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Review article

Potential impact of the herbicide 2,4-dichlorophenoxyacetic acid on human and ecosystems

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ABSTRACT

The herbicide 2,4-dichlorophenoxyacetic acid (2,4-D) is applied directly to aquatic and conventional farming systems to control weeds, and is among the most widely distributed pollutants in the environment. Non-target organisms are exposed to 2,4-D via several ways, which could produce toxic effects depending on the dose, frequency of exposure, and the host factors that influence susceptibility and sensitivity. An increasing number of experimental evidences have shown concerns about its presence/detection in the environment, because several investigations have pointed out its potential lethal effects on non-target organisms. In this review, we critically evaluated the environmental fate and behavior of 2,4-D along with its eco-toxicological effects on aquatic, plants and human life to provide concise assessment in the light of recently published reports. The findings demonstrate that 2,4-D is present in a low concentration in surface water of regions where its usage is high. The highest concentrations of 2,4-D were detected in soil, air and surface water surrounded by crop fields, which suggest that mitigation strategies must be implanted locally to prevent the entry of 2,4-D into the environment. A general public may have frequent exposure to 2,4-D due to its wide applications at home lawns and public parks, etc. Various in vivo and in vitro investigations suggest that several species (or their organs) at different trophic levels are extremely sensitive to the 2,4-D exposure, which may explain variation in outcomes of reported investigations. However, implications for the prenatal exposure to 2,4-D remain unknown because 2,4-D-induced toxicity thresholds in organism have only been derived from juveniles or adults. In near future, introduction of 2,4-D resistant crops will increase its use in agriculture, which may cause relatively high and potentially unsafe residue levels in the environment. The recent findings indicate the urgent need to further explore fate, accumulation and its continuous low level exposure impacts on the environment to generate reliable database which is key in drafting new regulation and policies to protect the population from further exposure.

1. Introduction

The high consumption of herbicides in modern agriculture, urban landscaping practices and the inadequate storage or disposal cause the contamination of these compounds in soil, groundwater, rivers, lakes, rainwater and air. Sometimes, herbicide/pesticide concentration levels in agricultural wastewater can reach as high as 500 mg L^{-1}, which can potentially cause environmental problems. The effects of chronic, sub-lethal exposure to increasing combinations of herbicides and other xenobiotics remain largely understudied, despite the potential risk to human health and the environment (Kurenbach et al., 2015; Bhat et al., 2015; Islam et al., 2017a).

2,4-Dichlorophenoxyacetic acid (2,4-D) is a widely used pre-/post-emergent systemic herbicide that controls broad-leaved weeds and other vegetation on rangelands, lawns, golf courses, forests, roadways and parks (Aquino et al., 2007). It was the first commercial herbicide to be introduced in the market for the control of broadleaf weeds in the 1940s. 2,4-D remains one of the most commonly used herbicides in the world because of its low cost, selectivity, efficacy and broad spectrum of weed control. Another reason is that commercial formations of 2,4-D

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are easily soluble in water and other solvents result in rapid penetration through the leaves/roots that make it a more effective herbicide. 2,4-D also regulates plant growth and acts like a mimicker of natural auxin, promoting cell division and elongation and increase shelf-life of fruits at low concentrations (Song, 2014; Islam et al., 2017b). Its formulations include esters, acids and numerous salts which vary in their chemical properties, environmental behavior, and to a lesser extent, toxicity (RED, 2005). The salt and ester formulations of 2,4-D are derived from the parent acid molecule. The dimethyl-amine salt (DMA) and 2-ethl-hexyl ester (EHE) are most commonly used formulations accounts of approximately 90 to 95% of the total use across the world. Additionally, over 1500 herbicide products contain 2,4-D as an active ingredient and it was also a part of Agent Orange, the herbicide widely used during the Vietnam war.

2,4-D is a high production volume herbicide and its annual usage is around 46 million lb in USA, that includes 66% in agriculture, 23% on pasture/rangeland and 11% by homeowners (RED, 2005). The major markets of 2,4-D are USA, South America, Europe and Russia, while its consumption was increased from 2002 to 2011 by almost 40% (USDA, 2014). Its consumption in USA was over 13,000–15,000 tons annually, where it was the third most used pesticide in 2001 (Kiely et al., 2004). In the UK, it was the seventh commonly used herbicide on grassland and fodder crops, while the twentieth among herbicides used in orchards in 1992 (Anonymous, 1996; Anonymous, 1994). In China, 5000–8000 tons of 2,4-D butyl ester are used for wheat, soybean, corn and other crops to control weeds every year (Zhang et al., 2010). Additionally, 2,4-D is used widely in developing countries like India used 1300 tons of 2,4-D in 1994 (Anonymous, 1995). In Argentina, about 2200 tons of 2,4-D are annually applied on different crops (particularly, 2,4-D tolerant corn and soybean), comprising a total area of 3.4×10^6 ha (Merini et al., 2007). Furthermore, there have been recent increases in using 2,4-D to control noxious weeds. Moreover, cultivation of 2,4-D resistant crops (EPA Registration Number 62719-649; Decision Number 457755) if adopted widely, potential increases in using 2,4-D raise the question of if and how this chemical will affect agroecosystems and the environment (Freydier and Lundgren, 2016).

2,4-D is a moderately persistent chemical with a half-life ($t_{1/2}$) between 20 and 312 days depending upon the environmental conditions (Walters, 2011; Ordaz-Guillén et al., 2014). The herbicide is directly applied onto soil or sprayed over crops, and from there, often reaches superficial waters and sediments (Chinalia and Killham, 2006). Due to low adsorption coefficients and high solubility in water, 2,4-D has often been detected in surface and ground water, which means an important environmental problem and health hazard (Table 1) (Gaultier et al., 2008; Kearns et al., 2014; Shareef and Shaw, 2008). About 91.7% of 2,4-D eventually end up in water (Mountassif et al., 2008). This contamination threatens the life of exposed vegetation and animals. Additionally, herbicides are also carried by runoff into the local river systems, thereby threatening the health of aquatic life as well. Unfortunately, 2,4-D has non-specific weed targets (Zabaloy and Gómez, 2014). It can reduce growth rates, induce reproductive problems, and produce changes in appearance or behavior, or could cause death of non-target species, including plants, animals and microorganisms. It is also known as endocrine disruptors, affecting developmental processes even at low concentrations (Pattanasupong et al., 2004).

In the present review, we have collected the scattered information on 2,4-D from literature (Web of Science, Google Scholar) at one platform, so it can give readers an overall view of 2,4-D presence and its potential impacts on the environment. In this review, we have explained, (i) why 2,4-D is ubiquitously present in the environment, (ii) why there is need to study higher doses of 2,4-D and their short time exposure under laboratory conditions and how such results are relevant to the environment, (iii) we also put forward the possible mechanism of 2,4-D interference in spermatogenesis of human based on the recently published reports on mammals, and (iv) we have also explained in details about how the general public is exposed to 2,4-D and its potential accumulative effects on the farmers. Furthermore, we have not only mentioned the toxicity of 2,4-D but also explain about the

Table 1
Presence of 2,4-D in different environmental compartments and in the human urine.

2,4-D concentration	Detection environment	References
Drinking and surface water		
62–207 ng L^{-1}	Drinking and surface water, Spain	(Rodil et al., 2012)
0.1–12.0 μg L^{-1}	Urban surface waters and sediments, California, USA	(Ensminger et al., 2013)
0.46 μg L^{-1}	Suburban surface waters, Massachusetts, USA	(Wijnja et al., 2014)
10.5 to 11.5 μg L^{-1}	urban runoff from residential areas in northern and southern California, USA	(Ensminger et al., 2013)
2.95 μg L^{-1}	Lake Edmonds, freshwater pond Charleston, North Carolina, USA	(Serrano and DeLorenzo, 2008)
7.87 μg L^{-1}	Kushiwah Creek Charleston, North Carolina, USA	(Serrano and DeLorenzo, 2008)
0.05 μg L^{-1}	Lake Chapala, Mexico	(Arévalo-Hernández et al., 2011)
1.16 μg L^{-1}	Pinios River Basin, Greece	(Tsaboula et al., 2016)
Air		
0.034 and 0.058 ng m^{-3}	Two child day care centers, North Carolina, USA	(Wilson et al., 2003)
0.085 and 0.025 ng m^{-3}	Homes of nine children, North Carolina, USA	(Wilson et al., 2003)
0.09–4.24 ng m^{-3}	2,4-D production company, China	(Wilson et al., 2003)
Food		
0.45 to 1.59 ng g^{-1}	Solid food and liquid food, at day care and home, North Carolina, USA	(Wilson et al., 2003)
Urine		
1.5 μg L^{-1}	Non-occupationally exposed adult's and children's urines of Vancouver residents, Canada	(Venners et al., 2016)
3.5 ng mL^{-1}	Non-occupationally exposed adults and children in USA	(Morgan et al., 2008)
2.9 μg L^{-1} to 19 μg L^{-1}	Urine concentration children live near 2,4-D treated farms	(Arbuckle et al., 2004)
33 μg L^{-1}	Farmers of North Carolina, day after applying 2,4-D to fields using a hand sprayer	(Thomas et al., 2010)
11 μg kg^{-1} day^{-1}	Forestry workers applying 2,4-D with PPE[a]	Zhang et al., 2011
13 μg L^{-1}	Farmers who sprayed 2,4-D on their crops	(Curwin et al., 2005)
Dust		
606 ng g^{-1} dust	Detroit, USA	(Colt et al., 2004)
1512 ng g^{-1}	Iowa, USA	(Colt et al., 2004)
87 ng g^{-1}	Los Angeles, USA	(Colt et al., 2004)
374 ng g^{-1}	Seattle, USA	(Colt et al., 2004)
33.9 to 967.1 ng mg^{-1}	Vancouver, Canada	(Arbuckle et al., 2004)

[a] PPE = personal protective equipment.