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The Impacts of Cadmium, an Environmental Pollutant, on Honeybees (*Apis Mellifira*, Hymenoptera: *Apidae*): A Review

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Abstract

Cadmium (Cd) is a toxic trace metal that can harm humans and other organisms. One route through which this trace element enters the human body is via consuming contaminated honeybees' products. This review highlights the sources, biogeochemistry, toxicity, and remediation of Cd, with a focus on its impact on honeybees. Natural and anthropogenic activities release Cd into the environment, which is then transported through the atmosphere, soil, water, and trophic levels. Honeybees are particularly susceptible to Cd toxicity, which can mimic essential elements like zinc (Zn) and calcium (Ca), disrupting physiological and biochemical processes. Despite their ability to filter and purify nectar, honeybees can accumulate Cd in their bodies and products. This makes them act as potential bioindicators of Cd pollution, but uncertainties exist due to multiple exposure pathways and the variable accumulation of Cd in different bee products. Remediation strategies for Cd-contaminated soils include chemical, physical, and biological methods. These approaches aim to reduce Cd bioavailability and promote its immobilization or removal from the environment. Understanding the biogeochemistry and toxicity of Cd is crucial for developing effective strategies to protect honeybees and mitigate the risks associated with Cd contamination in the environment.

Keywords: cadmium; honeybees; pollution; biogeochemistry; toxicity; remediation.

1. Introduction

The scope of bioinorganic chemistry is currently expanding, especially through multidisciplinary environmental research. Thus, the biogeochemistry of an element includes, not only the exchange routes of the element among the living and the non-living components of the ecosystem, but also the impacts of anthropogenic activities on these cycles; in addition to the biochemical bases of the element transportations from the non-living to the living components of the ecosystem, and thence through multiple trophic levels of the food webs. During the past few decades, the field of biological inorganic chemistry has seen significant advancements in understanding the accumulation, transportation, metabolism, and toxicity of metal ions. These efforts have also led to attempts to reduce metal ion contamination in both natural and agricultural ecosystems through the development of chemical remediation technologies.

A specific subset of metals and metalloids exhibits a propensity for high reactivity, often posing a threat of toxicity even at minimal concentrations. These elements enter the environment through various pathways, including both human activities (anthropogenic sources) and natural processes. Such chemicals penetrate soils, gain access to marine ecosystems, freshwater ecosystems, sediments, groundwater, and bio-accumulate in the successive trophic levels in the food webs. Persistent environmental pollutants, like Cd and other toxic elements, can remain in the environment for extended periods, posing long-term risks to living organisms even after the initial source of contamination is eliminated. These pollutants can migrate from contaminated soils into groundwater supplies. It can

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also enter food chains through plant uptake from the soil, resulting in bioaccumulation and potential toxicity to wildlife and humans through the food web. [1]. Studies have shown that exposure to Cd^{2+}can inhibit the activity of antioxidant enzymes and disrupt the mitochondrial electron transport chain [2]. This disrupts cellular homeostasis, leading to an increase in intracellular levels of reactive oxygen species (ROS) [2]. The elevated ROS levels can cause damage to DNA strands, lipid peroxidation, and the formation of oxidatively modified proteins [3]. These cellular alterations can ultimately lead to dysfunction and necrotic cell death [3]. Additionally, Cd^{2+} has been implicated in the activation of various signalling pathways, potentially triggering pro-apoptotic (cell death) and/or adaptive cellular responses [4].

Cadmium has been called the "disseminated element" [5], due to its high mobility and widespread distribution, rendering it a potential contaminant in numerous ecosystems. This elevated mobility, coupled with Cd propensity to form strong complexes with S-containing proteins, poses a significant threat to a wide range of living organisms [6].

The biogeochemistry of an element involves its transportation among the atmosphere, lithosphere, hydrosphere, and biosphere. Therefore, the biogeochemical cycling of Cd, as a toxic trace element, involves the biological, chemical, and geological aspects of the pathways by which it can be transported and circulated in nature. Cadmium originates from weathering of the bedrock, but its concentrations can be exacerbated by mining and land degradation or other operations [7–13]. Anthropogenic activities, particularly the rise in fossil fuel combustion and non-ferrous metal extraction since the Industrial Revolution, have demonstrably altered the biogeochemical cycle of Cd, significantly impacting its movement and circulation within the environment [14]. The geo-accumulation index (Igeo), introduced by Müller in 1969 [15], provides a valuable tool for evaluating environmental contamination. This index facilitates the assessment by comparing present-day concentrations of a pollutant to pre-industrial levels. The index has been used in some trace metal studies, e.g., [16–18]. This index was used in the evaluation of soil pollution by Cd in Egypt [19].

The trophic transfer of toxic metals and metalloids poses risks to both human and ecosystem health [20–23]. This is held true for bee products, where toxic metals enter the food chain through soil-to-plant transfer mechanisms and are transferred to bee products through bee-to-bee product transfer mechanisms. The toxicity of Cd continues to be a significant public health concern as Cd enters the food chain and is consumed by humans; for instance, Itai-Itai, a chronic Cd poisoning disease, was first discovered in Japan. It causes renal tubular dysfunction, osteomalacia, and osteoporosis. This disease occurs as a result of the competition between Cd and other nutrients [24–25]. Furthermore, chronic exposure to Cd has been linked to various health concerns, including cardiac failure, glucose metabolism disorders, cerebral infarction, and breast and lung cancer [26]. The biochemical basis for Cd toxicity in humans has been revised and discussed in detail by several authors, e.g., [27].

Honeybee (*Apis mellifera*) is a cosmopolitan species; this insect is an important ecological and agricultural resource. In addition to their natural products that can be used as food and for medical purposes, honeybees are among the most widely available pollinators worldwide, promoting sustainability in agriculture and natural ecosystems. In addition to honey, the main edible product of honeybees, this insect produces a variety of honeybee products, including pollen, bee bread, royal jelly, bee venom, and propolis. The consumption of beehive products has gained increasing popularity in recent times. These products are characterized by their high nutritional value and/or bioactive properties [28]. Notably, several honeybees' products, including honey, propolis, and bee venom, are utilized in traditional medicine for the prevention of illness and facilitation of healing processes. Therefore, this insect has a significant influence on humans' life and the ecosystem as well. While *Apis mellifera* populations are large, there are concerns that the widespread commercialization of apiculture, together with environmental contamination and bee pathogens, has led to considerable issues for honeybee health [29].

Generally, honeybees contribute directly to global agriculture by an estimated amount of €153 billion per year [30, 31]. Consequently, from an economical point of view, the contribution of primary honeybee products (beehive or apian products), is very important [32–34]. However, honeybee populations are susceptible to several environmental threats, including toxic metal pollutants. Indeed, many publications confirmed that honeybees are prone to environmental stressors, including trace metals that affect the physiology and development of honeybees e.g., [35–37]. Information on the contamination of bee products is not only of great importance to consumers but also in medicine. These products may be a tool for promising therapeutic and chemo-prophylactic strategies against COVID-19 (SARS-CoV2 [38–41]; other potential applications of honeybee venom are known in the treatment of arthritis, cancerous, and autoimmune diseases [42].

The current multidisciplinary review deals with the following topics:

1. Natural and anthropogenic sources of Cd pollution in the environment.
2. Biogeochemistry of Cd including atmospheric, River and irrigation systems, oceanic, soil and trophic transportation.
3. Toxicity of Cd against living organisms including toxicity to humans. Toxic effects on honeybees included physiological, neurological, immunological, and histopathological effects, as well as the effects of Cd on honeybee survival and development; besides the behavioural response and detoxification of Cd. The contamination of Cd to apian products and the reversal effects of royal jelly and propolis against Cd toxicity were reviewed.
4. The use of contaminated bees and beehive products as bioindicators of Cd toxicity in the environment, and the uncertainty created by these manipulations were discussed.
5. The rehabilitation of Cd-contaminated soils by physical, chemical, and biological remediation technologies in the areas of bee activities was reviewed.

2. Methods

The term “heavy metal” is inadequately used, especially in multidisciplinary studies; the International Union of Pure and Applied Chemistry discourages the use of this term, as no standardized definition currently exists [43]. Researchers should utilize only widely accepted terminology for consistency. Regarding "heavy metal," this phrase ought to be supplanted with "metal," "metalloid," or "trace metal" [43]. However, Pourret and Bollinger [44] deemed directly identifying or grouping the studied elements (as metals or metalloids) the optimal approach for clear description. In the present article, we shall use the chemical names and symbols of the elements. Trace metals and metalloid abbreviations used throughout this manuscript are those from the Periodic Table [45].

This article is a multidisciplinary approach outlines the interactions between cadmium (Cd) as a non-living component of the global ecosystem, and honeybee. The selection of revised publications is based on the systematic and literature survey of the publications concerning the environmental sources, biogeochemistry and toxicity of Cd, and therefore, the impacts of this trace element on honeybees, as well as soil remediation of the foraging areas. The review process involved the popular academic search engines viz. Google Scholar, PubMed, Science Direct, Scopus, Springer, as well as official websites concerning the revised topics e.g., UN, FAW, WHO, etc.

2.1. Natural and anthropogenic sources of cadmium pollution in the environment

2.1.1. Natural sources of cadmium

Cadmium is not recovered as a principal product of any mine [46]. It naturally occurs in certain metal–bearing ores and forms its own minerals as impurities in zinc (Zn), copper (Cu), lead (Pb), and base metal ores, which represent the main economic natural source of this element [47]. Cd is a relatively rare element in the earth crust, with an average concentration of 0.1-0.2 mg Cd/kg [48]. Cd abundance in the upper continental crust is about 0.098 ppm [49]. The concentration of Cd in the lithosphere was estimated to be roughly 650-fold lower than its Group 12 neighbour, Zn [50]. However, relatively high concentrations of Cd in nature can be found in marine sedimentary rocks owing to its high ability to accumulate in biota [14]. Levels as high as 300 Cd mg/kg have been recorded in marine sedimentary rocks [51]. Forest fires and volcanic eruptions constitute major natural sources of Cd, collectively releasing approximately 890 metric tons of Cd annually into the atmosphere [52]. Furthermore, the erosion and weathering of rocks are estimated to contribute an additional 15,000 metric tons of Cd per annum [53], which is ultimately transported by rivers to various environmental sinks, including oceans, groundwater, cultivated lands, plants, and other living organisms (Fig. 1).

2.1.2. Anthropogenic sources of cadmium

The United Nations Environment Programme (UNEP) [54] estimated global anthropogenic Cd emissions to be around 2,983 tons in the mid-1990s. While data from developed countries indicates a significant decrease in anthropogenic Cd emissions, averaging around 50% between 1990 and 2003, insufficient data hinders the assessment of emission trends in developing countries. Emissions primarily come from the production of non-ferrous metals and the combustion of fossil fuels [54].

Industrial processes including mining and smelting, particularly Zn [55], are the main sources of

Cd emissions to the atmosphere. Other sources include iron and steel production, oil and gas industries, cement production, as well as waste incineration [56]. Among the common sources are burning of vegetation, sea salt spray, and the production of marine biogenic aerosols [57–60]. Paints, plastic stabilizers, pigments, incineration of Cd-containing plastics, electroplating and phosphate fertilizers are also common sources of Cd pollution [61, 62]. Animal manure, sewage sludge (biosolids), compost, and phosphate fertilizer are also among the most common sources of Cd pollution [56, 61]. Phosphate fertilizers are one of the most common sources of Cd contamination in agricultural soils throughout the world, as Cd often occurs in high concentrations in the phosphate rocks which are used in the production of phosphate fertilizers [64, 65]. A recent review of fertilizers and pesticides as sources of heavy metal pollution has been given by Rashid et al. [66] (Fig. 1).

2.2. Biogeochemistry of cadmium

2.2.1. Cadmium chemistry

Cadmium is a member of Group 12 of the periodic table, (atomic number: 48, relative atomic mass: 112.41); it is like Zn and Hg in chemical and physical properties [67, 68]. Cadmium is a soft, silver-white metal in its elemental form. Its structure exhibits a slight elongation along the six-fold axis, a deviation from perfect hexagonal close packing [6]. Cadmium is quite volatile, with a melting point of 321°C and a boiling point of 767°C. Its heat of vaporization is 26.8 kcal/mol. [69].

Though Cd forms 27 minerals (10 sulfides, 7 sulfates, 4 arsenates, 2 phosphates, 1 oxide, 1 selenite, 1 carbonate, & native Cd) [53], it rarely occurs as a pure metal. Instead, it's typically found in complex oxides, sulfides, and carbonates associated with Zn, Pb, & Cu ores. It is rarely present in large quantities as chlorides and sulfates [70]. Cd may form a group of salts, and both its environment mobility and impacts depend mostly on the nature of these salts in combination with other elements such as chlorine (cadmium chloride), sulfur (cadmium sulfide) or oxygen (cadmium oxide) [46]. In aqueous solutions, Cd primarily exists as the divalent Cd^{2+} ion. Its mobility is highly influenced by various factors, including pH, redox conditions, and ionic strength of the solution. Cadmium solubility tends to be enhanced under acidic conditions and when abundant sorbents like hydrous metal oxides, clays, and organic matter are present to facilitate release from solid phases. [71]. Unlike most metals, Cd forms water-soluble complexes (e.g., $CdCl^{+}$, $Cd(SO_4)_2^{2-}$) and binds to dissolved organic matter, resisting sorption and precipitation, making it highly mobile in the environment [71].

2.2.2. Geochemical transportation of cadmium

Despite being a heavy metal, Cd exhibits exceptional mobility in soil due to factors like competition and ligand-induced desorption, leading to its faster release into groundwater compared to other trace metals [71]. The element is being fluxed among the living and non-living compartments of the ecosystem. Thus, Cd released into the atmosphere can be deposited in terrestrial and aquatic environments and transported through trophic levels of organisms. Soil Cd can be washed out to the aquatic environments over time. Atmospheric Cd transport range varies from local to intercontinental, influenced by particle size, emission height, and meteorology for both natural and anthropogenic sources. Because Cd has a relatively short residence time in the atmosphere (days or weeks), this metal is mainly transported over local, national, or regional distances (Fig. 2). The biogeochemistry of Cd was revised and discussed in the Northwest African upwelling [72], Kuroshio-Oyashio Extension region, Japan [73], subtropical gyre of the South West Pacific Ocean [74], waters of small lakes in European Russia (from the tundra to deserts) and large river systems - Volga, Severnaya Dvina, Pechora [47], Angola Basin [75], the Indian and Pacific sectors of the Southern Ocean [76], the Amundsen Sea, [77], coastal Antarctica [78].

2.2.2.1. Atmospheric transportation

Due to its chemical properties, Cd readily participates in atmospheric transport, constituting a crucial aspect of the global Cd cycle [79]. Compared to other elements like mercury, Cd atmospheric residence time is considerably shorter. This is primarily because most airborne Cd is associated with fine particulate matter (less than 1 µm) [48]. Cadmium chloride, cadmium sulfate, and cadmium oxide are the most prevalent forms of Cd found in ambient air [48]. Given its brief atmospheric lifespan (days to few weeks), Cd predominantly travels over local, national, or regional distances. Emission source and particle size significantly influence Cd atmospheric transport. While elevated Cd

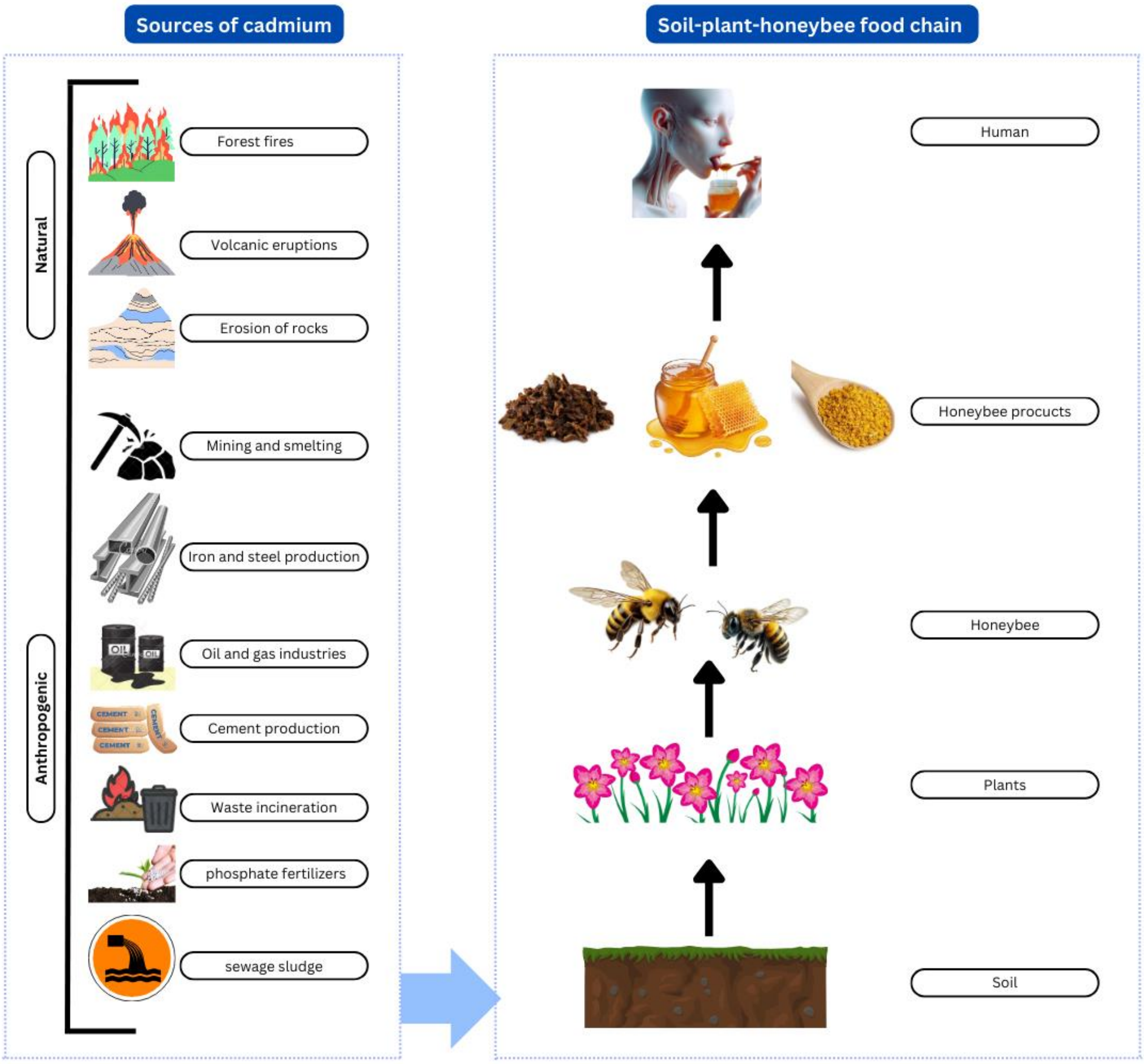

Fig. 1. Possible sources of cadmium input to honeybee and its product.

contamination can extend up to 30 km from the source [66], aerosols facilitate transport over much greater distances. Under specific conditions, air currents can carry Cd over hundreds or even thousands of kilometers, impacting human health and ecosystems far beyond the emission point [54]. Notably, combustion processes often release Cd as microscopic particles, contributing significantly to the overall atmospheric particulate matter burden [69]. Cd from atmospheric deposition concentrates in the upper humus soil layer [56] and appears to be easily available to plants [66]. However, the accumulation of atmospheric Cd on different organs of the plants (leaves, flowers, etc.) cannot be neglected.

2.2.2.2. Aquatic transportation

In natural environments, Cd primarily exists in the +2-oxidation state (Cd (II)). This valence state is virtually the only one observed in aquatic systems. [80]. Cadmium chloride and cadmium sulfate exhibit high solubility in water, whereas elemental Cd, cadmium oxide, and cadmium sulfide are almost insoluble [48].

Cadmium mobility in aquatic environments is increased under conditions of low pH, low water hardness, low suspended particulate matter, high redox potential, and low salinity. Natural water systems exhibit a reduced bioavailability of cadmium (Cd) due to sorption onto suspended particles. Consequently, higher Cd concentrations are required to elicit biological responses [81]. In aquatic environments, organisms tend to absorb Cd most readily directly from the water when it is present in its free ionic form [82]. Due to bioaccumulation within organisms, relatively high concentrations of Cd are observed in marine sedimentary rocks [14]. Dissolved Cd concentrations in river water typically range between less than 1 and 13.5 nanograms per Liter (ng/L) [83]. Notably, higher proportions of dissolved Cd are found in acidic waters. EU freshwater Cd concentrations have exhibited a general decline since the late 1970s. However, the rate of decrease has slowed since 1990 [81]. Several studies have highlighted the significance of major river systems as sources of various materials, including potentially harmful elements, delivered to coastal marine environments [84-88].

The average Cd concentration in seawater is reported to be around 0.1 µg/L or less [48]. Cd readily forms complexes with chloride ions. This complexation increases with increasing salinity [48]. Consequently, in typical seawater, Cd primarily exists as chloride species ($CdCl^+$, $CdCl_2^-$, $CdCl_3^-$) with a minor fraction present as free Cd²+ ions (National Toxicology Program, 1991 as cited by ATSDR [70]). The complexation of Cd with chloride significantly influences its bioavailability, impacting its potential toxicity to marine organisms [70]. A marked bioaccumulation of Cd has been reported in large migrating mammals such as dolphins [89] and whales [90]. Therefore, a minor role in the biological intercontinental oceanic transfer of Cd cannot be excluded.

Macdonald et al. [91] highlight the crucial role of ocean currents in heavy metal transport, particularly in the Arctic Ocean. Their findings suggest that atmospheric deposition and land-based runoff (rivers, etc.) contribute minimally compared to the significant influx from ocean currents. Natural oceanographic processes lead to elevated Cd concentrations in the North Pacific, approximately five times higher than those observed in the North Atlantic [92]. Oceanic transport and response times to anthropogenic pollution far exceed those in the atmosphere. Unlike atmospheric pollutants with hemispheric transport timescales measured in days to weeks, ocean circulation patterns, such as the thermohaline circulation (estimated at 600 years for a single water molecule to complete the cycle) [93], significantly influence the movement and response of pollutants within the marine environment. This translates to a much slower large-scale response to anthropogenic inputs. The estimated residence time of Cd in the ocean is around 15,000 years [54]. This extended timeframe suggests that the current anthropogenic contributions of Cd to surface waters are relatively insignificant compared to the vast oceanic reservoir of the element [53].

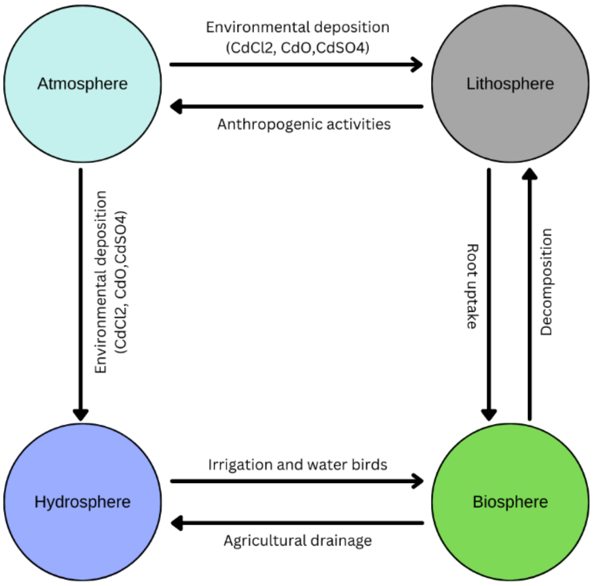

Fig. 2. Geochemical transportation of cadmium.

2.2.2.3. Soil transportation

Cadmium accumulates in the soil as a result of a combination of natural processes including rock weathering, volcanic activity, forest fires, erosion and deposition in river sediments, as well as anthropogenic activities, including mining and industrial activities, in addition to agricultural practices such as irrigation and fertilization that can result in Cd input into the soil (Fig. 1). He et al. [94] pointed out that the contribution of natural processes to soil Cd is 3 to 10-fold lower than that of anthropogenic activities. Cadmium solubility increases under acidic conditions [95]. Chloride readily forms soluble $CdCl^+$ complexes, reducing Cd^{2+} adsorption onto soil particles. Unlike inorganic ligands, organic matter can enhance Cd^{2+} adsorption on kaolinite (a variable-charge mineral) by forming an adsorbed layer on its surface [96]. However, research indicates that critical limits for Cd contamination in agricultural soils vary based on texture [97]. Soils with higher clay content generally exhibit higher tolerance levels compared to those with lower clay content. The established critical limits are light-textured soils: 5.33 mg/kg, medium-textured soils: 6.33 mg/kg and heavy-textured soils: 9.29 mg/kg. Regulations limit the Cd concentration in sewage sludge intended for land application to a range of 20-40 mg/kg dry matter [98]. Furthermore, the total Cd content in the soil after sludge application should not exceed 1-3 mg/kg. Cd accumulation in soil poses a risk of mobilization through leaching processes. This can contaminate groundwater or surface water resources [99, 100]. Toxic metals from soil also leached down to the groundwater reservoirs making it unfit for drinking purposes [1]. Kubier et al. [71] discussed the hydrogeochemistry of Cd in groundwater, exploring its reaction pathways within aquatic environments. It should be mentioned, however, that some elements cannot be transported from soil to plants; for instance, Pb is not transported by plants, while Cd is transported from the soil to plants and can then contaminate nectar and honeydew. Atmospheric deposition accounts for only minor cadmium contamination in honey, primarily in proximity to incineration facilities [101].

2.2.2.4. Trophic transportation

Toxic metals and metalloids transport from soil to plant; and subsequently to animals through food webs, and ultimately to human beings (Fig. 1). Thus, plants take up Cd, together with other non-biodegradable metals and metalloids from contaminated soil and distribute it in successive trophic levels, where it is ingested by herbivorous animals, and subsequently higher trophic levels. The increased concentration of trace metals, due to their non-degradability is known as biomagnification, while the accumulation of heavy metals in living systems is known as bioaccumulation. The amount of the Cd compound identified analytically is not necessarily equivalent to the bioavailable amount [70].

Trophic transportation of Cd and other trace elements can be concluded from earlier studies; for example, Hunter and Johnson [102] found a much greater food chain transfer potential for Cd than for Cu irrespective of their concentration in the environment. The biogeochemistry of Cd in the terrestrial habitat, the soil-plant-insect system, was studied by Zhang et al. [103]. A general review of the transfer of metals and metalloids collectively (without specification of each metal separately) through terrestrial food webs was given by Gall et al. [104], while Chen et al. [105] examined the trophic transfer of Cd in various components of soybean-dodder parasitic. Singh et al. [106] reported that much pollinator diversity is being lost due to toxic metal exposure, which poses a serious threat to agriculture. Recently, Khan et al. [107] have evaluated the allocation and bioaccumulation of Cd through successive trophic levels from soil to cotton plants, cotton plants to herbivore pests, and herbivorous pests to a natural enemy predator. On the other hand, Mochizuki et al. [108] reported that the ranges of the Cd contents in the kidneys and livers of 85 wild birds collected from 9 different prefectures in Japan were ND-174.4 and ND-21.2 µg g-1 dry wt., respectively. However, Cd and other metals can be transported from water bodies in aquatic ecosystems to terrestrial ecosystems through avian tissue after death and decay of the predatory birds.

2.3. Toxicity of cadmium *against living organisms*

Metallic compounds cannot be easily degraded, even at low levels [109, 110, 111]. Owing to their toxicity, persistence in the atmosphere, and bioaccumulation potential in human body, these compounds pose significant environmental concerns [112]. Cadmium is a toxic transition metal that accumulates in cell tissues and has no mechanism for expelling from the body. Cd is ranked as the 7th most hazardous substance for living organisms [113]. The toxicity of Cd to living organisms can be explained based on its chemical properties; for example, Zn and Ca are essential metal ions in numerous biological processes in humans and other organisms, including honeybees. The ionic radius, identical charge, and similar chemical behavior of Cd to both Zn and Ca enable Cd to replace them, causing physiological and biochemical disorders. Studies have proposed that free Cd^{2+} ions exploit transporters meant for essential elements like Ca^{2+}, iron (Fe^{2+}), and Zn^{2+} to gain entry into cells [114]. Toxicological effects of Cd on humans were discussed by many authors, e.g., [115–126].

2.3.1. Cadmium has only one biological function

Although Cd is not generally considered a bio-essential metal; yet it has been indicated that this trace element can perform the physiological function of Zn, when ambient bioavailable Zn becomes depleted in the planktonic marine diatoms, *Thalassiosira weissflogii* [127–129], *Phaeodactylum tricornutum* and *Pseudonitzschia delicatissima* [130] as well as in the phytoplanktonic coccolithophoride *Emiliania huxleyi* [131–134]. This could be attributed to the chemical similarities of Cd to the divalent ions of Zn. Thus, only one well-defined biological function has been established for Cd. In marine diatoms, Cd can potentially replace Zn within the enzyme carbonic anhydrase, a crucial component of their photosynthetic machinery [135–137]. However, the biological mechanisms of Cd absorption by phytoplankton are poorly understood [129, 138–140].

Some marine plankton have evolved the ability to substitute Cd, a toxic non-essential metal, in place of the biologically essential element Zn in certain physiological functions. This evolutionary adaptation demonstrates how these organisms have developed over millions of years to exhibit a diverse array of structural, metabolic, and physiological adaptations enabling them to thrive in a wide range of oceanic environments. On the other hand, phytoplankton can take up free Cd^{2+} ions through transporters originally designated for essential metals like Ca^{2+}, Fe^{2+} and Zn^{2+} [114]. This unintended cellular uptake is attributed to ionic mimicry. Due to their similar chemical properties, Cd^{2+} can bind to the active sites of membrane proteins specific to these essential elements, facilitating its entry into the cell.

2.3.2. Guideline values

Due to its long persistence in the human body (10-35 years), the safe monthly intake of cadmium is limited to 25 μg/kg body weight. Each member state of the European Community developed their procedures to determine a limit value, which ranged from 0.08 to 27 μg/L [119]. The recommended level for Cd in drinking water is set to 3 μg/L [122]. The Environmental Protection Agency of the United States set the maximum permissible level for Cd to 5 μg/L, which is the same as in the European Union [56] and China [141]. In Denmark, the environmental quality criteria for Cd in groundwater is 0.5 μg/L; while it has been set at 10 μg/L in Japan and China [54, 71,142]. Some of the permissible limits for Cd in honey and beeswax, food, water, and soil are given in (Table 1).

2.3.3. Cadmium toxicity to honeybees

The toxicity of Cd to living organisms can be explained based on its chemical properties; for example, both Ca and Zn are essential nutritive elements in numerous biological processes, including the function and structure of many proteins in honeybees and other insects [143, 144]. The ionic radius, identical charge and similar chemical behavior of Cd to both Zn and Ca enable Cd to displace them if encountered, causing physiological, biochemical, and genetic disorders. Honeybees are exposed to environmental pollutants, including heavy metals while flying [145] and collecting food resources (water, pollen grains, and flower nectars) [146, 147]. Metals bio-accumulate in honeybee bodies [148, 149] and in their hive products [150, 151], impacting their survival [152], physiology [153], and behavior [154, 155]. However, atmospheric Cd may gain access to Arthropod bodies directly from the atmosphere to the tracheal system. It has been reported that accumulation of essential trace elements, e.g., Zn, can be checked through homeostatic control mechanisms; in contrast to non-essential ones including Cd, where no homeostatic control can check accumulation of this element [102, 156]. Gekière et al. [157] Listed publications on the effects of 68 'trace metals and metalloids' on honeybees, bumblebees, stingless bees, and solitary bees.

2.3.3.1. Effects of Cd on survival and food consumption

The mortality of honeybees increases, and the growth rate decreases in larvae, pupae, and foragers, exposed to sublethal doses of Cd, in a dose-dependent manner [152, 158]. The exposure to sugar syrup containing either CdO nanoparticles alone or a combined mixture of CdO and PbO nanoparticles resulted in a significant decrease in both the survival and feeding rates of the bees. [159].

2.3.3.2. Physiological effects of Cd

Cadmium exposure disrupts the physiological regulation of cellular signaling pathways, leading to subsequent dysfunction [160]. This disruption stems from two primary mechanisms: firstly, the substitution of essential Ca^{2+} ions with Cd^{2+} ions within signaling processes, and secondly, the replacement of Zn^{2+} ions in crucial enzymes and transcription factors [161, 162]. This Zn^{2+} substitution can trigger aberrant gene expression, potentially stimulating uncontrolled cell proliferation or inhibiting apoptosis [162]. Additionally, research by Nikolić et al. demonstrates that exposure to heavy metals like Cu, Pb and Cd significantly alters gene expression, enzyme activity, and cellular redox state [153]. Notably, the effects are metal-specific and dose-dependent. While both Cd and Cu exposure impacted the expression of genes encoding catalase and superoxide dismutase (antioxidant enzymes), Pb exposure solely induced the expression of superoxide dismutase genes [153].

2.3.3.3. Histopathological effects

Cadmium oxide (PbO) and nanoparticles of cadmium oxide (NPs) induced rupture of the midgut peritrophic membrane, in addition to common cytological alterations in epithelial cells, including irregular distribution or/and condensation of nuclear chromatin, mitochondrial swelling and lysis, and rough endoplasmic reticulum (rER) dilation, fragmentation, and vesiculation [163].

Table 1
Permissible limits (ppm) for Cd in food, water and soil

Matrices	Area of application	Value in ppm	Source
Honey and beeswax	Global	$0.25 \mu g g^{-1}$	WHO/FAO (Kebebe 2019) [311]
Honey	European Union	0.05–0.3.00 mg/kg	(EC) No. 1881/2006 as quoted from Šerevičienė et al. (2022) [312]; Bogdanov, 2006 [101]
Food (in general)	International	0.05-2.00	Joint FAO/WHO (2015) [313]
	European Union	0.05-3.00	Commission Regulation (EU 2015) [314]
	China	0.05	Li et al. (2006) [315]
Leafy vegetables	Global	0.2 mg kg^{-1}	FAO/ WHO (1996) [316]
Root vegetables	Global	0.3 mg kg^{-1}	FAO/ WHO (1996) [316]
Other vegetables	Global	0.1 mg kg^{-1}	FAO/ WHO (1996) [316]
Drinking water	International	0.003	Joint FAO/WHO (2015) [313]
	European Union	0.005	European Commission (EU 2019) [317]
	USA	0.005	US EPA (2017) [318]
	China	0.005	Ministry of Health, China (2006) [141]
Irrigation water	International	0.01	Ayers RS, Westcot DW (1994) [319]
	USA	0.005- 0.01	US EPA (2006) [320]
Soil	International	0.9-3	de Vries et al. (2002) [321] WHO/FAO (2001) [322]
	Finland	1.-20.0	Ministry of the Environment, Finland (2007) [323]
	UK	10-230	UK Environment Agency (2009) [324]
	USA	0.48	US EPA (2002) [325]
	China	0.3-0.6	Environmental Protection Ministry of China (2015) [326]

2.3.3.4. Neurotoxicity

Honeybee exposure to cadmium oxide nanoparticles (NPs) disrupts their nervous system by affecting the enzyme acetylcholinesterase (AChE). AChE, belonging to the Carboxyl/cholinesterases family, normally breaks down the neurotransmitter acetylcholine (ACh) into choline and acetate. However, CdO NPs inhibit AChE, leading to ACh accumulation. This excess ACh hyperstimulates receptors, disrupting neurotransmission and causing altered locomotor behavior in honeybees, as observed in other insect studies [164, 165]. A significant decrease in acetylcholinesterase activity was reported in honeybees treated with 0.001 and 0.01 mg L^{-1} $CdCl_2$ [153]. Acetylcholinesterase activity in the heads of honeybees was inhibited by 3.8-, 3.0-, and 2.8-fold relative to control, respectively, in response to exposure to Cd or/and Pb oxide nanoparticles [159]. Furthermore, Cd exposure in honeybees triggered dysregulation of genes related to oxidative stress response and odor sensing, suggesting oxidative stress and reduced chemoreceptor expression, likely leading to impaired olfactory learning [166].

2.3.3.5. Immunological response and detoxification

Glutathione S-transferases (GSTs) constitute a diverse family of multifunctional enzymes found throughout various organisms [166]. They play a critical role in detoxification by catalyzing the conjugation of the tripeptide glutathione (GSH) with a wide range of electrophilic substrates. This conjugation process effectively reduces the reactivity and enhances the water solubility of these substrates [167]. Cd-induced genomic instability via a complex interplay of diverse mechanisms [168]. Various combinations alter xenobiotic detoxification gene expression. For example, a binary sublethal mixture of CdO and PbO nanoparticles in sugar syrup triggered a 13.6-fold increase in catalase expression compared to unexposed bees [159].

Exposure to Cu, Pb and Cd significantly alters gene expression patterns, enzyme activity levels, and the cellular redox state in bees. However, the specific effects depend on the particular metal involved and the dose to which the bees are exposed. Exposure to Cd and Cu altered expression of both catalase and superoxide dismutase genes, while Pb only affected superoxide dismutase [153]. Distinct microbial communities inhabit the honeybee gut and its products, actively supporting the host's health and nutrient availability. Moreover, it inhibits food spoilage and contributes to maintaining hygienic conditions within the hive [28]. The honeybee gut microbiome is actively involved in bee protection against infectious diseases [169], as well as in the degradation of pollen wall polysaccharides [31, 170]. In addition to the detoxification of pollutants and toxic plant compounds [31, 171]. Moreover, the honeybee microbiome is essential for honey and bee bread production during maturation [169, 170, 172–175].

Research suggests a degree of resilience in the honeybee microbiome regarding Cd exposure. Notably, certain bee-associated bacterial strains exhibit the ability to bioaccumulate Cd [176]. This phenomenon might offer a protective mechanism for bees against metal and metalloid contamination. Additionally, these bacterial strains potentially possess genes involved in the detoxification of such chemicals [176]. In vitro studies with liquid cultures demonstrated the capacity of specific bee-associated bacteria to remove Cd from the surrounding medium [176].

2.3.3.6. Behavioral response to Cd exposure

Chronically exposed honeybees displayed significantly impaired olfactory learning and lower head weight compared to controls [166], highlighting Cd's impact on this vital foraging behavior crucial for plant-bee interactions [36].

Concerning the feeding behavioral response of the honeybee to toxic metal-contaminated plants; several studies indicate that restrained bees will ingest solutions containing selenium (Se) or Cd [154]. Interestingly, they do not exhibit any behavioral signs of aversion to these solutions. In contrast, Cu seems to be palatable to bees at specific concentrations [154]. Electrophysiological studies [177] revealed no evidence of specific mechanisms in honeybees enabling selective detection of toxic metals (arsenic and Pb) compared to Zn, which is essential for biological functions. The overall, cellular, and behavioral responses of honeybees to these metals did not support such selective detection capabilities.

Burden et al. [154] investigated the discriminatory gustatory responses of bees towards different metals. Their findings revealed that bees readily rejected sucrose solutions containing Cu upon antennal contact, while solutions containing Cd were not. Interestingly, Cd ingestion did not affect the bees' sensitivity to sucrose. These observations suggest distinct mechanisms underlying the detection of each metal and the potential pathways of metal-induced toxicity. However, the challenge lies in the chemical similarity between Zn, a crucial trace element for bees and other organisms, and Cd. Notably, even at the highest reported concentrations, Cd did not deter feeding behavior, and copper-laced nectar was readily consumed following proboscis contact, as documented in the same study by Burden et al. [154]. Honeybees seem unable to sense certain toxicants through their antennae or proboscis. For instance, they readily ingest sucrose contaminated with even fatal Se levels [178]. Similarly, Cd showed no rejection or impact on sucrose sensitivity [154]. This leaves them vulnerable to undetected or unrecognized harmful xenobiotics like Se and Cd.

2.3.4. Cadmium in honeybee products

Understanding the contamination levels of bee products is crucial not only for consumer safety but also for medical applications. Notably, the degree of contamination can vary significantly within different bee products, even when collected from the same apiary. Cadmium, for instance, poses a particular concern. Once absorbed by plant roots, it is transported through the vascular system into nectar and pollen. This process leads to bioaccumulation in pollinators, subsequently impacting bee products like honey, propolis, beeswax, and others [152]. Research by Leita et al. [179] demonstrates this phenomenon, highlighting a positive correlation between the Cd content in honey and the Cd levels found in Trifolium pratense L. flowers foraged by bees near a heavily trafficked highway. Studies conducted in Switzerland [101, 180] have revealed a descending trend in the level of contamination across various bee products: bees > propolis > comb > wax > honey. This phenomenon is likely attributed to the filtering process employed by bees during honey production. It is also possible that Pb and Cd are partially removed during the comb melting process used to obtain pure beeswax. It is noteworthy that Gabriel et al. [181] developed a novel method for determining Cd residue in bee products like propolis and pollen. This technique, known as square wave anodic stripping voltammetry (SWASV), utilizes a lab-made Bismuth Bulk Electrode (BiBE).

2.3.4.1. Propolis

Propolis is a complicated material that has many biologically active compounds valuable to the human organism, e.g., lipids and wax, bio-elements, vitamins, proteins, and other compounds [182, 183, 184]. Bees leverage propolis, a resinous substance collected from plants, to construct and repair their hives. It seals openings, smooths internal walls, and acts as a protective barrier against external threats and weather. The contamination of propolis by Cd has been documented, e.g., Roman and Popiela-Pleban [185]. Worker bees do not perform purification steps while processing raw materials into propolis. Consequently, the mineral and trace element composition of propolis directly reflects the natural abundance of these elements in the bees' surrounding environment. [186, 187].

2.3.4.2. Honey

Nectar is a sugary liquid secreted by specialized plant structures called nectaries [188, 189]. This aqueous solution contains a complex blend of nutrients, including sugars, amino acids, organic acids, proteins, fats, vitamins, and minerals. Forager bees create beebread by combining pollen with nectar and their own glandular secretions [190]. This fermented mixture is a highly nutritious food source, particularly for young bees. Upon returning to the hive, beekeepers can carefully harvest and market beebread for its potential health benefits [191].

The collected nectar is stored at the bottom of the esophagus in the honey stomach before being transported to the hive. During transportation to the hive, the nectar undergoes transformation via enzymatic treatment. This chemical transformation is based on the hydrolysis of sucrose, a biochemical process catalyzed by an invertase enzyme. This is followed by the nectar loads transfer from "bee nectar collectors" to "food-storing bees". Honeybees transform nectar into honey through a ripening process. Food-storing bees regurgitate and deposit nectar in honeycomb cells, where it undergoes further conversion of sucrose to glucose and fructose, accompanied by water evaporation. This process, lasting 1-3 days, is finalized by capping the nectar-filled cells with beeswax [192, 193]. Contamination of honey with Cd was reported by earlier authors, e.g., [186, 194–198].

Trace elements and metalloids in honey have high nutritive values; however, at high concentrations, they may cause serious health problems. Cd levels have been measured in honey in different countries; e.g., Egypt [199, 200, 201], Turkey [202], Poland [203, 204, 205], Spain [206], New Zealand [207], Italy [208], Russia [209], Romania [210], and Iran [211]. Historical records indicate significant variations in Cd contamination levels in honey across different regions. Concentrations range from a low of 4.4 µg/kg in Spain to a concerning high of 390 µg/kg in Iran. Due to the potential health risks associated with Cd exposure, a recent Romanian study conducted a complex risk assessment analysis to evaluate the safety of honey consumption from three distinct regions within the country. [212].

2.3.4.3. Beeswax

Numerous studies have reported that metal contamination levels are lower in honey compared to those observed in the bodies of bees and the surrounding environment [101, 213]. This observation has led to the suggestion that bees possess the ability to filter and purify nectar, thereby removing these contaminants during the process of honey production [214, 215]. Specifically, Dżugan et al. [216] have defined bees as "biofilters" that prevent the penetration of elements into bee products, particularly honey. Recently, Borsuk et al. [217] conducted research to investigate the mechanism of nectar purification by bees. Their findings indicated that Cd and certain other elements were partially immobilized or metabolized in the bee fat body, with the residues being excreted through feces from the gut. Furthermore, Ullah et al. [218] determined and compared heavy metal levels in honey, beeswax, and bees obtained from apiaries located in different regions of Pakistan, subsequently estimating the risk level for those residing in areas where honey consumption is prevalent.

Intensive beekeeping relies on beeswax foundations, but the practice of recycling wax can lead to decades-long accumulation of toxic metals. Tlak Gajger et al. [219] analyzed beeswax samples during foundation production and found metal concentrations (mg kg^{-1}) in the final comb products ranging as follows: As 0.01-0.88; Cd 1.26-3.55; Pb 82.5-171; and Hg 0.29-1.46.

2.3.4.4. Bee pollen

Pollen, rich in lipids, proteins, vitamins, and minerals, is crucial for honeybee growth, development, and reproduction [220]. It fuels hypopharyngeal gland and body fat development in young workers, essential for brood rearing and winter survival [221]. Bees collect and transport pollen on their hind leg structures called corbiculae [222]. Bee pollen is an antioxidant and antimicrobial bee product; used in apitherapy. Its structure contains various enzymes, co-enzymes, steroids, vitamins, antibiotics, mineral substances, and flavonoids [101, 223]. Despite its therapeutic value, bee pollen may be contaminated with environmental pollutants, including Cd. The Cd concentration of bee pollen has been reported by several authors [186, 224–226]. The average concentration of Cd ranged between 2 µg/kg [227] and 2965 µg/kg [150]. Vegh et al. [228] conducted a risk assessment for the most common pesticide-active substances, including Cd in bee pollen.

2.3.4.5. Royal Jelly

Young worker bees produce royal jelly, a secretion from their hypopharyngeal glands. royal jelly nourishes drone and worker bee larvae for their first three days and the queen throughout her life. Unlike worker and drone larvae, which receive royal jelly along with honey and pollen, the queen bee exclusively consumes royal jelly [28, 228, 229]. It has been reported that the amount of Pb, Zn, and Cd accumulated in royal jelly [179, 231]. The royal jelly is initially fed to all larvae (not just queens), therefore its contamination with toxic metals can potentially affect all members of the colony directly [232]. However, as will be discussed later, royal jelly has a protective role against Cd-induced genotoxicity and oxidative stress in mice, due to its antioxidant effects [113].

2.3.4.6. Honeybee venom

Honeybee venom is a defensive secretion produced by specialized glands and delivered externally through a stinger. The reported lethal dose (LD50) for humans is approximately 2.8–3.5 mg/kg, equivalent to the venom from 400–1500 stingers. The LD50 for intravenous administration in mice is 0.6 mg/kg. Dried bee venom presents as a very fine, lightly yellow powdered substance. It exhibits partial solubility in water, forming an opalescent solution. The composition of bee venom has been extensively documented by several authors [233–236]. Honeybee venom harbors traces of substances bees encounter, including environmental toxins like Cd. Choinska et al. [237] developed a method to measure specific heavy metals, including Cd, in bee venom.

2.3.5. Reversal Effects of Royal Jelly and Propolis Against Cadmium Toxicity

Propolis and royal jelly are essential natural products that possess a wide array of active biological properties. These properties encompass antioxidant, anti-inflammatory, antibacterial, antitumor, immunomodulatory, and anti-infertility effects, as documented by several researchers [238–241]. Furthermore, Royal jelly and propolis exhibit potential in alleviating the toxic effects of Cd. Cavuşoğlu et al. [242] suggest that the antioxidant properties of royal jelly act against Cd-induced genotoxicity and oxidative stress in mice. Amr et al. [113] concluded that Honeybee products like propolis and royal jelly may alter Cd absorption, increase excretion, and mitigate oxidative stress, potentially preparing the organism against harmful effects.

2.4. Honeybees and apian products as bioindicators of cadmium pollution

Due to a specific lipid-based chemical composition, Cd is one of the main toxic heavy metals in environmental pollution that can contaminate beehive products. Thus, combs and the inside of the hives can also be contaminated as a consequence of the order and social activity of foragers and house bees [196]. It has been suggested that there is a close correlation between the level of metal accumulation in soil and plants and their content in bee products. The beehive products have been regarded as bio-indicators of a polluted environment by earlier and recent authors e.g., [186, 187, 203, 224, 243–247]. However, honeybees can filter and purify nectar to remove these contaminants during honey production; honeybees were defined as “biofilters” that prevent elements from penetrating bee products, especially honey. Lower heavy metal content in honey compared to bees suggests effective "filtering" by bees. [179, 198, 248]. Thus, honey concentrates metals well below typical detection limits [249], rendering it unreliable as an environmental indicator. Research by Borsuk et al. [217] suggests that bees can partially immobilize or metabolize certain elements, including Cd, within their fat bodies. Residues are then excreted through the gut. In another study, Costa et al. [250] explored the use of honeybees as bioindicators for atmospheric Pb and Cd levels. Their study suggests bees could serve as alternative tools for monitoring environmental pollution by these metals. In the Netherlands, Van der Steen et al. [251] found air metal concentrations too low and variable to link them to bee metal levels, suggesting honeybees are not reliable air pollution indicators compared to mechanical devices. Furthermore, Beeswax foundations can be recycled [252], accumulating toxic metals in these foundations for decades.

The absence of interdependencies in metal accumulation between consecutive products is likely attributable to the accidental exposure of bees and plants to contamination. Furthermore, it is noteworthy that different plant species and plant organs may exhibit varying concentrations of metals [253]. Honeybees primarily collect nectar and pollen from the same plant species. However, at any given time, a colony utilizes less than half of the plant genera they encounter for both nectar and pollen collection. This limited overlap in plant use raises concerns about the accuracy of bee products (like honey) as indicators of specific metal contamination in the environment. Different plant species accumulate these pollutants at different rates. Recently, DNA-metabarcoding by Leponiemi et al. [190] revealed floral sources of honey and pollen, showing workers leverage similar plants for both, yet use less than half the plant genera per colony for both nectar and pollen simultaneously. Finally, it can be suggested that there is a high level of uncertainty if the honeybees and/or beehive products as environmental bioindicators for Cd pollution for the following reasons: The use of honeybees or apian products as bio-indicators for environmental pollution by trace element creates a high level of uncertainty due to the following reasons: i) trace elements may gain access to internal organs from the atmosphere via spiracles and direct contact with contaminated bodies, as well as from the collected nectar, ii) bees remove contaminants from nectar and honey by metabolizing and immobilizing metals in their fat bodies. The residues are then excreted in the bees' faeces during honey production., iii) bee workers use mostly the same plants for both nectar and pollen, while different plant species and plant organs may contain different concentrations of metals, iv) the lack of interdependences in metal accumulation between the consecutive products probably reflects accidental exposure of bees and plants to contamination, v) as a beekeeping practice, wax may be recycled, and heavy metals can accumulate in wax foundations for decades.

2.5. Remediation of cadmium

The rehabilitation of soils contaminated with toxic metals, in the areas of bee activities, should be considered to avoid the toxicity of this element against honeybees and their beehive products. Common remediation strategies include soil excavation and replacement, chemical precipitation, physicochemical adsorption, biosorption, phytoremediation, etc. [254–256]. Remediation technologies of Cd include digging and filling [257], frozen soil remediation technology [258], vitrification technology also referred to as melting and solidification technology [259], electro-kinetic remediation [260–262], Lime/volcanic ash solidification [263], stabilization technology [264–266], Cement-based binders [267, 268], the plastic material containment method [263, 269], chemical solidification technology [270, 270], Adsorption and coordination [272, 273], chemical complexion mechanism [274, 275], Chemical extraction technology [276, 277]; in addition to bioremediation technologies including soil invertebrates repair technology [278], phytoremediation, and microbial remediation. Generally, remediation procedures can be classified into 4 major categories: physical remediation, Chemical remediation, Electrokinetic remediation, and biological remediation.

2.5.1. Physical remediation

Soil removal and isolation may be applied for seriously contaminated soil with a small area; while adding a huge amount of clean soil to the polluted soil surface or blending the clean soil with it [255, 279, 280].

2.5.2. Chemical remediation

Contaminated soil can be cleaned by soil leaching, using certain reagents, thereby removing heavy metal complexes and dissolved iron adsorbed on solid-phase particles. The removed heavy metals are then recovered from the extraction solution [255]. Contaminated soil can be cleaned also by fixation and adsorption using clay minerals, for example, bentonite, zeolite, and so forth [281]. On the other hand, the removal of Cd(II) ions from polluted solutions has been studied in Egypt by Swelam et al.[282], who have compared adsorption and coagulation techniques in the removal of Cd(II) ions from polluted solutions, using *Moringa oleifera* Seeds; while a nano-magnetite could be used in laboratory as an eco-friendly sorbent (without the usage of surfactants during the synthesis) for removing Pb(II), Cd(II) and Cr(III) from both Nile river water and wastewater[283].

2.5.3. Electrokinetic remediation

Electrokinetic (EK) migration is a synonymous term for EK remediation, which self-explanatorily describes the fundamental principles underlying this technology [284]. The application of EK remediation for the treatment of heavy metals in soil has gained increasing attention, serving as both a remediation approach and a resource recovery method [284–287]. The process involves the application of a direct current voltage to generate an electric field gradient across the sides of an electrolytic tank containing the contaminated soil. The pollutants present in the soil are transported to the processing chamber and concentrated at the two poles of the electrolytic cell through mechanisms such as electromigration, electroosmosis, or electrophoresis, thereby facilitating the reduction of pollution. This method has demonstrated efficacy in the treatment of low-permeability soils [255, 288]. Electrokinetic remediation has been widely studied for Cd and other metals at both laboratory and field scales. In situ application of these methods has been investigated [255, 256, 289]. However, heavy metals immobilized within the soil matrix pose a persistent risk due to the potential for environmental disturbances, and phytoremediation techniques for the uptake of these contaminants are characterized by inefficient and prolonged treatment timelines. A comprehensive review of the electrokinetic remediation of Cd has been provided by Zongping et al. [284]. The integration of EK remediation and other remediation strategies has also been investigated [290–292].

2.5.4. Bioremediation

Two major technologies are used in bioremediation: Phytoremediation and Microbial remediation.

2.5.4.1. Phytoremediation

Phytoremediation was defined as "a set of techniques or processes where plants are used for extracting, containing, degrading/destroying or restraining contaminants from the medium (soil, water or sediments)" [293]. However, other definitions [294–299] reflect the concept. Phytoremediation can both immobilize heavy metals mainly in the plant rhizosphere and uptake heavy metals aboveground [299]. Phytoremediation leverages the power of plants and their associated microbial communities to remediate and cleanse environments contaminated with heavy metals. This environmentally friendly technology plays a crucial role in safeguarding both the environment and public health. Saxena et al. [300] explored the potential of phytoremediation as a sustainable approach for managing heavy metal contamination in soil. This technique involves planting specific plant species, like those belonging to the Cruciferae family (e.g., genera Brassica and Alyssum) in the contaminated soil [255, 288, 301]. Plants employed in phytoremediation are termed "hyperaccumulators." These hyperaccumulators have the unique ability to concentrate heavy metals in their aboveground tissues at significantly higher levels compared to the surrounding soil or neighboring non-accumulating plants [302, 303]. It's important to note that hyperaccumulators represent an extreme example within the broader category of accumulator plants [304]. They are hyper-tolerant to the toxic metals, which they accumulate in their organs. For Cd hyperaccumulator plant species can accumulate greater than 100 mg kg−1 dry weight [304, 305]. These authors suggested also quantitative values for other metals. The plant hyper-accumulators of Cd include *Azolla pinnata* Rai [306], *Eleocharis acicularis* Sakakibara et al. [307] and *Rorippa globosa* Wei et al. [308]. Generally, the choice of a plant species for remediation of a specific pollutant should be based on some criteria. Thus, the plant species must have A fully developed system to secret a substantial quantity of catalyst for degradation of the xenobiotics, a tolerance to the xenobiotics at a degree found in soil, a quick growth rate, and a comparatively high biomass [309].

2.5.4.2. Microbial remediation

Microbial remediation, on the other hand, involves the use of several microorganisms (bacteria, archaea, and fungi) to carry out the absorption, deposition, oxidation, and reduction of heavy metals in the soil [255, 288, 310]. However, just like other nonessential toxic metals, Cd is non-biodegradable; such chemicals accumulate in the environment and may be transported to living organisms through the food webs. Thus, Cd taken by microorganisms will eventually re-accumulate in the soil after death of microorganisms. Conversely, in phytoremediation applications, hyperaccumulator plants can be removed from the soil and dumped away or recycled.

3. Conclusions

This review article highlights the major aspects of Cd biogeochemistry and toxicity against honeybees. The main conclusions are: 1) Cadmium is a toxic heavy metal with no known biological function, except for its potential replacement of Zn in some marine plankton. Its presence in the environment is mainly from anthropogenic sources such as mining, fossil fuel combustion, and industrial activities; 2) The biogeochemical cycling of Cd involves transportation through the atmosphere, aquatic systems, and soil. Cadmium can bioaccumulate and biomagnified in organisms and trophic levels; 3) Cadmium is toxic to most organisms including humans and honeybees. Its mechanisms of toxicity include displacement of essential metals like Ca and Zn, and induction of oxidative stress; 4) Honeybees and bee products can accumulate Cd from the environment. However, their reliability as bioindicators of Cd pollution is limited due to factors like nectar filtering by bees and wax recycling practices; and 5) Remediation of Cd contaminated soils is necessary to protect honeybees. Strategies like phytoremediation using hyperaccumulator plants, microbial bioremediation, chemical stabilization, and electrokinetic remediation show promise. In summary, this review integrates research across multiple disciplines to highlight cadmium's environmental behavior, toxicity mechanisms, and impacts on an ecologically and economically vital insect species - the honeybee. A better understanding of these interactions can inform efforts to monitor and rehabilitate environments affected by Cd pollution.

4. Conflicts of interest

There are no conflicts to declare.

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