (Otieno et al., 2011). Several samples of surface water from paddy fields were found to contain carbofuran at concentrations ranging from 0–3.395 µg/L, and those from lakes had carbofuran concentrations ranging from 0.949–1.671 µg/L, respectively (Chowdhury et al., 2012). It has been discovered that concentrations of carbamate insecticides in the environment that are higher than the limit set by the European Community (0.5 g/L) are unusual (Plese et al., 2005; Zhang et al., 2016).

Table 2

Concentration of carbofuran residues in water from the various matrixes

Concentration	Matrix	Reference
0.03–158.5 mg/L	Freshwater	Health Canada (2020)
1 µg/L	Streams	Papadakis et al. (2015)
1–30 µg/L	Groundwater	Conway and Pretty (2013)
0.18–14 µg/L	Drinking water	Howard (2017)
1–5 µg/L	Water table aquifers	Howard (2017)
0.1–0.5 µg/L	Rainwater	Howard (2017)
0.005–0.495 mg/L	Rivers	Otieno et al. (2011)
2.301 mg/L	Ponds and dams	Otieno et al. (2011)
0.949–1.671 µg/L	Lake's water	Chowdhury et al. (2012)
0–3.395 µg/L	Paddy water	Chowdhury et al. (2012)
233 µg/L	Paddy water	Clasen et al. (2014)
16–28 µg/L	Runoff water	Larson et al. (2019)
4.3 µg/L	Ground water	Moreira et al. (2015)

The highest values found in the paddy water exceed the values approved by the American Environmental Protection Agency (EPA) (40.0 g/L) and the European Community (<0.10 µg/L). The concentration of paddy water, 0–3.395 µg/L reported by Chowdhury et al. (2012), was below both MRL, but Clasen et al. (2014) showed carbofuran concentration exceeded the MRL with 233 µg/L. The United States Environmental Protection Agency (EPA) has set a Maximum Residual Disinfectant Level (MRDL) of carbofuran in drinking water at 0.04 parts per million (ppm), which is the highest level of a disinfectant allowed in drinking water, while the World Health Organization (WHO) recommends a detection limit of 0.9 µg/litre for carbofuran in water and provides analytical methods to measure its concentration (Edzwald, 2011; World Health Organization, 2020).

Also, Farahani et al. (2007) and Khuntong et al. (2010) measured the amount of carbofuran residue in agricultural fields, rivers, and estuaries worldwide. However, understanding the breakdown of carbofuran and its transformation products is limited solely to the parent compounds. To date, researchers have not considered the potential hazards of its derivative products. Carbofuran pollution in rice-field waterways, mainly contributed through runoff, is plausible due to its widespread use in paddy cultivation and relatively good solubility in water (320 mg/L at 20°C) (Clasen et al., 2014).

Table 3 shows carbofuran concentrations in surface soil. Even though soil residue levels were low, water contamination by runoff and secondary transfer to smaller birds were still feasible. Carbofuran concentrations were relatively higher in the rainy season than in the dry season, indicating that it dissolves quickly and can be detected in the soil soon after application. Moreover, Otieno et al. (2012) reported that pesticide residues, including

Table 3
Carbofuran concentration residues in soil from various agricultural areas

Concentration	Soil type	Region	Reference
0.146 mg/kg	Farm soil	Isiolo	Otieno et al. (2011)
0.176 mg/kg	Farm soil	Laikipia	Otieno et al. (2011)
4.9 mg/dm	Sandy soil	Netherland	Leistra and Boesten (2008)
0.01–0.54 µg/kg	Polish soil	Poland	Ukalska-Jaruga et al. (2020)
0.2479 mg/L	Paddy soil	Brazil	de Melo Plese et al. (2005)
2.35 µg/g	Sandy clay soil	N. Sembilan	Farahani et al. (2008)
5.80 µg/g	Clay soil	Perak	Farahani et al. (2008)
148 µg/g	Alluvial soil	Orissa	Ripley and Chau (2020)
202 µg/g	Laterite soil	Kerala	Ripley and Chau (2020)
0.178 ± 0.01 mg/kg	Paddy soil	Bangkok	Khuntong et al. (2010)
0.01–1.08 mg/g	Clay soil	Kenya	Jemutai-Kimosop et al. (2014)

carbofuran were elevated during the monsoon season due to increased agricultural runoff that discharged large amounts of pesticide residues into waterways.

In addition, carbofuran is known to be more resistant to insecticides than other organophosphorus (OP) or carbamate insecticides. Since 0.15–0.33 mg/kg of carbofuran was found in milk products, hens' tissues, and eggs (World Health Organization, 2020), carbofuran has been banned in several countries (Mishra et al., 2020). Plants are more tolerant to carbofuran than animals. Migratory waterflow risks can be decreased by restricting granular formulations with more than 3% active components.

Trevisan et al. (2004) found more carbofuran traces in the bagasse than in the whole fruit, but they decreased quickly during the sampling time. This insecticide was found to stay in the bagasse for at least 28 days, and there was evidence that it tended to build up when treated with multiple sprays and went down more slowly during this time. It shows that carbofurans are degraded quickly into their metabolites. Also, 3-hydroxy-carbofuran was found in a few bagasse samples from the treatment with the double rate (20 g a.i.100 L-1 water), but only in very small amounts (0.05–0.09 mg/kg). The summary of concentrations of carbofuran residues in vegetables, fruits, and food from the various agricultural industries is shown in Table 4.

Food safety is a major public concern worldwide, and most governments, private companies, and international organisations have established MRLs for food commodities to control an unacceptable risk of human toxicity. To avoid unacceptable health risks, pesticide residues in food commodities such as fruits and vegetables must be below MRLs. In developing countries, more cases of pesticide poisoning were reported than in developed countries (Azam et al., 2020; Latif et al., 2011). Carbamate concentrations significantly exceeded MRLs in many samples; carbofuran concentrations exceeded MRLs in 80 samples, respectively. Carbamates, like OPs, are acetylcholinesterase enzyme system

Table 4

Concentration of carbofuran residues in vegetables, fruits, and food from various agricultural products

Concentration	Vegetable, fruit, and food	Reference
0.15–0.33 mg/kg	Milk product & eggs	Health Canada (2020)
48.3±5.3 µg/g	Long bean	Lan et al. (2019)
73.7±4.9 µg/g	Chives	Lan et al. (2019)
22.6±3.2 µg/g	Mango	Lan et al. (2019)
51.9±6.1 µg/g	Watermelon	Lan et al. (2019)
0.001 mg/kg	Apples	EFSA (2014)
0.001 mg/kg	Potato	EFSA (2014)
0.002 mg/kg	Lettuce	EFSA (2014)
0.01 mg/kg	Citrus fruit	EFSA (2014)
8-17 µg/kg	Tobacco	USEPA (2006)
19–36 µg/kg	Corn	USEPA (2006)
14–18 µg/kg	Cotton	USEPA (2006)
0.075 mg/kg	Sugarcane	Kabir et al. (2007)
0.86 ± 0.10 mg/kg	Orange (bagasse)	Trevisan et al. (2004)
0.07 ± 0.02 mg/kg	Orange (Whole fruit)	Trevisan et al. (2004)

inhibitors, but because of their high mammalian toxicity and the even greater toxicity of their intermediates, carbamates are a potential environmental concern (Liu et al., 2019; Syed et al., 2014).

TOXICITY OF CARBOFURAN

The acute toxicity level of carbofuran differs between organisms. The toxicity of carbofuran to mammals is higher through the oral and inhalation routes than the dermal route. Furthermore, carbofuran effects in humans are associated with reproductive disorders, endocrine-disrupting activity, and cytotoxic and genotoxic abnormalities (Mishra et al., 2020). In past years, carbofuran has emerged as a global contaminant that can harm health and the environment (Figure 4). Massive carbofuran use can significantly affect non-target species via many pathways.

The World Health Organization (2020) classified carbofuran as a highly hazardous class 1b pesticide (rat oral [lethal dose 50%] LD50 ranging from 5 to 50 mg/kg). Despite the decision by WHO, the classification does not take into consideration the fact that the technical product provided a safer profile through the dermal route (LD50 > 1,000 mg/kg and LD50 > 2,000 mg/kg in rats and rabbits, respectively), which should have classified carbofuran as class II or III (moderately or slightly hazardous) under WHO guidelines (Numan et al., 2018). Although such classifications help standardise the comparison of technical products, the information becomes less relevant under practical field applications as pesticide users are in direct contact with the formulations and not the technical product.
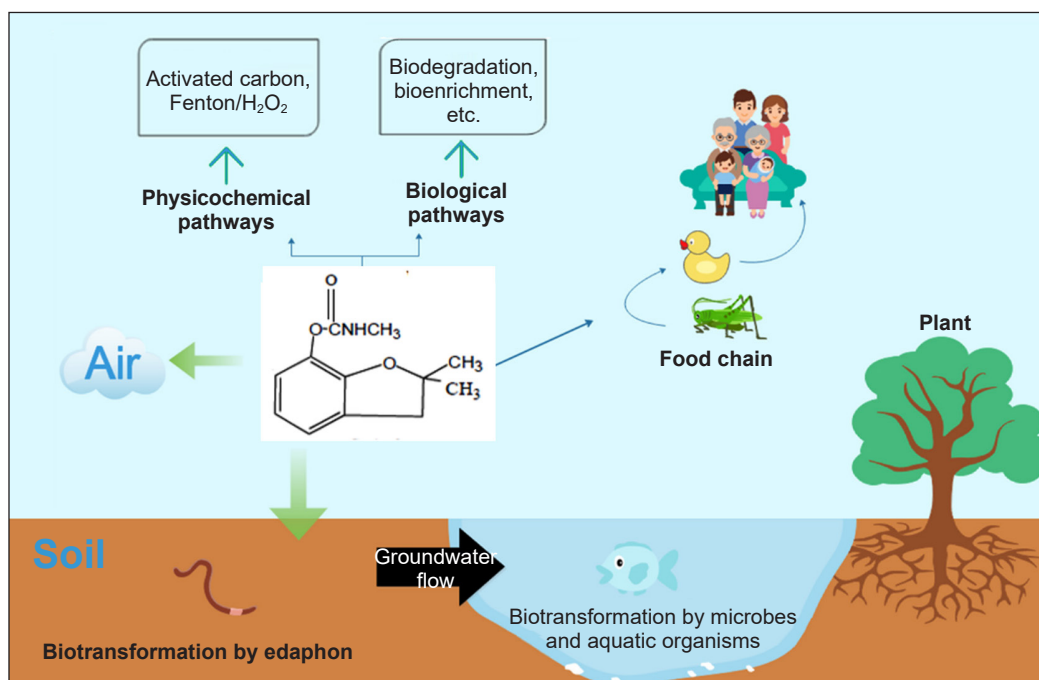
Figure 4. Contamination and degradation of carbofuran from the natural environment (Zhang et al., 2021)

Hence, the information regarding the toxicity of the end-use formulation only serves as a guideline to establish relevant warnings for users.

Carbofuran has caused the deaths of irregular fish, animals, and invertebrates recommended application rates and compositions. In short-term laboratory studies, sensitive aquatic biota died at 200 ppb carbofuran (in water), 238 ppb (acute oral), 190,000 ppb for birds, 2,000 ppb (acute oral) and 100,000 ppb (dietary) for mammals. Carbofuran is toxic and often life-threatening to fish at > 15 ppb and aquatic invertebrates at > 2.5 ppb. A level of 10 to 50 ppb in food and 1,000 ppb in drinking water is toxic to birds and mammals (Eisler, 1985; Kanedi, 2017). "Safe" carbofuran levels in beef are 50 ppb. The current allowable carbofuran aerosol levels of 0.05 ppb (50.0 g/m^3) appear sufficient to preserve animals, but data suggests they should never exceed 2 ppb (Eisler, 1985; Otieno et al., 2010b).

According to the National Centre for Biotechnology Information (2023), carbofuran has one of the highest acute toxicities to humans of any insecticide widely used on field crops, and it is stated that 1 ml (1/4 teaspoon) of carbofuran can be fatal to humans. This statement is supported by the National Oceanic and Atmospheric Administration's Chemical Emergency Response Tool, which indicates that a lethal oral dose for humans is 5 to 50 mg/kg or 7 drops to 1 teaspoon for a 150 lb. person (Alexeeff, 2000). It is important to note that carbofuran can cause serious effects on the maternal-placental foetal unit, and its toxicity can be potentiated by simultaneous exposure to other cholinesterase inhibitors.

The acceptable daily intake (ADI) estimates the amount of a substance that can be ingested daily over a lifetime without posing an appreciable health risk. The Food and Agriculture Organization (FAO) and the World Health Organization (WHO) have derived the ADI of carbofuran as 1.0 mg/kg bw per day (Ostergaard & Knudsen, 1998). The National Institute for Occupational Safety and Health (NIOSH) and American Conference of Governmental Industrial Hygienists (ACGIH) stated that the recommended airborne exposure limit for carbofuran is 0.1 mg/m^3 averaged over an 8 or 10-hour work shift (Satar et al., 2005).

In rats, mice, and lactating cows, carbofuran metabolism and excretion have been the subject of significant research. Absorption, degradation, and elimination from the oral dosage occur very quickly. Mixed-function oxidases are mammals' main enzymes responsible for metabolism, as 3-hydroxycarbofuran and 3-ketocarbofuran are the most prevalent carbamate metabolites. The toxicological effects of the carbofuran range on various matrixes are shown in Table 5.

A recent study (Mishra et al., 2020) found that grain farmers exposed to a low dose of carbofuran through the skin and the air for four days had carbofuran in their urine. Even though none of the farmers showed outward signs of being poisoned, the blood cholinesterase was significantly slowed down. Moreover, another study thoroughly discussed the metabolic

Table 5
Toxicological effects of carbofuran range on various matrixes

Study Sample	Concentration/Median Lethal Concentration (LC50)/Median Lethal Dose (LD50)	Reference
Cattle	3–19 mg/kg	Choez and Evaristo (2018
Chickens	2.5 mg/kg	Lehel et al. (2010)
Hamster	5–100 mg/mL	Soloneski et al. (2008
Rat	75 mg/kg	Gammon et al. (2012
Rat	1 mg/kg mg/kg	Islam et al. (2008)
Rat	1.2×10^{-8} mg/kg	Ferguson et al. (1984)
Human	4.6×10^{-8} mg/kg	Soreq and Zakut (1989)
Fly	2.5×10^{-8} µg/kg	Metcalf et al. (1968)
Birds	238 µg/kg	Eisler (1985)
Mammals	2000 µg/kg	Eisler (1985)
Catfish	23 µg/kg	Liong (1988)
Fish fillets	10.50 µg/kg	Tejada (1995)
Cat	2.5–3.5 mg/kg	Daul et al. (2012)
Guinea pig	9.2 mg/kg	Daul et al. (2012)
Dog	15.38 mg/k	Daul et al. (2012)
Rabbit	7.5 mg/kg	Daul et al. (2012)
Honeybees	0.16 µg/bee	USEPA (2006)
Japanese quail	1.7–1.9 mg/kg	Daul et al. (2012)
Pheasant	4.15 mg/kg	Smith (1992)

activity of carbofuran since the metabolites pose a substantial effect on the general toxicity of carbofuran (Ruíz-Hidalgo et al., 2016). Due to frequent reports of bird poisoning, carbofuran has been prohibited in several countries, particularly the United States, Canada, and the European Union (Sparling, 2016). The Royal Society for the Protection of Birds reported 316 incidents of bird poisoning due to carbofuran in the United Kingdom between 2002 and 2011 (Vincent, 2014). In addition, 3-ketocarbofuran and 3-hydroxycarbofuran, secondary metabolites of carbofuran, were also identified as poisonous. It was recorded that 187 vultures and hyenas died in 2004 after they scavenged bird carcasses containing carbofuran residue and its by-products (Plaza et al., 2019). Regardless of its severe effects, carbofuran is still broadly applied in Asia, South America, Australia, and Malaysia, which registered carbofuran as a legal pesticide (Sim et al., 2019).

CARBOFURAN DEGRADATION PATHWAYS IN THE ENVIRONMENT

Pesticide degradation breaks down pesticides into less toxic derivatives or their original elements (Sidhu et al., 2019). The degradation occurs through various processes or dissipation mechanisms once the pesticide enters the water and soil. Pesticides from the soil usually migrate into surface water, such as rivers, lakes, streams, and estuaries. Once in the water, it degrades according to the pseudo-first-order rate equation (Villaverde et al., 2018). The half-life of carbofuran in the environment is 30–120 days, based on where it is, the temperature, the pH of the soil or water, and medium humidity. The most common ways carbofuran and its by-products degrade are through hydrolysis, sunlight exposure, and biodegradation (Morales et al., 2012).

Various factors have been identified to influence the dispersion and degradation of pesticides, including the country's climate and the properties of the water and soil. In addition, the physical-chemical properties of the pesticides also determine how they disperse and degrade in the environment (Kumar et al., 2015). Because of its widespread use in agriculture, Carbofuran can react with water to form C–N bonds and break C–X bonds (X representing –OH group) (Jaiswal et al., 2017). Biodegradation regulates the fate and transformation of carbofuran use in nature. Research into the degradation of pesticides is widespread. Generally, carbofuran is degraded by hydrolysis, photolysis, microbial degradation and oxidation, as described in Figure 5 (Prosen, 2012; Elbashir & Aboul-Enein, 2015).
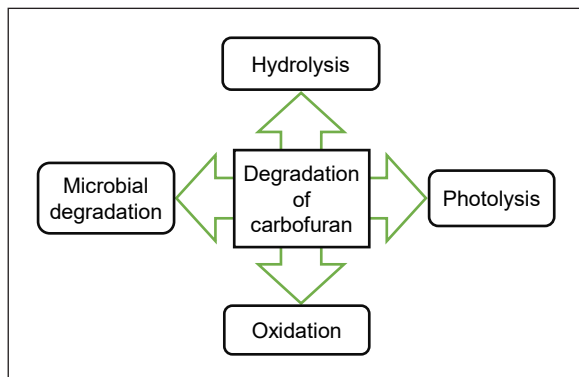

Figure 5. Degradation pathways for carbofuran

Hydrolysis Degradation

Most studies have concluded that hydrolysis and photolysis are the two most important degradation pathways for pollutants. Understanding the fate of a pesticide in water requires knowledge of the transformation mechanisms. Pesticide hydrolysis is a secondary and nucleophilic substitution reaction and fits first-order reaction kinetics (Singh et al., 2017). Morrica et al. (2001) state that temperature and pH are common hydrolysis factors. The degradation pathway takes place in both water and sediment through base-catalysed hydrolysis, which generates carbofuran phenol as well as other degradation products, such as 3-hydroxy-7-phenolcarbofuran and N-methylcarbamic acid via hydroxylation of the benzofuranyl moiety (Evert, 2002; Howard, 2017; Nafeesa et al., 2017; Sandín-España & Sevilla-Morán, 2012). The carbofuran (2,3-dihydro-2,2-dimethyl-7-benzofuranol methylcarbamate) molecule degrades when it reacts with water to form a new C–N bond and break a C–X bond in the parent molecule. The net reaction is a direct removal of X by OH (Plese et al., 2005; Ripley & Chau, 2020).

Carbofuran is generally stable in water at acidic and neutral pH, but the hydrolysis rate increases rapidly with increasing pH. The chemical degradation controls the environmental persistence of carbofuran, as shown in Figure 6. Hydrolysis is an effective alternative degradation route, with average lifetimes in waters ranging from 2 days at pH = 9.5 to 1,700 days at pH = 5.2 (Marine, 1999). Besides the pH, the temperature directly influences the degradation rate in hydrolysis.

It was reported that the hydrolysis half-life, $t^{1/2,}$ of carbofuran was 35 days at pH 7.0 and 350 days at pH 6.0 (Gammon et al., 2012). Acidic hydrolysis occurs under acidic conditions, which degrades slower than in alkaline conditions. For carbofuran, hydrolysis involves the cleavage of the carbamate bond in the compound, resulting in the formation of 3-hydroxy-carbofuran, which is less toxic than the original compound. Another previous study reported that carbofuran spikes recovered between 80% and 95% after 1, 3, and 6 hours at 25 °C and pH 8. On the contrary, the original amount of carbofuran recovered at pH 10 after 1, 3, and 6 hours was only 65, 35, and 10%, respectively (Bailey et al., 1996;
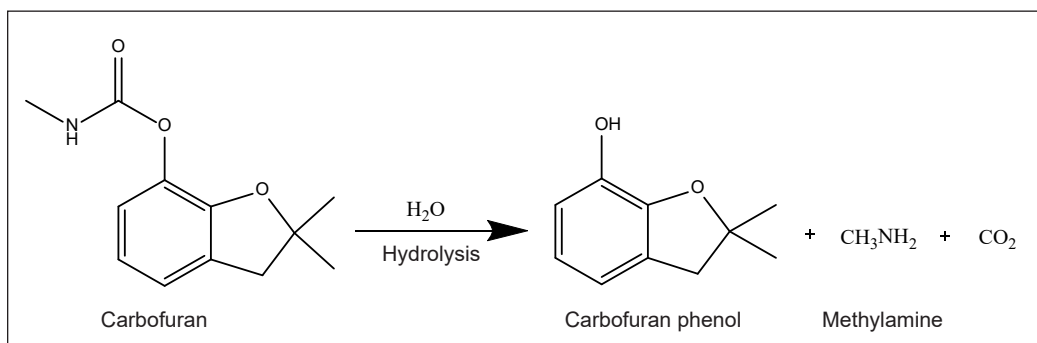

Figure 6. Hydrolysis mechanism of carbofuran (Filik and Çekiç, 2011)

Cycoń et al., 2017). The measured half-lives of carbofuran under acidic and alkaline conditions were 320 days and 150 days, respectively (Pinakini & Kumar, 2006).

Seiber and colleagues demonstrated that at pH 10, carbofuran hydrolysed 700 times faster than at pH 7, with half-lives of 1.2 and 864 hours, respectively. These results were collected from granule-treated paddy water. In addition, paddy water was hydrolysed faster than deionised water. At pH 7, paddy water half-lives were 240 and DI water 864 hours. At pH 8.7, paddy water and deionised water each had half-lives of 13.9 hours. Based on the results, the carbofuran half-life in paddy water (laboratory) at pH 8 was 40 hours, which was similar to the 57-hour half-life recorded from field samples at the same pH level, given slight variations in several factors, such as the source of light, pH level, the surrounding temperature, and the rate of microbial degradation (Howard, 2017; Mackay et al., 2006; Seiber et al., 1978).

Moreover, a higher rate of carbofuran hydrolysis was reported in anaerobic conditions. The hydrolysis rate of carbofuran under aerobic environments was compared to that in stable and undisturbed flooded conditions. Nevertheless, the degradation products, consisting of carbofuran phenol and 3-hydroxycarbofuran, were stable under anaerobic conditions, while further degradation was only observed under aerobic conditions. So, it was thought that the rapid hydrolysis of carbofuran was caused by cycles of flooding and drying that led to alternating anaerobic conditions (Venkateswarlu & Sethunathan, 1978; Ramakrishnan et al., 2019; Mohamed et al., 2021).

Hydrolysis was considered the most important degradation pathway, with a half-life ranging from 0.2 days at pH 9.5 to 1,700 days at pH 5.2. The rate of carbofuran hydrolysis in aqueous solutions accelerates significantly as the pH of the solution increases. The hydrolysis half-lives of carbofuran in water at 25°C is 690, 8.2, and 1.0 weeks at pH values of 6.0, 7.0, and 8.0, respectively. Hydrolysis reactions involve adding water to a large molecule to break it into multiple smaller molecules (Bailey et al., 1996).

The degradation pathways of carbofuran in water systems are shown in Figure 7. Hydrolysis was reported as the main mechanism leading to degradation in alkaline soils. On the other hand, acidic and neutral soils were dominated by microbial and chemical mechanisms, which led to slower degradation. Carbofuran phenol, 3-hydroxycarbofuran, and 3-ketocarbofuran are among the transformation products of carbofuran degradation that can be detected in soil (Acharid et al., 2006; Achik & Schiavon, 1989; Katagi, 2016).

One factor that reduces the effectiveness of insecticides in controlling the infestation of the brown planthopper Nilaparvata lugens, a significant pest of rice plants, is the rapid chemical hydrolysis of carbofuran in paddy water (Hayasaka et al., 2012). It was revealed that carbofuran phenol production from carbofuran degradation took only 5 days under alkaline paddy water conditions.

Furthermore, the effect of paddy water pH on carbofuran persistence was demonstrated in another study in which less than 5% of carbofuran remained after 5 days of application
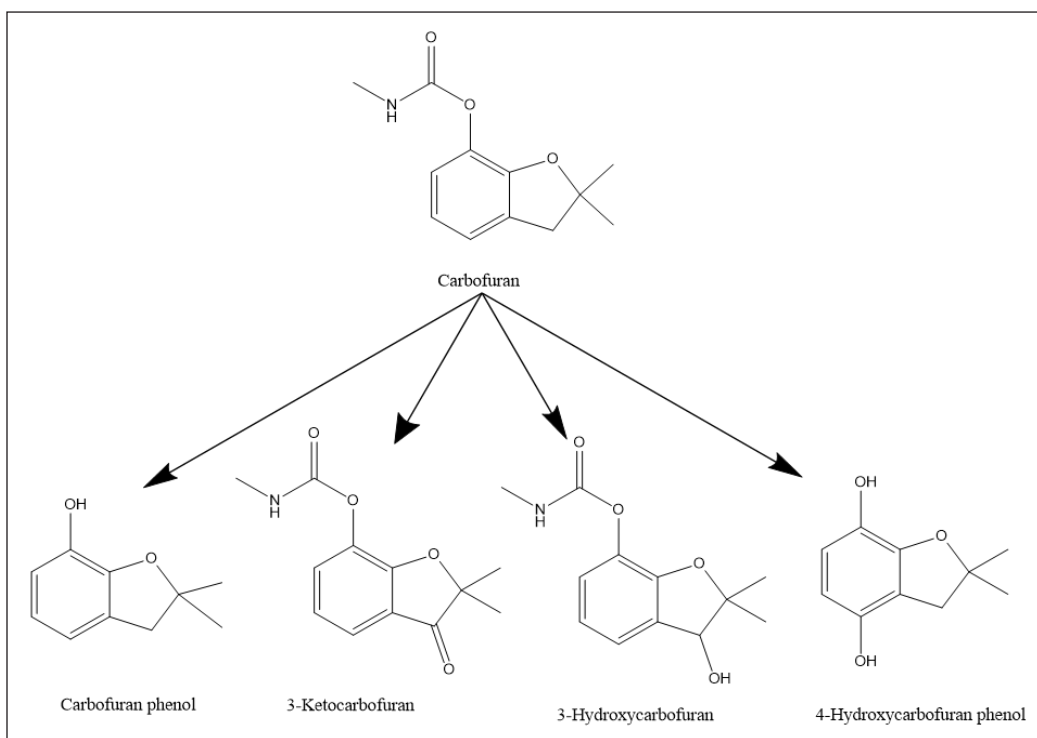
Figure 7. Environmental fate of carbofuran in water (Evert, 2002)

at pH 8. In contrast, the remaining amount of intact carbofuran after 10 days was 70% and 14% at pH 6 or lower and pH 7.1, respectively (Siddaramappa & Seiber, 1979; Roger & Bhuiyan, 2012; Xu et al., 2014). Other studies have also shown that hydrolysis and photochemical degradation are the major degradation pathways for carbofuran in water (Farahani et al., 2012; Tien et al., 2017). The biodegradation and pH of the water were among the main factors influencing the degradation of carbofuran.

Photolysis Degradation

Photolysis of pesticides leads to chemical changes in pesticides by absorbing light radiation directly and indirectly. In direct photolysis, the pesticide molecules absorb the photons directly, whereas in indirect photolysis, a carrier and other photochemical processes (photosensitizers) are involved (Fang et al., 2022). Photolysis and hydrolysis produce more polar and stable pesticides than the parent compounds. Some pesticides persist for several months, polluting the environment (Tien et al., 2017; Sim et al., 2019). There is, thus, a need for research into the by-products of carbofuran.

A less significant degradation pathway of carbofuran is through the photolysis reaction. Carbofuran is not likely to accumulate in sunlight-exposed water and does not bioaccumulate (Baumart et al., 2011). The metabolic product of photolysis includes

2,3-dihydro-2,2 dimethyl benzofuran-4,7-diol and 2,3-dihydro-3 keto-2,2 dimethyl benzofuran-7-yl carbamate (3-ketocarbofuran) (Mahalakshmi et al., 2007; Remucal, 2014). A comparison was made between the rate of carbofuran recovery in deionized water exposed to sunlight and laboratory light for 96 hours. According to the results, the average recovery of carbofuran was 75.6% for the sunlight-exposed samples and 93.3% for the artificial light-exposed samples, respectively. The large difference suggested the significant photolytic aqueous decomposition of carbofuran (de Melo Plese et al., 2005; Gunther & Gunther, 2013).

Carbofuran photolyzes directly, producing photoproducts. At the same pH level, photolysis occurs more rapidly in pesticides in seawater, freshwater, and humic acid solutions than in distilled water. Meanwhile, although no control was used, carbofuran in freshwater photolyzes faster than seawater. In one case, adding humic acids decreased carbofuran's direct photolysis rate (Raha & Das, 1990; Mahalakshmi et al., 2007). Figure 8 shows the metabolites' chemical structure. The transformation of carbofuran generated
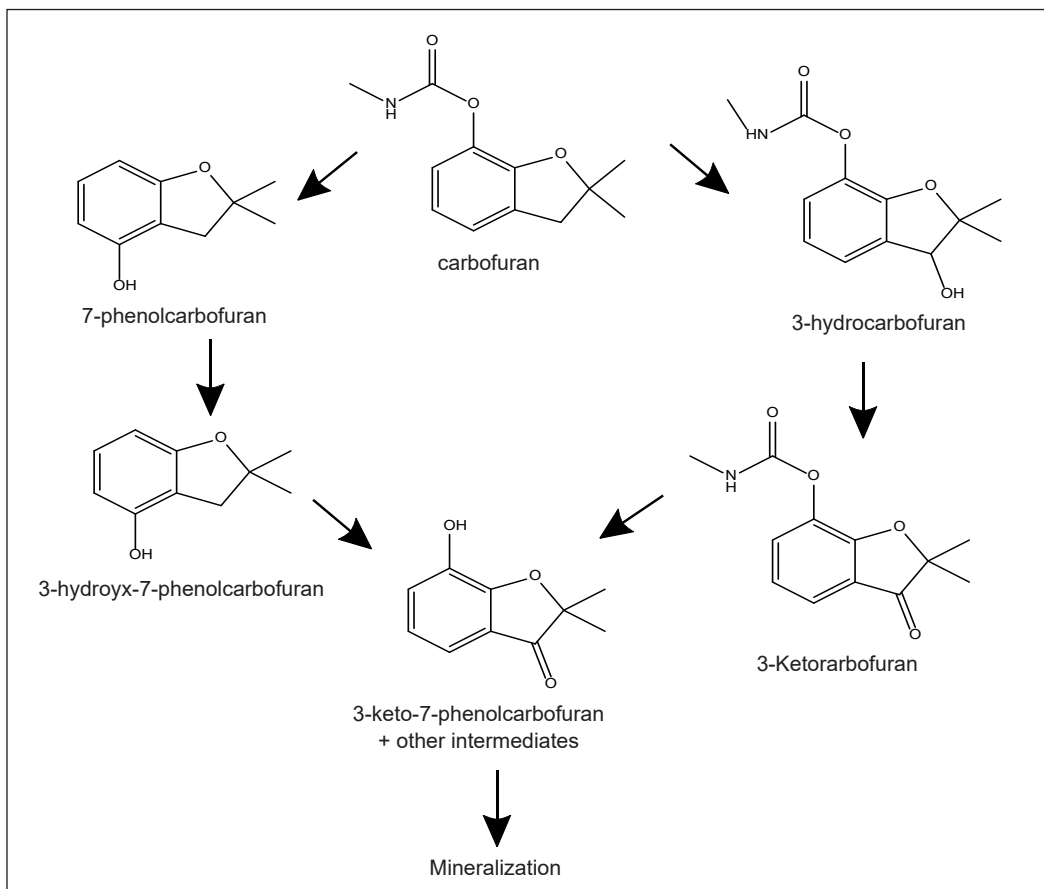

Figure 8. The chemical structure for the detected by-products of carbofuran (Mishra et al., 2020)

7-phenolcarbofuran, 3-hydroxycarbofuran, and 3-ketocarbofuran in all cases, while ZnO formed 3-keto-7-phenolcarbofuran.

Meanwhile, the vapour pressure and Henry's Law constant of carbofuran in the air are low, indicating that carbofuran has a low potential to volatilise from moist soils or water (Cid et al., 2011). Once carbofuran vaporises into the air, it is subjected to vapour-phase photooxidation by reacting with hydroxyl radicals. The half-life of this reaction at standard atmospheric conditions was estimated to be 4.6 hours (Howard, 2017). However, the oxidation and volatilisation of carbofuran in water were considered insignificant dissipation pathways (Wijesinghe et al., 2011).

As demonstrated in Table 6, the carbofuran half-lives in the Laysan and Ottawa sands were comparable (40–41 days), according to Campbell et al. (2004). In comparison, Seiber et al. (1978) found that the half-lives of carbofuran in DI water and paddy water (pH 7) were only slightly different when both were exposed to ultraviolet (UV) light and darkness in the lab. Bachman and Patterson (1999) suggested that the increase in the amount of dissolved organic matter (DOM) inversely reduced the photolysis rate of carbofuran. The assumption was made that the level of inhibition is proportional to the binding capacity of a specific DOM sample. Therefore, the binding of DOM reduced the rate of photolysis and slightly improved the persistence of carbofuran (Bolan et al., 2011).

It is interesting to highlight that the rate constant for the degradation of carbofuran in sunlight-exposed seawater was higher than in sunlight-exposed fresh water. Consequently, the half-life of carbofuran in sunlight-exposed fresh water was longer than that in sunlight-exposed seawater, in line with a similar trend observed by others (Farahani et al., 2012). Campbell et al. (2004) observed that the half-life of carbofuran in sunlight-exposed seawater (7.5 hours) was approximately 6 times faster than in sunlight-exposed DI water (41.6 hours), with the same rate of degradation in seawater (0.1 hours) as in DI water (3.1 hours) under a light intensity of 300 nm. This difference (6–31 folds) and the differences

Table 6

Carbofuran half-lives and photodegradation constants, k

Matrix	Light source	-k	Half-life
Ottawa sand	Dark	0.0151/day	39.7 day
Laysan sand	Dark	0.0182/day	40.9 day
Distilled deionised water	300 nm	0.1941/h	3.1 h
Seawater	300 nm	0.328/h	0.1 h
Distilled deionised water	Sunlight	0.0162/h	41.6 h
Seawater	Sunlight	0.1284/h	7.5 h
Distilled deionised water	Ultraviolet (UV) light	0.105×10^{-2}	27.5 day
Paddy water	Ultraviolet (UV) light	0.04	7.2 day
Distilled deionised water	Dark	0.092	31.4 day
Paddy water	Dark	0.41	9.3 day

observed in the present research were presumably due to differences in water composition (Campbell et al., 2004; Remucal, 2014; Mishra et al., 2020; Maksuk, 2021). Carbofuran's photodegradation may be aided by the existence of organic compounds, ions, and chemical sensitizers (Wang et al., 1998; Huang & Mabury, 2000; Seo et al., 2012; Wols & Hofman-Caris, 2012).

The degradation rate of pesticides also varies between countries with tropical and temperate climates. Among the main climate elements that affect the rate of pesticide degradation are the mean temperature in the region, the mean amount of rainfall, the average amount of sunlight emitted, and the existence of microbes (Daam et al., 2008). Tropical countries generally experience more rainfall than temperate-climate countries. According to past studies, the pesticide contamination of soil and water can be influenced by rainfalls through the dilution of the concentration of pesticides in the environment or by leading to pesticide runoffs that could flow into the watersheds and irrigation channels (Abdullah et al., 1997; Daam & Van den Brink, 2010).

Microbial Degradation

Microbial degradation mainly occurs in water and soil when microorganisms are present. Microbial degradation includes complex biological processes. Therefore, it requires ideal conditions such as pH, temperature, and nutrient availability (Grandclément et al., 2017). The pH level and microorganism types in the water determine the rate of microbial degradation in a flooded rice field (Hayasaka et al., 2012). Depending on the metabolic pathways of microbes, microbial degradation can occur under either aerobic or anaerobic conditions, depending on oxygen availability.

Aerobic metabolism is the process of converting organic compounds into energy using oxygen. This reaction occurs in the presence of oxygen, and the end products are typically carbon dioxide and water. Aerobic microorganisms are commonly used to degrade organic pollutants in the environment in bioremediation processes. These microorganisms use enzymes such as monoxygenases and dioxygenases to oxidise and degrade organic compounds (Diale et al., 2022).

Breaking down organic compounds without using oxygen is known as anaerobic metabolism. This process occurs without oxygen and can be carried out by microorganisms such as bacteria and fungi. In terms of energy production, anaerobic metabolism is less efficient than aerobic metabolism, and the end products vary depending on the metabolic pathway. Some anaerobic bacteria, for example, use sulphate or nitrate as a final electron acceptor, producing hydrogen sulphide or nitrogen gas.

Fungi are also essential in microbial degradation, particularly in the breakdown of lignin, a complex polymer found in plant cell walls. Fungi use enzymes like lignin peroxidase and manganese peroxidase to break down lignin into simpler compounds that

other microorganisms in the environment can use. The fungal metabolism of carbofuran is a new area of study, and it has been shown that different fungal strains from the genera Trichoderma, Pichia, Trametes, Aspergillus, Aschochyta, Xylaria, Acremonium, Gliocladium, and Mucor can degrade carbamate pesticides (Mustapha et al., 2019).

Carbofuran was metabolised by *Mucor ramannian* to produce carbofuran phenol, which was then metabolised to yield 2-hydroxy-3-(3-methylpropan-2-ol) phenol, also known as 7a-(hydroxymethyl)-2,2-dimethylhexahydro-6H-furo[2,3-b]pyran6-one and 3-hydroxy carbofuran-7-phenol (Sun et al., 2022). Among the pyrethroid pesticides, *Trametes versicolor* has been found to degrade carbofuran, imiprothrin, and cypermethrin. In the spent media analysis, 3-hydroxycarbofuran was the only intermediate of carbofuran degradation. It has been reported that the non-specific *monooxygenase cytochrome*-P450 plays a significant role in carbofuran metabolism in this strain. (Mir-Tutusaus et al., 2014).

Pesticides degraded by microorganisms serve as a food supply for growth and energy. Based on recent studies, microbes are responsible for the breakdown of natural organic materials and the degradation of numerous xenobiotic chemicals such as petroleum hydrocarbons, pesticides, and organic solvents (Ariffin & Rahman, 2020). Strachan et al. (2018) reported that microorganisms used s-triazine herbicide as an energy source during their degradation. The conversion of contaminants into less harmful substances via microbial degradation is likely in the case of mineralisation, while in certain situations, mostly under anaerobic transformation, toxic products can also be produced (Onunga et al., 2015).

Bacteria capable of efficiently degrading carbofuran have been discovered in soil, sludge, and water contaminated with carbofuran (Mishra et al., 2020). *Pseudomonas, Flavobacterium, Achromobacterium* sp*., Sphingomonas* sp*., Arthrobacter* sp*., Enterobacter* sp*., Burkholderia* sp. *PLC3, Cupriavidus* sp. *ISTL7* and *Bacillus* sp. were isolated and characterised to determine their mechanisms for degrading pesticides. *Sphingomonads (Sphingomonas, Novosphingobium, Sphingopyxis,* and *Sphingobium*) may be the ideal carbofuran-degrading bacteria. These bacteria degrade carbofuran and carbofuran-phenol better than others (Nguyen et al., 2015; Yan et al., 2007). So far, numerous bacterial strains from the genera *Stenotrophomonas, Achromobacter, Flavobacterium, Pseudomonas, Sphingomonas, Novosphingobium, Paracoccus, Aminobacter*, and *Cupriavidus* can degrade carbamate insecticides (Gupta et al., 2019; Jiang, Zhang, et al., 2020).

Microbial degradation can benefit the environment by using microorganisms to break down and transform pollutants into less harmful substances. Microbes play key roles in biodegradation, which recycles biologically essential elements within the earth's biogeochemical cycles (Jørgensen, 2008). Microbial degradation is a possible and environmentally friendly way to degrade carbofuran. However, most prior studies on carbofuran degradation have focused on bacterial degradation, and the degradation rates remain slow (Mishra et al., 2020).

In general, the use of microbial degradation for environmental remediation can have several advantages over other methods, such as physical or chemical treatments. For example, microbial degradation can be a cost-effective and environmentally friendly approach, as it can occur naturally and may not require additional chemicals or energy (Liu et al., 2021). Continuous exposure to pollutants and synergy with other strains make microbial consortiums more suitable for environmental remediation. Microbial consortiums or mixed cultures degrade carbofuran residues on a large scale. Tondon et al. (2018) discovered four carbofuran-degrading bacterial strains from contaminated soil samples: *Arthrobacter globiformis, Bhargavaea indica, Bacillus beijingensis,* and *Streptomyces sp.* Table 7 shows an overview of the microbial species studied for carbofuran biodegradation. Several strains of bacteria and fungi from different sources have been studied.

Microbial degradation completely mineralizes carbofuran into non-toxic substances and CO_2. As a result, microbial carbofuran degradation is an effective and practical method. Microbes mostly use oxidative and hydrolytic mechanisms to eliminate carbofuran. Figure 9 illustrates carbofuran's comprehensive microbial degradation pathway and describes carbofuran's microbial degradation into its significant metabolites: carbofuran phenol, methylamine, and CO_2. Carbofuran and carbofuran phenol are formed in *Sphingomonas* sp, but the bacterium cannot grow on them. The hydroxylase-reductase pair CfdCX and *Novosphingobium* sp conduct carbofuran phenol production.(Malhotra et al., 2021).

Table 7
Microbial degradation of carbofuran in soil by different microbes

Microbial species, Strain or Community	Sample sources	Reference
Sphingomonas sp.	Soil	Park et al. (2006)
Mucor ramannianus	Soil	Seo et al. (2007)
Novosphingobium sp. FND-3	Sludge	Yan et al. (2007)
Paracoccus sp. YM3	Sludge	Peng et al. (2008)
Enterobacter sp.	Soil	Mohanta et al. (2012)
Pseudomonas and *Alcaligenes*	Soil	Omolo et al. (2012)
Burkholderia sp. PLC3	Soil	Plangklang and Reungsang (2012)
Novosphingobium sp	Soil	Nguyen et al. (2014)
Bacillus sp.	Soil	Onunga et al. (2015)
Consortia	Soil	Tien et al. (2017)
Pseudomonas sp.	Soil	Devi et al. (2017)
Aspergillus sp.	Soil	Devi et al. (2017)
Enterobacter cloacae strain TA7	Soil	Fareed et al. (2017)
Arthobater globiformes	Soil	Tondon et al. (2018)
Streptomyces sp.	Soil	Tondon et al. (2018)
Cupriavidus sp. ISTL7	Landfills	Gupta et al. (2019)
Sphingbium sp. CFD-1	Sludge	Jiang et al. (2020)

Carbofuran phenol is further degraded into novel metabolites by carbofuran-degrading microorganisms and their hydrolase enzymes. In *Novosphingobium* sp. In KN65.2, the initial step involves hydrolysis of the carbamate linkage to form carbofuran phenol, methylamine, and CO_2 (Duc, 2022; Yan et al., 2018).

The hydrolytic pathway is more uncomplicated and produces fewer toxic by-products than the oxidative pathway (Kim et al., 2004; Nguyen et al., 2014). Hydrolase enzymes break methyl and N-methyl carbamic acid's amide and ester bonds to yield carbofuran 7-phenol, CO_2, and methylamine. The inducible oxidative enzyme hydroxylase transformed carbofuran to 4-hydroxycarbofuran. (Malhotra et al., 2021).

According to Garcia-Saavedra et al. (2018), a bacterial consortium degraded 34.99% of carbofuran in soil samples. Advances in biochemical, molecular, and biotechnological techniques have increased the potential of carbofuran-degrading microorganisms. Catabolic genes, enzymes, plasmids, mobile elements, and transposons all play essential roles in catalysing novel biochemical pathways during microbial degradation (Mishra et al., 2020). However, dehydrogenase and alkaline phosphatase activities in fertilised soil were greatly decreased by increasing carbofuran dosage (0.02–1.0 kg/ha to 5.0 kg/ha) compared to control soils (Singh et al., 2012).

The degradation process involves microbes (biodegradation), chemical reactions (chemical degradation), or light (photodegradation) (Tiryaki & Temur, 2010). The process relies on the pesticide's chemical composition and environmental conditions. Degradation of herbicides by soil bacteria and fungi can take hours to years. The degradation rate by 11 microorganisms increased under warm temperatures, ideal soil pH, appropriate oxygen, soil moisture, and good soil fertility and decreased under less favourable conditions (Meftaul et al., 2020). Pesticides degrade when they react with soil chemicals like water or oxygen. As soil pH becomes more alkaline or acidic, chemical degradation increases because microbial activity decreases (Tiryaki, 2017). In aerobic conditions, microorganisms convert organic contaminants to CO_2 and H_2O. On the contrary, anaerobic metabolic reactions occur without molecular oxygen (Furmanczyk et al., 2018; Kaida et al., 2018; Chaudhary & Kim, 2019).

Oxidation and Volatilization

Carbofuran is a commonly used carbamate derivative pesticide and a priority pollutant. Several studies have been conducted on the degradation of carbofuran by oxidation and volatilization processes. Considering that biological treatment methods involve lengthy residence times and thermal treatment can generate secondary pollutants, oxidative reactions are favoured for the rapid degradation of contaminants (Zheng et al., 2022). Therefore, a variety of effective treatment techniques, such as ultrasonic process, UV + Fe(III), UV/TiO_2 and UV/O_3 have been applied for carbofuran removal from aqueous samples (S. Lu et al., 2021; Oliveira et al., 2006).
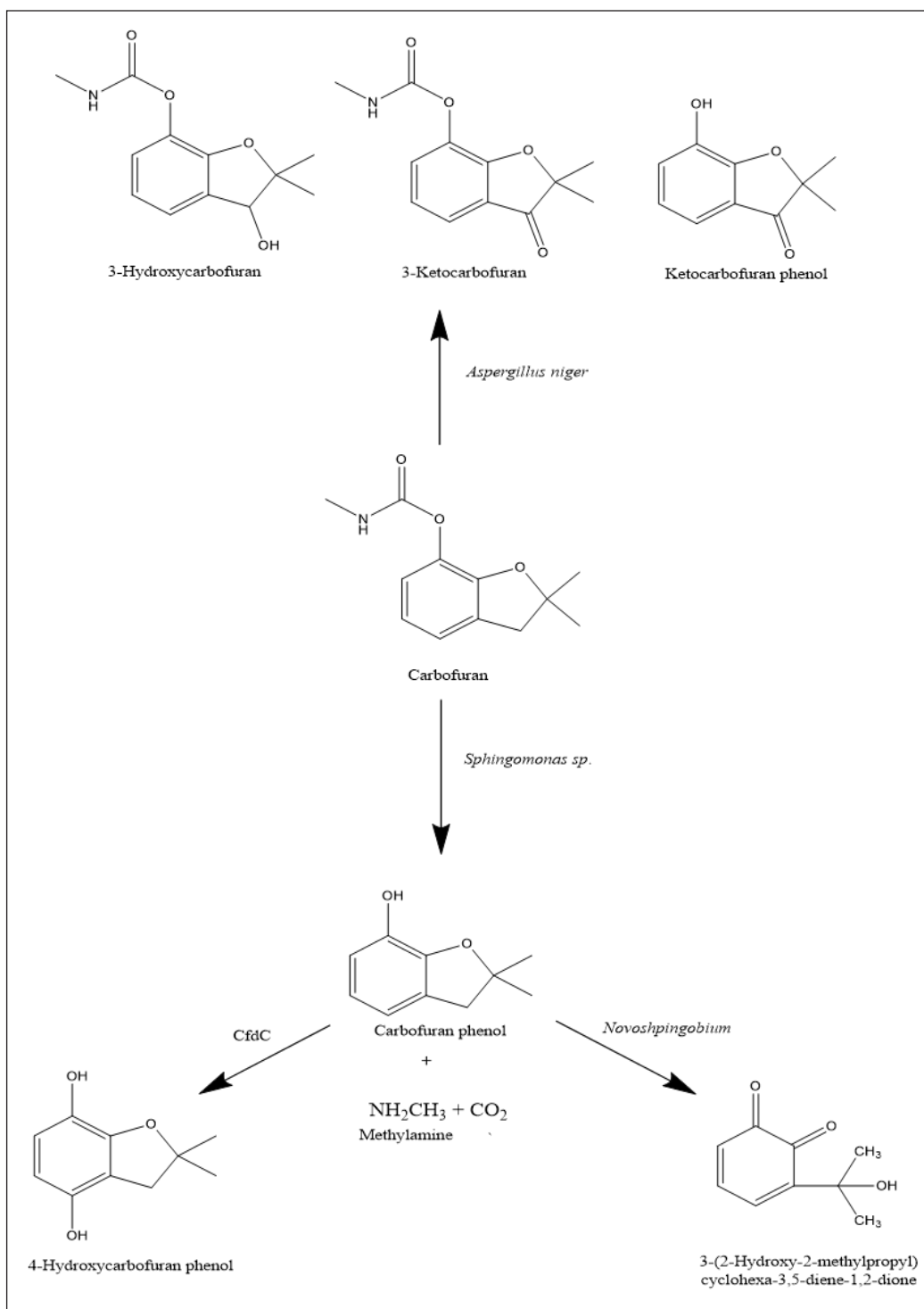
Figure 9. The microbial metabolic mechanisms for the carbofuran degradation in *Asperagillus niger, Sphingomonas* sp*.,* and *Novosphingobium* sp*.* (Jiang, Gao et al., 2020; Mishra et al., 2021)

Ma et al. (2009) analysed four degradation products that produced three intermediates, including 1,4-benzenedicarboxaldehyde anion, 7-benzofuranol, 2,3-dihydro-2,2-dimethyl (also known as 2,3-dihydro-2,2-dimethyl-benzofuran-7-ol), and 7-hydroxy-2,2-dimethyl-benzofuran-3-one, using GC/MS at retention times of 3.6 min, 7.44 min, and 13.8 min, respectively. The experimental results show that the Fenton process is an effective method for degrading carbofuran-contaminated water.

Javier Benitez et al. (2002) investigated how ozonation affects the breakdown of carbofuran. The research concluded that pseudo-first-order kinetics could be used to explain the global ozonation reaction. Temperature and partial ozone pressure significantly influence the removal rate of carbofuran. In contrast, similar degradation rates are obtained for pH 2 and 9 experiments, indicating a negligible contribution of the reaction with hydroxyl radicals generated by ozone self-decomposition at pH 9. The apparent pseudo-first-order rate constants for the ozonation reaction are calculated and found to be in the 5.1×10^{-4} to 19.5×10^{-4} s^{-1} range. A kinetic competition model was used to calculate the actual rate constant for the reaction between ozone and carbofuran at 20°C, which was 1108 l/mols (Bhat & Gogate, 2021; Javier Benitez et al., 2002).

In addition to these studies, advanced oxidation processes (AOP)s, which include ultraviolet radiation, ozone, and hydrogen peroxide, are the most effective at degrading carbofuran. Several studies have proven that AOPs are promising and attractive alternatives in treating organic pollutants that are either toxic or refractory to biological treatments (Pignatello et al., 2006; M. Zhang et al., 2019). AOPs mainly generate highly oxidative free radicals, mostly the hydroxyl radical (•OH) with an E° of 2.8 V/SHE (L.-A. Lu et al., 2011; Thomas et al., 2021).

In a separate investigation by Ma et al. (2010), the degrading of carbofuran was investigated using three different processes: ultrasound, the Fenton reaction, and a combination of the two. The researchers monitored the effects of various factors on the kinetics of carbofuran's degradation, including the dosages of H_2O_2 and Fe_2+ as well as the initial concentrations of carbofuran. After 30 minutes of reaction time with an initial carbofuran concentration of 20 mg/L and H_2O_2 and Fe_2+ dosages of 100 mg/L and 20 mg/L, more than 99% carbofuran degradation efficiency and 46% mineralization were achieved, all at pH 3, respectively. Increases in the Fenton reagents H_2O_2 and Fe_2+ improved degradation efficiency, but increases in the initial carbofuran concentration had the opposite effect (Anandan et al., 2020; Bhat & Gogate, 2021; Ma et al., 2010).

CONCLUSION

This review focused on carbofuran usage, toxicity, and degradation pathways for agricultural purposes. Hydrolysis and photolysis were suggested as the major degradation routes of carbofuran, followed by microbial degradation and oxidation. This process

generally reduces aqueous carbofuran concentrations when combined with microbial activity.

Several metabolites are formed during the breakdown of carbofuran. These include 3-hydroxy-carbofuran, 3-ketocarbofuran, carbofuran-phenol, and 3-hydroxy-5-nitrophenol. These metabolites vary in toxicity and persistence in the environment, with some being more lethal than the parent compound. The detailed pathways and mechanisms of their formation are determined by the degradation method involved. For example, microbial degradation can involve hydrolysis, oxidation, or reduction pathways, while photolysis can generate various metabolites via direct or indirect light reactions.

Based on the current research on carbofuran degradation, there are a few recommendations for future studies, such as bioremediation, advanced oxidation processes (AOPs), enzymes, and phytoremediation. Combining these methods can be an effective strategy for remediating soil and water bodies contaminated with carbofuran. Further studies are needed to enhance the conditions and increase the efficacy of these methods, not only on a laboratory level but also on a wide scale in field applications to benefit the community.

ACKNOWLEDGMENTS

REFERENCES

Abdullah, A. R., Bajet, C. M., Matin, M. A., Nhan, D. D., & Sulaiman, A. H. (1997). Ecotoxicology of pesticides in the tropical paddy field ecosystem. *Environmental Toxicology and Chemistry, 16*(1), 59-70. https://doi.org/https://doi.org/10.1002/etc.5620160106

Acharid, A., Quentel, F., Elléouet, C., Olier, R., & Privat, M. (2006). Coadsorption of carbofuran and lead at the air/water interface. Possible occurrence of non-volatile pollutant cotransfer to the atmosphere. *Chemosphere, 62*(6), 989-997.

Achik, J., & Schiavon, M. (1989). Carbofuran transfer and persistence in drained agricultural soils related to their structure and adsorption properties. *Ecotoxicology and Environmental Safety, 18*(1), 83-92. https://doi.org/https://doi.org/10.1016/0147-6513(89)90094-8

Al-Ahmadi, M. S. (2019). Pesticides, anthropogenic activities, and the health of our environment safety. In M. Larramendy & S. Soloneski (Eds.), *Pesticides - Use and Misuse and their Impact in the Environment* (pp. 73-95). IntechOpen. https://doi.org/10.5772/intechopen.84161

Fan, A. M., & Alexeeff, G. V. (2000). *Public Health Goals for Chemicals in Drinking Water*. California Environmental Protection Agency. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=58eef5d5e0102c8e7ea84da41ddf095d545ff50a

Anandan, S., Ponnusamy, V. K., & Ashokkumar, M. (2020). A review on hybrid techniques for the degradation of organic pollutants in aqueous environment. *Ultrasonics Sonochemistry, 67*, Article 105130.

Ariffin, F., & Rahman, S. A. (2020). Biodegradation of carbofuran: A review. *Journal of Environmental Microbiology and Toxicology, 8*(1), 50-57.

Ayilara, M. S., Adeleke, B. S., Akinola, S. A., Fayose, C. A., Adeyemi, U. T., Gbadegesin, L. A., Omole, R. K., Johnson, R. M., Uthman, Q. O., & Babalola, O. O. (2023). Biopesticides as a promising alternative to synthetic pesticides: A case for microbial pesticides, phytopesticides, and nanobiopesticides. *Frontiers in Microbiology*, *14*, 1-16. https://doi.org/10.3389/fmicb.2023.1040901

Azam, S. M. R., Ma, H., Xu, B., Devi, S., Siddique, M. A. B., Stanley, S. L., Bhandari, B., & Zhu, J. (2020). Efficacy of ultrasound treatment in the removal of pesticide residues from fresh vegetables: A review. *Trends in Food Science & Technology, 97*, 417-432. https://doi.org/10.1016/j.tifs.2020.01.028

Bachman, J., & Patterson, H. H. (1999). Photodecomposition of the carbamate pesticide carbofuran: Kinetics and the influence of dissolved organic matter. *Environmental Science & Technology, 33*(6), 874-881. https://doi.org/10.1021/es9802652

Bailey, H. C., Digiorgio, C., Kroll, K., Hinton, D. E., Miller, J. L., & Starrett, G. (1996). Development of procedures for identifying pesticide toxicity in ambient waters: Carbofuran, diazinon, chlorpyrifos. *Environmental Toxicology and Chemistry: An International Journal, 15*(6), 837-845. https://doi.org/10.1002/etc.5620150604

Baumart, J., Dalosto, M., & Santos, S. (2011). Effects of carbofuran and metsulfuron-methyl on the benthic macroinvertebrate community in flooded ricefields. *Acta Limnologica Brasiliensia, 23*(2), 138-144. https://doi.org/10.1590/S2179-975X2011000200004

Bedair, H., Rady, H. A., Hussien, A. M., Pandey, M., Apollon, W., AlKafaas, S. S., & Ghosh, S. (2022). Pesticide detection in vegetable crops using enzyme inhibition methods: A comprehensive review. *Food Analytical Methods, 15*(7), 1979-2000. https://doi.org/10.1007/s12161-022-02254-x

Benitez, F. J., Acero, J. L., & Real, F. J. (2002). Degradation of carbofuran by using ozone, UV radiation and advanced oxidation processes. *Journal of Hazardous Materials*, *89*(1), 51-65. https://doi.org/https://doi.org/10.1016/S0304-3894(01)00300-4

Bhat, A. P., & Gogate, P. R. (2021). Degradation of nitrogen-containing hazardous compounds using advanced oxidation processes: A review on aliphatic and aromatic amines, dyes, and pesticides. *Journal of Hazardous Materials, 403*, Article 123657. https://doi.org/10.1016/j.jhazmat.2020.123657

Boh, C. U., & Yeang, L. K. (2002). *Pesticide residues and microbial contamination of water resources in the MUDA rice agroecosystem*. Malaysian Institute for Nuclear Technology Research MINT. http://inis.iaea.org/search/search.aspx?orig_q=RN:37065380

Bolan, N. S., Adriano, D. C., Kunhikrishnan, A., James, T., McDowell, R., & Senesi, N. (2011). Dissolved organic matter: Biogeochemistry, dynamics, and environmental significance in soils. *Advances in Agronomy, 110*, 1-75. https://doi.org/10.1016/B978-0-12-385531-2.00001-3

Bose, S., Kumar, P. S., Vo, D. V. N., Rajamohan, N., & Saravanan, R. (2021). Microbial degradation of recalcitrant pesticides: A review. *Environmental Chemistry Letters, 19*, 3209-3228. https://doi.org/10.1007/s10311-021-01236-5

Brasel, J. M., Collier, A. C., & Pritsos, C. A. (2007). Differential toxic effects of carbofuran and diazinon on time of flight in pigeons (*Columba livia*): Potential for pesticide effects on migration. *Toxicology and Applied Pharmacology, 219*(2-3), 241-246. https://doi.org/10.1016/j.taap.2006.11.028

Cáceres, T., Maestroni, B., Islam, M., & Cannavan, A. (2019). Sorption of 14C-carbofuran in Austrian soils: Evaluation of fate and transport of carbofuran in temperate regions. *Environmental Science and Pollution Research, 26*(1), 986-990. https://doi.org/10.1007/s11356-018-3730-3

Campbell, S., David, M. D., Woodward, L. A., & Li, Q. X. (2004). Persistence of carbofuran in marine sand and water. *Chemosphere, 54*(8), 1155-1161. https://doi.org/10.1016/j.chemosphere.2003.09.018

Marine, N. R. G. (1999). *Canadian Water Quality Guidelines for the Protection of Aquatic Life*. Canadian Council of Ministers of the Environment. https://mde.maryland.gov/programs/Marylander/Documents/canadian_WQ_Chloride_(en)[1].pdf

Chaudhary, D. K., & Kim, J. (2019). New insights into bioremediation strategies for oil-contaminated soil in cold environments. *International Biodeterioration & Biodegradation, 142*, 58-72. https://doi.org/10.1016/j.ibiod.2019.05.001

Choez, A., & Evaristo, R. R. (2018). Acute intoxication by carbofuran in cattle. *Journal of Veterinary Medicine*, *2*(1), Article 20. https://doi.org/10.4172/2574-2868.100020

Chowdhury, A. Z., Jahan, S. A., Islam, M. N., Moniruzzaman, M., Alam, M. K., Zaman, M. A., Karim, N., & Gan, S. H. (2012). Occurrence of organophosphorus and carbamate pesticide residues in surface water samples from the Rangpur District of Bangladesh. *Bulletin of Environmental Contamination and Toxicology, 89*(1), 202-207. https://doi.org/10.1007/s00128-012-0641-8

Cid, A., Mejuto, J. C., Moldes, Ó. A., & Morales, J. (2011). Basic degradation of 3-keto-carbofuran in the presence of non-ionic self-assembly colloids. *Fresenius Environmental Bulletin, 20*(2), 354-357

Clasen, B., Leitemperger, J., Murussi, C., Pretto, A., Menezes, C., Dalabona, F., Marchezan, E., Adaime, M. B., Zanella, R., & Loro, V. L. (2014). Carbofuran promotes biochemical changes in carp exposed to rice field and laboratory conditions. *Ecotoxicology and Environmental Safety, 101*, 77-82. https://doi.org/https://doi.org/10.1016/j.ecoenv.2013.12.012

Conway, G. R., & Pretty, J. N. (2013). *Unwelcome Harvest: Agriculture and Pollution*. Routledge.

Cossi, P. F., Herbert, L. T., Yusseppone, M. S., Pérez, A. F., & Kristoff, G. (2020). Toxicity evaluation of the active ingredient acetamiprid and a commercial formulation (Assail® 70) on the non-target gastropod *Biomphalaria straminea* (Mollusca: Planorbidae). *Ecotoxicology and Environmental Safety, 192*, Article 110248. https://doi.org/10.1016/j.ecoenv.2020.110248

Ćwieląg-Piasecka, I., Debicka, M., & Medyńska-Juraszek, A. (2021). Effectiveness of carbaryl, carbofuran and metolachlor retention in soils under the influence of different colloid. *Minerals, 11*(9), Article 924. https://doi.org/10.3390/min11090924

Cycoń, M., Mrozik, A., & Piotrowska-Seget, Z. (2017). Bioaugmentation as a strategy for the remediation of pesticide-polluted soil: A review. *Chemosphere, 172*, 52-71. https://doi.org/10.1016/j.chemosphere.2016.12.129

Daam, M. A., Crum, S. J. H., Van den Brink, P. J., & Nogueira, A. J. A. (2008). Fate and effects of the insecticide chlorpyrifos in outdoor plankton-dominated microcosms in Thailand. *Environmental Toxicology and Chemistry, 27*(12), 2530-2538. https://doi.org/10.1897/07-628.1

Daam, M. A., & Van den Brink, P. J. (2010). Implications of differences between temperate and tropical freshwater ecosystems for the ecological risk assessment of pesticides. *Ecotoxicology, 19*(1), 24-37. https://doi.org/10.1007/s10646-009-0402-6

Daliya, P., Ljungqvist, O., Brindle, M. E., & Lobo, D. N. (2020). Guidelines for guidelines. In O. Ljungqvist, N. K. Francis & R. D. Urman (Eds.), *Enhanced Recovery After Surgery* (pp. 23-28). Springer. https://doi.org/10.1007/978-3-030-33443-7_3

De Melo Plese, L. P., Paraiba, L. C., Foloni, L. L., & Trevizan, L. R. P. (2005). Kinetics of carbosulfan hydrolysis to carbofuran and the subsequent degradation of this last compound in irrigated rice fields. *Chemosphere, 60*(2), 149-156. https://doi.org/10.1016/j.chemosphere.2005.02.049

Diale, M. O., Abrahams, A., & Serepa-Dlamini, M. H. (2022). *Isolation and Characterization of Bacteriocin-Like Substances from Bacillus paranthracis Strain MHSD3, a Potential Probiotic*. Research Square. https://doi.org/10.21203/rs.3.rs-1553916/v1

Duc, H. D. (2022). Enhancement of carbofuran degradation by immobilized *Bacillus* sp. strain DT1. *Environmental Engineering Research, 27*(4), Article 210158. https://doi.org/10.4491/eer.2021.158

Daul, J. A., Seng, M. M. K. B., Ikeda, M. M., Ombajo, M. P. S. O., Goji, M. I., Khan, M. M. B., & Magdalena, M. (2012, March 19-23). Rotterdam convention on the prior informed consent procedure for certain hazardous chemicals and pesticides in international trade. In Chemical Review Committee Eighth meeting (pp. 1-39). Geneva, Switzerland

Edzwald, J. (2011). *Water Quality & Treatment: A Handbook on Drinking Water*. McGraw-Hill Education.

EFSA. (2014). Reasoned opinion on the review of the existing MRLs for carbofuran, carbosulfan, benfuracarb and furathiocarb and the setting of an import tolerance for carbofuran in cultivated mushrooms. *EFSA Journal, 12*(2), Article 3559. https://doi.org/10.2903/j.efsa.2014.3559

Eisler, R. (1985). *Carbofuran Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review*. U.S. Department of the Interior, Fish and Wildlife Service

Elbashir, A. A., & Aboul-Enein, H. Y. (2015). Separation and analysis of triazine herbcide residues by capillary electrophoresis. *Biomedical Chromatography, 29*(6), 835-842. https://doi.org/10.1002/bmc.3381

Evert, S. (2002). *Environmental Fate of Carbofuran*. California Environmental Protection Agency, Department of Pesticide Regulation, Sacramento. https://www.cdpr.ca.gov/docs/emon/pubs/envfate.html

Fang, N., Lu, Z., Hou, Z., Zhang, C., & Zhao, X. (2022). Hydrolysis and photolysis of flupyradifurone in aqueous solution and natural water: Degradation kinetics and pathway. *Chemosphere, 298*, Article 134294. https://doi.org/10.1016/j.chemosphere.2022.134294

Farahani, G. H. N., Zakaria, Z., Kuntom, A., Omar, D., & Ismail, B. S. (2007). Adsorption and desorption of carbofuran in Malaysian soils. *Advances in Environmental Biology*, *1*(1), 20-26.

Farahani, G. H. N., Zakaria, Z., Kuntom, A., Omar, D., & Ismail, B. S. (2008). Persistence of carbofuran in two Malaysian soils. *Plant Protection Quarterly, 23*(4), 179-183.

Farahani, G. H. N., Zuriati, Z., Aini, K., & Ismail, B. S. (2012). Persistence of carbofuran in Malaysian waters. *American-Eurasian Journal of Agricultural & Environmental Sciences, 12*(5), 616-623.

Fatah, F. A., Yaakub, N., Ridzuan, R. M., & Ahmad, A. R. (2017). The study on the economic fertilizer requirement for paddy production on a Malaysian soil. *Journal of Fundamental and Applied Sciences, 9*(2S), 777-798. https://doi.org/10.4314/jfas.v9i2s.48

Fenner, K., Canonica, S., Wackett, L. P., & Elsner, M. (2013). Evaluating pesticide degradation in the environment: Blind spots and emerging opportunities. *Science*, *341*(6147), 752-758.

Filik, H., & Çekiç, S. D. (2011). Cloud point extraction of pesticide residues. In M. Stoytcheva (Ed.), *Pesticides in the Modern World-Trends in Pesticides Analysis* (pp. 247-280). IntechOpen.

FOA. (2020). *The State of World Fisheries and Aquaculture 2020: Sustainability in Action.* Food and Agiculture Organization. https://doi.org/10.4060/ca9229en

Furmanczyk, E. M., Kaminski, M. A., Lipinski, L., Dziembowski, A., & Sobczak, A. (2018). *Pseudomonas laurylsulfatovorans* sp. nov., sodium dodecyl sulfate degrading bacteria, isolated from the peaty soil of a wastewater treatment plant. *Systematic and Applied Microbiology, 41*(4), 348-354. https://doi.org/10.1016/j.syapm.2018.03.009

Gammon, D. W., Liu, Z., & Becker, J. M. (2012). Carbofuran occupational dermal toxicity, exposure and risk assessment. *Pest Management Science*, *68*(3), 362-370. https://doi.org/10.1002/ps.2270

Garcia-Saavedra, Y., Rivera, A., Hernandez-Aladana, F., Romero-Arenas, O., Sanchez-Morales, P., & Giono-Cerezo, S. (2018). Carbofuran, malathion and 2, 4-D degradation by bacterial activity. *Journal of Pure and Applied Microbiology*, *12*(3), 1331-1335. http://dx.doi.org/10.22207/JPAM.12.3.35

Gc, Y. D., Palikhe, B. R., Gu, B., & Beatrice, G. (2021). Status of highly hazardous pesticides and their mitigation measures in Asia. *Advances in Entomology*, *10*(1), 14-33. https://doi.org/10.4236/ae.2022.101002

Grandclément, C., Seyssiecq, I., Piram, A., Wong-Wah-Chung, P., Vanot, G., Tiliacos, N., Roche, N., & Doumenq, P. (2017). From the conventional biological wastewater treatment to hybrid processes, the evaluation of organic micropollutant removal: A review. *Water Research*, *111*, 297-317. https://doi.org/10.1016/j.watres.2017.01.005

Gunther, F. A., & Gunther, J. D. (2013). *Residue Reviews: Residues Of Pesticides And Other Foreign Chemicals In Foods And Feeds* (Vol. 40). Springer Science & Business Media.

Gupta, J., Rathour, R., Singh, R., & Thakur, I. S. (2019). Production and characterization of extracellular polymeric substances (EPS) generated by a carbofuran degrading strain *Cupriavidus* sp. ISTL7. *Bioresource Technology*, *282*, 417-424. https://doi.org/10.1016/j.biortech.2019.03.054

Halimah, M., Tan, Y. A., & Ismail, B. S. (2005). The fate of fluroxypyr in the soil in an oil palm agroecosystem. *Weed Biology and Management*, *5*(4), 184-189. https://doi.org/10.1111/j.1445-6664.2005.00179.x

Vincent, K. (2014). Reforming wildlife law: Proposals by the Law Commission for England and Wales. *International Journal for Crime, Justice and Social Democracy, 3*(2), 67-80.

Hayasaka, D., Korenaga, T., Suzuki, K., Saito, F., Sánchez-Bayo, F., & Goka, K. (2012). Cumulative ecological impacts of two successive annual treatments of imidacloprid and fipronil on aquatic communities of

paddy mesocosms. *Ecotoxicology and Environmental Safety*, *80*, 355-362. https://doi.org/10.1016/j.ecoenv.2012.04.004

Health Canada. (2020). *Guidelines for Canadian Drinking Water Quality Summary Table*. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Health Canada, Ottawa, Ontario. https://www.canada.ca/content/dam/hc-sc/migration/hc-sc/ewh-semt/alt_formats/pdf/pubs/water-eau/sum_guide-res_recom/summary-table-EN-2020-02-11.pdf

Howard, P. (2017). *Handbook of Environmental Fate and Exposure Data: For Organic Chemicals, Volume III Pesticides*. Routledge.

Huang, J., & Mabury, S. A. (2000). A new method for measuring carbonate radical reactivity toward pesticides. *Environmental Toxicology and Chemistry: An International Journal*, *19*(6), 1501–1507.

Ibitoye, O. O., Nawi, N. M., Kamarulzaman, N. H., & Man, N. (2014). Consumers' awareness towards organic rice in Malaysia. *International Food Research Journal, 21*(5), 1711-1718.

Idayu, M., Anis, N., Akmal, S., & Esa, N. (2014). A survey on use , hazards and potential risks of rice farming pesticides in Permatang Keriang, Pulau Pinang (Malaysia). *International Journal of Scientific and Research Publications*, *4*(10), 1-11.

Islam, A., Naskar, S., Mazumder, U. K., Gupta, M., & Ghosal, S. (2008). Estrogenic properties of phyllanthin and hypophyllanthin from *Phyllanthus amarus* against carbofuran induced toxicity in female rats. *Pharmacologyonline*, *3*, 1006-1016.

Ismail, B. S., & Kalithasan, K. (2004). Adsorption, desorption, and mobility of permethrin in Malaysian soils. *Journal of Environmental Science and Health, Part B*, *39*(3), 419-429. https://doi.org/10.1081/PFC-120035927

Ismail, B. S., Ngan, C. K., Cheah, U. B., & Abdullah, W. Y. W. (2004). Leaching potential of pesticides in a vegetable farm in the Cameron Highlands, Malaysia. *Bulletin of Environmental Contamination and Toxicology*, *72*(4), 836-843. https://doi.org/10.1007/s00128-004-0320-5

Ismail, B. S., Prayitno, S., & Tayeb, M. A. (2015). Contamination of rice field water with sulfonylurea and phenoxy herbicides in the Muda Irrigation Scheme, Kedah, Malaysia. *Environmental Monitoring and Assessment*, *187*(7), 1-13. https://doi.org/10.1007/s10661-015-4600-9

Jaiswal, D. K., Verma, J. P., & Yadav, J. (2017). Microbe induced degradation of pesticides in agricultural soils. In S. N. Singh (Ed.), *Microbe-induced degradation of pesticides* (pp. 167-189). Springer.

Jemutai-Kimosop, S., Orata, F. O., K'Owino, I. O., & Getenga, Z. M. (2014). The dissipation of carbofuran in two soils with different pesticide application histories within Nzoia River Drainage Basin, Kenya. *Bulletin of Environmental Contamination and Toxicology*, *92*(5), 616-620. https://doi.org/10.1007/s00128-014-1234-5

Jiang, W., Gao, Q., Zhang, L., Wang, H., Zhang, M., Liu, X., Zhou, Y., Ke, Z., Wu, C., & Qiu, J. (2020). Identification of the key amino acid sites of the carbofuran hydrolase CehA from a newly isolated carbofuran-degrading strain *Sphingbium* sp. CFD-1. *Ecotoxicology and Environmental Safety*, *189*, Article 109938. https://doi.org/10.1016/j.ecoenv.2019.109938

Jiang, W., Zhang, C., Gao, Q., Zhang, M., Qiu, J., Yan, X., & Hong, Q. (2020). Carbamate CN hydrolase gene ameH responsible for the detoxification step of methomyl degradation in *Aminobacter aminovorans* strain MDW-2. *Applied and Environmental Microbiology*, *87*(1), Article e02005-20. https://doi.org/10.1128/AEM.02005-20

Jørgensen, S. E. (2008). *Biodegradation.* In S. E. Jørgensen & B. D. Fath (Eds.), *Encyclopedia of Ecology* (pp. 366–367). Academic Press. https://doi.org/https://doi.org/10.1016/B978-008045405-4.00260-3

Kabir, K. H., Abdullah, M., Prodhan, M. D. H., Ahmed, M. S., & Alam, M. N. (2007). Determination of carbofuran residue in the samples of sugarcane (*Sacharum officinarum* L) and soil of sugarcane field. *The Agriculturists, 5*(1&2), 61-66.

Kaida, N., Habib, S., Yasid, N. A., & Shukor, M. Y. (2018). Biodegradation of Petroleum Hydrocarbons by *Bacillus* sp.: A Review. *Bioremediation Science and Technology Research*, *6*(2), 14-21.

Kanedi, M. (2017). Physiological effects of carbofuran on earthworm *Pheretima javanica* Gates. *Advances in Life Sciences*, *7*(2), 21-25.

Katagi, T. (2016). Pesticide behavior in modified water-sediment systems. *Journal of Pesticide Science, 41*(4), 121-132. https://doi.org/10.1584/jpestics.D16-060

Khairatul, A. M., Ngan, C. K., & Ismail, B. S. (2013). Adsorption and leaching studies of molinate, carbofuran and propiconazole in Muda agricultural soils. *Journal of Tropical Agriculture and Food Science*, *41*(1), 127-136.

Khuntong, S., Sirivithayapakorn, S., Pakkong, P., & Soralump, C. (2010). Adsorption kinetics of carbamate pesticide in rice field soil. *Environment Asia*, *3*(2), 20-28.

Kim, I. S., Ryu, J. Y., Hur, H. G., Gu, M. B., Kim, S. D., & Shim, J. H. (2004). *Sphingomonas* sp. strain SB5 degrades carbofuran to a new metabolite by hydrolysis at the furanyl ring. *Journal of Agricultural and Food Chemistry*, *52*(8), 2309-2314. https://doi.org/10.1021/jf035502l

Kumar, R., Ali, M., Kumar, A., & Gahlot, V. (2015). Comparative bioremedial effect of withania somnifera and curcuma longa on ovaries of pesticide induced mice. *European Journal of Pharmaceutical and Medical Research, 2*(7)*,* 249-253.

Kumar, S. A., Krishna, A. J., Suvarna, T., Balaji, P. B., & Hyndhavi, K. (2020). An experimental study on suitability on treated sewage water for agriculture. *International Research Journal of Engineering and Technology*, *7*(3), 2010-2013.

Kuswandi, B., Futra, D., & Heng, L. Y. (2017). Nanosensors for the detection of food contaminants. In A. E. Oprea & A. M. Grumezescu (Eds.), *Nanotechnology Applications in Food* (pp. 307-333). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-811942-6.00015-7

Lan, J., Wang, M., Ding, S., Fan, Y., Diao, X., Li, Q. X., & Zhao, H. (2019). Simultaneous detection of carbofuran and 3-hydroxy-carbofuran in vegetables and fruits by broad-specific monoclonal antibody-based ELISA. *Food and Agricultural Immunology*, *30*(1), 1085-1096. https://doi.org/10.1080/09540105.2019.1664997

Larson, S. J., Capel, P. D., & Majewski, M. S. (2019). *Pesticides in Surface Waters: Distribution, Trends, and Governing Factors*. CRC Press.

Latif, Y., Sherazi, S. T. H., & Bhanger, M. I. (2011). Assessment of pesticide residues in commonly used vegetables in Hyderabad, Pakistan. *Ecotoxicology and Environmental Safety*, *74*(8), 2299-2303.

Lehel, J., Laczay, P., Déri, J., Darin, E. G., & Budai, P. (2010). Model study on the clinical signs and residue concentrations of sublethal carbofuran poisoning in birds. *Journal of Wildlife Diseases*, *46*(4), 1274-1278.

Leistra, M., & Boesten, J. (2008). *Movement of Bromide-Ion and Carbofuran in the Humic Sandy Soil of a Potato Field with Ridges and Furrows: Measurements in the Field and Computations with the PEARL Model* (No. 1750). Alterra. https://library.wur.nl/WebQuery/wurpubs/371006

Liong, P. C. (1988). *Toxicity of Some Pesticides Towards Freshwater Fishes*. Department of Fisheries.

Liu, L., Helbling, D. E., Kohler, H. P. E., & Smets, B. F. (2019). Modelling carbofuran biotransformation by *Novosphingobium* sp. KN65. 2 in the presence of coincidental carbon and indigenous microbes. *Environmental Science: Water Research & Technology*, *5*(4), 798-807.

Liu, T., Xin, Y., Liu, X., Wu, B., & Xiang, M. (2021). Advances in microbial degradation of plastics. *Chinese Journal of Biotechnology*, *37*(8), 2688-2702. https://doi.org/10.13345/j.cjb.200624

Lu, L. A., Ma, Y. S., Kumar, M., & Lin, J. G. (2011). Photochemical degradation of carbofuran and elucidation of removal mechanism. *Chemical Engineering Journal*, *166*(1), 150-156.

Lu, S., Liu, L., Demissie, H., An, G., & Wang, D. (2021). Design and application of metal-organic frameworks and derivatives as heterogeneous Fenton-like catalysts for organic wastewater treatment: A review. *Environment International, 146*, Article 106273. https://doi.org/10.1016/j.envint.2020.106273

Ma, Y. S., Kumar, M., & Lin, J. G. (2009). Degradation of carbofuran-contaminated water by the Fenton process. *Journal of Environmental Science and Health, Part A, 44*(9), 914-920. https://doi.org/10.1080/10934520902958807

Ma, Y. S., Sung, C. F., & Lin, J. G. (2010). Degradation of carbofuran in aqueous solution by ultrasound and Fenton processes: Effect of system parameters and kinetic study. *Journal of Hazardous Materials*, *178*(1), 320-325. https://doi.org/https://doi.org/10.1016/j.jhazmat.2010.01.081

Mackay, D., Shiu, W. Y., & Lee, S. C. (2006). *Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals*. CRC press.

Mahalakshmi, M., Arabindoo, B., Palanichamy, M., & Murugesan, V. (2007). Photocatalytic degradation of carbofuran using semiconductor oxides. *Journal of Hazardous Materials*, *143*(1-2), 240-245.

Mahindru, S. N. (2009). *Food Contaminants-Origin, Propagation & Analysis*. APH Publishing.

Maksuk, M. (2021). Analisis residu pestisida karbofuran dalam air sungai di kawasan pertanian padi [Analysis of carbofuran pesticide residues in river water at paddy field area]. *Seminar Nasional Hari Air Sedunia*, *3*(1), 1-5.

Malhotra, H., Kaur, S., & Phale, P. S. (2021). Conserved metabolic and evolutionary themes in microbial degradation of carbamate pesticides. *Frontiers in Microbiology*, *12*, Article 648868. https://doi.org/10.3389/fmicb.2021.648868

Meftaul, I. M., Venkateswarlu, K., Dharmarajan, R., Annamalai, P., & Megharaj, M. (2020). Pesticides in the urban environment: A potential threat that knocks at the door. *Science of The Total Environment*, *711*, Article 134612. https://doi.org/10.1016/j.scitotenv.2019.134612

Mir-Tutusaus, J. A., Masís-Mora, M., Corcellas, C., Eljarrat, E., Barceló, D., Sarrà, M., Caminal, G., Vicent, T., & Rodríguez-Rodríguez, C. E. (2014). Degradation of selected agrochemicals by the white rot fungus Trametes versicolor. *Science of the Total Environment*, *500*, 235-242. https://doi.org/10.1016/j.scitotenv.2014.08.116

Mishra, S., Pang, S., Zhang, W., Lin, Z., Bhatt, P., & Chen, S. (2021). Insights into the microbial degradation and biochemical mechanisms of carbamates. *Chemosphere*, *279*, Article 130500. https://doi.org/10.1016/j.chemosphere.2021.130500

Mishra, S., Zhang, W., Lin, Z., Pang, S., Huang, Y., Bhatt, P., & Chen, S. (2020). Carbofuran toxicity and its microbial degradation in contaminated environments. *Chemosphere, 259*, Article 127419. https://doi.org/10.1016/j.chemosphere.2020.127419

Mohamed, B., Rachid, M., & Amina, A. (2021). Study on biodegradation and dissipation of 14 C-carbofuran in clay soil from Loukkos Perimeter, Northwestern Morocco. *New Ideas Concerning Science and Technology, 7*, 92-103.

Mohanta, M. K., Saha, A. K., Zamman, M. T., Ekram, A. E., Khan, A. E., Mannan, S. B., & Fakruddin, M. (2012). Isolation and characterization of carbofuran degrading bacteria from cultivated soil. *Biochemical and Cellular Archives, 12*(2), 313-320.

Morales, J., Manso, J. A., & Mejuto, J. C. (2012). Basic hydrolysis of carbofuran in the presence of cyclodextrins. *Supramolecular Chemistry*, *24*(6), 399-405. https://doi.org/10.1080/10610278.2012.688121

Moreira, R. A., da Silva Mansano, A., & Rocha, O. (2015). The toxicity of carbofuran to the freshwater rotifer, *Philodina roseola*. *Ecotoxicology*, *24*(3), 604-615. https://doi.org/10.1007/s10646-014-1408-2

Morrica, P., Barbato, F., Iacovo, R. Dello, Seccia, S., & Ungaro, F. (2001). Kinetics and mechanism of imazosulfuron hydrolysis. *Journal of Agricultural and Food Chemistry*, *49*(8), 3816-3820. https://doi.org/10.1021/jf010088f

Mukaj, M., Mai, S., Cara, M., & Ruci, T. (2017). Influence of pH in concentration of persistent organic pesticides residues in agricultural soils. *Albanian Journal of Agricultural Sciences, 2017*, 173-178.

Mustapha, M. U., Halimoon, N., Johar, W. L. W., & Abd Shukor, M. Y. (2019). An overview on biodegradation of carbamate pesticides by soil bacteria. *Pertanika Journal of Science & Technology*, *27*(2), 547-563.

Nafeesa, M., Ramaraju, K., Kuttalam, S., & Doraisamy, P. (2017). Studies on growth and carbofuran degradation potential of bacterial isolates. *Madras Agricultural Journal*, *104*(1-3), 58-63.

Nashriyah, M., & Azimahtol, H. L. P. (2002). *Residue Levels of Molinate in Rice Field Soil: Their effects on Populations of Aquatic Flora and Fauna under Recycling and Non-Recycling Practices in the MUDA Area*. International Atomic Energy Agency. https://inis.iaea.org/search/search.aspx?orig_q=RN:37065383

Nguyen, T. P. O., De Mot, R., & Springael, D. (2015). Draft genome sequence of the carbofuran-mineralizing *Novosphingobium* sp. strain KN65. 2. *Genome Announcements*, *3*(4), Article e00764-15. https://doi.org/10.1128/genomea.00764-15

Nguyen, T. P. O., Helbling, D. E., Bers, K., Fida, T. T., Wattiez, R., Kohler, H.-P. E., Springael, D., & De Mot, R. (2014). Genetic and metabolic analysis of the carbofuran catabolic pathway in *Novosphingobium* sp. KN65. 2. *Applied Microbiology and Biotechnology*, *98*, 8235-8252. https://doi.org/10.1007/s00253-014-5858-5

Numan, A., Khan, M., Uddin, R., Rahman, M., Bhuiyan, M., & Akter, N. (2018). Risk assessment of commonly used major pesticides for tomato (*Solanum lycopersicum* L.) cultivation in Bangladesh. *Advances in Nutrition and Food Science, 1*(2), 1-24.

Okoli, U. A., Nubila, N. I., & Okafor, M. T. (2017). Organophosphorous pesticide: An environmental pollutant perspective. *Journal of Chemical and Pharmaceutical Research, 9*(9), 126-130.

Oliveira, R., Almeida, M. F., Santos, L., & Madeira, L. M. (2006). Experimental design of 2, 4-dichlorophenol oxidation by Fenton's reaction. *Industrial & Engineering Chemistry Research*, *45*(4), 1266-1276. https://doi.org/10.1021/ie0509544

Onunga, D. O., Kowino, I. O., Ngigi, A. N., Osogo, A., Orata, F., Getenga, Z. M., & Were, H. (2015). Biodegradation of carbofuran in soils within Nzoia River Basin, Kenya. *Journal of Environmental Science and Health, Part B, 50*(6), 387-397.

Organization, W. H. (2020). *The WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification 2019*. World Health Organization. https://www.who.int/publications/i/item/9789240005662

Ostergaard, G., & Knudsen, I. (1998). The applicability of the ADI (Acceptable Daily Intake) for food additives to infants and children. *Food Additives and Contaminants*, *15*, 63-74. https://doi.org/10.1080/02652039809374617

Otieno, P. O., Lalah, J. O., Virani, M., Jondiko, I. O., & Schramm, K. W. (2010a). Carbofuran and its toxic metabolites provide forensic evidence for Furadan exposure in vultures (*Gyps africanus*) in Kenya. *Bulletin of Environmental Contamination and Toxicology*, *84*(5), 536-544.

Otieno, P. O., Lalah, J. O., Virani, M., Jondiko, I. O., & Schramm, K. W. (2010b). Soil and water contamination with carbofuran residues in agricultural farmlands in Kenya following the application of the technical formulation Furadan. *Journal of Environmental Science and Health, Part B*, *45*(2), 137-144. https://doi.org/10.1080/03601230903472058

Otieno, P. O., Lalah, J. O., Virani, M., Jondiko, I. O., & Schramm, K. W. (2011). Carbofuran use and abuse in Kenya: Residues in soils, plants, water courses and the African white-backed vultures (Gyps africanus) found dead. *Environmentalist*, *31*(4), 382-393. https://doi.org/10.1007/s10669-011-9350-9

Otieno, P. O., Schramm, K.-W., Pfister, G., Lalah, J. O., Ojwach, S. O., & Virani, M. (2012). Spatial Distribution and temporal trend in concentration of carbofuran, diazinon and chlorpyrifos ethyl residues in sediment and water in Lake Naivasha, Kenya. *Bulletin of Environmental Contamination and Toxicology*, *88*(4), 526-532. https://doi.org/10.1007/s00128-012-0529-7

Papadakis, E. N., Tsaboula, A., Kotopoulou, A., Kintzikoglou, K., Vryzas, Z., & Papadopoulou-Mourkidou, E. (2015). Pesticides in the surface waters of Lake Vistonis Basin, Greece: Occurrence and environmental risk assessment. *Science of the Total Environment*, *536*, 793-802. https://doi.org/10.1016/j.scitotenv.2015.07.099

Park, M. R., Lee, S. W., Han, T. H., Oh, B. T., Shim, J. H., & Kim, I. S. (2006). A new intermediate in the degradation of carbofuran by *Sphingomonas* sp. strain SB5. *Journal of Microbiology and Biotechnology*, *16*(8), 1306-1310.

Park, Y., Kim, Y., Kim, J., Yoon, K. S., Clark, J., Lee, J., & Park, Y. (2013). Imidacloprid, a neonicotinoid insecticide, potentiates adipogenesis in 3T3-L1 adipocytes. *Journal of Agricultural and Food Chemistry*, *61*(1), 255-259. https://doi.org/10.1021/jf3039814

Peng, X., Zhang, J. S., Li, Y. Y., Li, W., Xu, G. M., & Yan, Y. C. (2008). Biodegradation of insecticide carbofuran by *Paracoccus* sp. YM3. *Journal of Environmental Science and Health. Part. B, Pesticides, Food Contaminants, and Agricultural Wastes*, *43*(7), 588-594. https://doi.org/10.1080/03601230802234492

Pignatello, J. J., Oliveros, E., & MacKay, A. (2006). Advanced oxidation processes for organic contaminant destruction based on the Fenton reaction and related chemistry. *Critical Reviews in Environmental Science and Technology*, *36*(1), 1-84. https://doi.org/10.1080/10643380500326564

Pinakini, K. S., & Kumar, T. S. M. (2006). Serial cholinesterase estimation in carbamate poisoning. *Journal of Clinical Forensic Medicine*, *13*(5), 274-276. https://doi.org/10.1016/j.jcfm.2005.11.005

Plangklang, P., & Reungsang, A. (2012). Isolation and characterisation of a carbofuran degrading *Burkholderia* sp. PCL3 from carbofuran-phytoremediated rhizosphere soil. *Chemistry and Ecology*, *28*(3), 253-266. https://doi.org/10.1080/02757540.2011.645032

Plaza, P. I., Martínez-López, E., & Lambertucci, S. A. (2019). The perfect threat: Pesticides and vultures. *Science of the Total Environment*, *687*, 1207-1218. https://doi.org/10.1016/j.scitotenv.2019.06.16

Prosen, H. (2012). Fate and determination of triazine herbicides in soil. In M. N. Hasaneen (Ed.), *Herbicides-Properties, Synthesis and Control of Weeds* (pp. 43-58). IntechOpen.

Pyne, E. L. (2015). *Occurrence and Distribution of Pesticide Residues in Soil as a Result of Long-Term Application* (Master thesis). Utrecht University, Netherlands. https://studenttheses.uu.nl/handle/20.500.12932/20943

Racke, K. D., Skidmore, M. W., Hamilton, D. J., Unsworth, J. B., Miyamoto, J., & Cohen, S. Z. (1997). Pesticides Report 38. Pesticide fate in tropical soils (Technical Report). *Pure and Applied Chemistry, 69*(6), 1349-1372. https://doi.org/doi:10.1351/pac199769061349

Raha, P., & Das, A. K. (1990). Photodegradation of carbofuran. *Chemosphere*, *21*(1-2), 99-106.

Ramakrishnan, B., Venkateswarlu, K., Sethunathan, N., & Megharaj, M. (2019). Local applications but global implications: Can pesticides drive microorganisms to develop antimicrobial resistance? *Science of the Total Environment*, *654*, 177-189. https://doi.org/10.1016/j.scitotenv.2018.11.041

Ramasubramanian, T., & Paramasivam, M. (2018). Persistence and metabolism of carbofuran in the soil and sugarcane plant. *Environmental Monitoring and Assessment*, *190*(9), 1-9.

Ramesh, M., Narmadha, S., & Poopal, R. K. (2015). Toxicity of furadan (carbofuran 3% g) in *Cyprinus carpio*: Haematological, biochemical and enzymological alterations and recovery response. *Beni-Suef University Journal of Basic and Applied Sciences*, *4*(4), 314-326.

Remucal, C. K. (2014). The role of indirect photochemical degradation in the environmental fate of pesticides: A review. *Environmental Science: Processes & Impacts*, *16*(4), 628-653.

Ripley, B. D., & Chau, A. S. Y. (2020). Carbamate pesticides. In *Analysis of Pesticides in Water* (pp. 1-182). CRC Press.

Roger, P. A., & Bhuiyan, S. I. (2012). Behavior of pesticides in rice-based agroecosystems. In P. L. Pingali & P. A. Roger (Eds.), *Impact of Pesticides on Farmer Health and the Rice Environment* (pp. 111-148). Springer.

Ruíz-Hidalgo, K., Masís-Mora, M., Barbieri, E., Carazo-Rojas, E., & Rodríguez-Rodríguez, C. E. (2016). Ecotoxicological analysis during the removal of carbofuran in fungal bioaugmented matrices. *Chemosphere*, *144*, 864-871. https://doi.org/10.1016/j.chemosphere.2015.09.056

Satar, M. D. S., Satar, S., Sebe, A., & Yesilagac, H. (2005). Carbofuran poisoning among farm workers. *The Mount Sinai Journal of Medicine*, *72*(6), 389-392.

Sandín-España, P., & Sevilla-Morán, B. (2012). Pesticide degradation in water. In *Pesticides: Avaluation of Environmental Pollution* (pp. 79-130). CRC Press.

Sapari, P., & Ismail, B. S. (2012). Pollution levels of thiobencarb, propanil, and pretilachlor in rice fields of the muda irrigation scheme, Kedah, Malaysia. *Environmental Monitoring and Assessment*, *184*(10), 6347-6356.

Seiber, J. N., Catahan, M. P., & Barril, C. R. (1978). Loss of carbofuran from rice paddy water: Chemical and physical factors. *Journal of Environmental Science and Health, Part B*, *13*(2), 131-148. https://doi.org/10.1080/03601237809372083

Seo, J. S., Moon, J. K., & Kim, J. H. (2012). Photodegradation of pyribenzoxim in water. *Journal of the Korean Society for Applied Biological Chemistry*, *55*(3), 391-396. https://doi.org/10.1007/s13765-012-2042-4

Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G. P. S., Handa, N., Kohli, S. K., Yadav, P., Bali, A. S., & Parihar, R. D. (2019). Worldwide pesticide usage and its impacts on ecosystem. *SN Applied Sciences*, *1*(11), 1-16.

Siddaramappa, R., & Seiber, J. N. (1979). Persistence of carbofuran in flooded rice soils and water. *Progress in Water Technology, 11*, 103-111.

Sidhu, G. K., Singh, S., Kumar, V., Dhanjal, D. S., Datta, S., & Singh, J. (2019). Toxicity, monitoring and biodegradation of organophosphate pesticides: A review. *Critical Reviews in Environmental Science and Technology*, *49*(13), 1135-1187.

Sim, S. F., Chung, L. Y., Jonip, J., & Chai, L. K. (2019). Uptake and dissipation of carbofuran and its metabolite in Chinese kale and brinjal cultivated under humid tropic climate. *Advances in Agriculture*, *2019*, Article 7937086. https://doi.org/10.1155/2019/7937086

Singh, R. P., Varshney, G., & Srivastava, G. (2012). Effect of carbofuran on enzymatic activities and growth of tomato plants in natural, fertilized and vermicompost-amended soils. *Archives of Agronomy and Soil Science*, *58*(12), 1349-1364.

Singh, S. P., Guha, S., Bose, P., & Kunnikuruvan, S. (2017). Mechanism of the hydrolysis of endosulfan isomers. *The Journal of Physical Chemistry A*, *121*(27), 5156-5163.

Smith, G. J. (1992). *Toxicology and Pesticide use in Relation to Wildlife, Organophosphorus, and Carbamate Compounds*. CRC Press.

Soloneski, S., Reigosa, M. A., Molinari, G., González, N. V, & Larramendy, M. L. (2008). Genotoxic and cytotoxic effects of carbofuran and furadan® on Chinese hamster ovary (CHOK1) cells. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, *656*(1-2), 68-73. https://doi.org/10.1016/j.mrgentox.2008.07.007

Sparling, D. W. (2016). *Ecotoxicology Essentials: Environmental Contaminants and Their Biological Effects on Animals and Plants*. Academic Press.

Strachan, W. M. J., Glooschenko, W. A., & Maguire, R. J. (2018). Environmental impact and significance of pesticides. In *Analysis of Pesticides in Water* (pp. 1-23). CRC Press.

Sun, M., Xu, W., Zhang, W., Guang, C., & Mu, W. (2022). Microbial elimination of carbamate pesticides: Specific strains and promising enzymes. *Applied Microbiology and Biotechnology*, *106*(18), 5973-5986. https://doi.org/10.1007/s00253-022-12141-4

Syed, J. H., Alamdar, A., Mohammad, A., Ahad, K., Shabir, Z., Ahmed, H., Ali, S. M., Sani, S. G. A. S., Bokhari, H., & Gallagher, K. D. (2014). Pesticide residues in fruits and vegetables from Pakistan: A review of the occurrence and associated human health risks. *Environmental Science and Pollution Research*, *21*, 13367-13393. https://doi.org/10.1007/s11356-014-3117-z

Tejada, A. W. (1995). Pesticide residues in foods and the environment as a consequence of crop protection. *Philippine Agriculturist, 78*, 63-79.

Thomas, N., Dionysiou, D. D., & Pillai, S. C. (2021). Heterogeneous Fenton catalysts: A review of recent advances. *Journal of Hazardous Materials*, *404*, Article 124082. https://doi.org/10.1016/j.jhazmat.2020.124082

Tien, C., Huang, H., & Chen, C. S. (2017). Accessing the carbofuran degradation ability of cultures from natural river biofilms in different environments. *CLEAN–Soil, Air, Water*, *45*(5), Article 1600380. https://doi.org/10.1002/clen.201600380

Tiryaki, O. (2017). Pesticide residues and organic production. *Journal of Biological and Environmental Sciences*, *11*(31), 11-23.

Tiryaki, O., & Temur, C. (2010). The fate of pesticide in the environment. *Journal of Biological and Environmental Sciences*, *4*(10), 29-38.

Tondon, S. A., Deore, R., & Parab, A. (2018). Isolation, identification and the use of carbofuran degrading microorganisms for the removal of carbofuran pesticide from contaminated waters. *Global Journal of Bio-Science and Biotechnology, 6*, 89-95.

Torres, J. B., & Bueno, A. de F. (2018). Conservation biological control using selective insecticides - A valuable tool for IPM. *Biological Control*, *126*, 53-64.

Trevisan, M. J., Baptista, G. C. De, Trevizan, L. R. P., & Papa, G. (2004). Residues of carbosulfan and its carbofuran metabolites and 3-hydroxy-carbofuran in oranges. *Revista Brasileira de Fruticultura*, *26*(2), 230-233. https://doi.org/10.1590/S0100-29452004000200012

Ukalska-Jaruga, A., Smreczak, B., & Siebielec, G. (2020). Assessment of pesticide residue content in polish agricultural soils. *Molecules, 25* (3), Article 587. https://doi.org/10.3390/molecules25030587

USEPA. (2006). *Interim Reregistration Eligibility Decision (IRED) Document for Carbofuran*. US Environmental Protection Agency. https://archive.epa.gov/pesticides/reregistration/web/pdf/carbofuran_red.pdf

Valente-Campos, S., Spry, D. J., Palhares, J. C. P., Rudez, L. M. J., & de Aragão Umbuzeiro, G. (2019). Critical issues and alternatives for the establishment of chemical water quality criteria for livestock. *Regulatory Toxicology and Pharmacology*, *104*, 108-114. https://doi.org/10.1016/j.yrtph.2019.03.003

Venkateswarlu, K., & Sethunathan, N. (1978). Degradation of carbofuran in rice soils as influenced by repeated applications and exposure to aerobic conditions following anaerobiosis. *Journal of Agricultural and Food Chemistry*, *26*(5), 1148-1151. https://doi.org/10.1021/jf60219a019

Villaverde, J. J., Sevilla-Morán, B., López-Goti, C., Calvo, L., Alonso-Prados, J. L., & Sandín-España, P. (2018). Photolysis of clethodim herbicide and a formulation in aquatic environments: Fate and ecotoxicity assessment of photoproducts by QSAR models. *Science of the Total Environment*, *615*, 643-651. https://doi.org/10.1016/j.scitotenv.2017.09.300

Wang, L., Cai, W.-F., & Li, Q. X. (1998). Photolysis of phloxine B in water and aqueous solutions. *Archives of Environmental Contamination and Toxicology*, *35*(3), 397-403. https://doi.org/10.1007/s002449900394

Wijesinghe, M. R., Jayatillake, B., & Ratnassoriya, W. D. (2011). Solar radiation alters toxicity of carbofuran: Evidence from empirical trials with Duttaphyrnus melanostictus. *Journal of Tropical Forestry and Environment*, *1*(1), 48-55.

Wols, B. A., & Hofman-Caris, C. H. M. (2012). Review of photochemical reaction constants of organic micropollutants required for UV advanced oxidation processes in water. *Water Research*, *46*(9), 2815-2827. https://doi.org/10.1016/j.watres.2012.03.036

World Health Organization. (2020). *The WHO recommended classification of pesticides by hazard and guidelines to classification 2019*. World Health Organization. https://www.who.int/publications-detail-redirect/9789240005662

Xu, G. F., Shen, Z. X., & Guo, R. X. (2014). The kinetics studies for the adsorption of furadan from aqueous solution by orange peel. *Advanced Materials Research*, *842*, 187-191. https://doi.org/10.4028/www.scientific.net/AMR.842.187

Yan, Q. X., Hong, Q., Han, P., Dong, X. J., Shen, Y. J., & Li, S. P. (2007). Isolation and characterization of a carbofuran-degrading strain *Novosphingobium* sp. FND-3. *FEMS Microbiology Letters*, *271*(2), 207-213. https://doi.org/10.1111/j.1574-6968.2007.00718.x

Yan, X., Jin, W., Wu, G., Jiang, W., Yang, Z., Ji, J., Qiu, J., He, J., Jiang, J., & Hong, Q. (2018). Hydrolase CehA and monooxygenase CfdC are responsible for carbofuran degradation in *Sphingomonas* sp. strain CDS-1. *Applied and Environmental Microbiology*, *84*(16), Article e00805-18. https://doi.org/10.1128/AEM.00805-18

Zhang, C. P., He, H. M., Yu, J. Z., Hu, X. Q., Zhu, Y. H., & Wang, Q. (2016). Residues of carbosulfan and its metabolites carbofuran and 3-hydroxy carbofuran in rice field ecosystem in China. *Journal of Environmental Science and Health, Part B*, *51*(6), 351-357. https://doi.org/10.1080/03601234.2015.1120606

Zhang, M., Dong, H., Zhao, L., Wang, D., & Meng, D. (2019). A review on Fenton process for organic wastewater treatment based on optimization perspective. *Science of the Total Environment*, *670*, 110-121.

Zhang, Y., Zhang, W., Li, J., Pang, S., Mishra, S., Bhatt, P., Zeng, D., & Chen, S. (2021). Emerging technologies for degradation of dichlorvos: A review. *International Journal of Environmental Research and Public Health*, *18*(11), Article 5789. https://doi.org/10.3390/ijerph18115789

Zheng, W., Cui, T., & Li, H. (2022). Combined technologies for the remediation of soils contaminated by organic pollutants. A review. *Environmental Chemistry Letters*, *20*(3), 2043-2062. https://doi.org/10.1007/s10311-022-01407-y