Review Article

Honey as a Valuable Bioindicator of Environmental Pollution

Abdel-Razak M. Kadry[1], Aham G. Khalifa[2], Walaa A. Moselhy[2], Aya H. Abd-Elhakam[2] and Khaled A. H. Abdou[2]

[2]Department of Toxicology, Environmental Metrology&Policy Program, Georgetown University, Washington, DC, USA

[2]Department of Forensic and Toxicology, Faculty of Veterinary Medicine, Beni-Suef University, 62511 Beni-Suef, Egypt

ahlamgamal2013@gmail.com

Abstract

Monitoring environmental pollutants, pesticides, and pathogens is essential for safeguarding human health, agricultural productivity, and ecosystem stability. Various approaches from physical sensors to bioindicators have been employed for environmental surveillance. Honeybees, as globally managed pollinators, serve as an effective continuous biomonitoring species. Foraging bees encounter contaminants, transporting them back to their hives for analysis. While individual bees are sensitive to environmental stressors such as pesticides and temperature extremes, the colony exhibits remarkable resilience, accumulating contaminants or adapting without collapse. This enables long-term tracking of pollutants across geographic regions and the study of ecotoxicological trends over time. The well-established role played by honeybees and hive products (pollen, honey, and wax) as sensitive bioindicators for environmental contaminants, such as pesticides, heavy metals, and airborne pollutants, is highlighted in this review. To improve its dependability for worldwide environmental assessments, more research and standardized procedures are required.

Keywords: Honeybees, Bio-indicators, Ecotoxicological, Pollinators, Environmental Pollutants

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1. Introduction

Honey, the only insect-produced food consumed by humans, is a vital energy source and a key ingredient in numerous products, especially cereals, for its sweetness, color, and texture. It requires no prior processing for industrial use, making it unique among sweeteners. Global honey production is increasing. The Codex Alimentarius defines it as a natural sweet substance made by bees from nectar or secretions from plants, which they collect, transform, dehydrate, and store in honeycombs to mature (Bogdanov et al., 2008).

Different types of honey are classified by production method (e.g., comb, extracted, filtered), origin (nectar or honeydew), or use (e.g., baker's honey for industrial purposes). It primarily consists of sugars—fructose (38.5%) and glucose (31.0%)—with smaller amounts of sucrose, maltose, and complex carbohydrates, varying by raw material. Minor components include amino acids, proteins, flavonoids, antioxidants (e.g., pinobanksin, vitamin C), organic acids (0.57%) contributing to flavor and acidity, and minerals (0.1–1.0%) like potassium, calcium, and magnesium. Water is the second most significant component. The composition depends on the nectar or honeydew source (Kumar et al., 2010).

Healthy bees collect nectar from clean forage and their strong immune system resists viruses and mite infestation leads to an increase in the colony's productivity. The effect of field-realistic quantities of three pesticides found in the pollen and nectar of commercial melon farms on the solitary bee *Osmia bicornis L*, was investigated. Using pollen and sugar syrup, eight treatments for females of this species throughout their lives, which combined two neonicotinoid insecticides (acetamiprid and imidacloprid) with a triazole fungicide (myclobutanil) were administered. All imidacloprid-containing treatments caused significant drops in bee activity and thoracic temperature, as well as decreased syrup consumption (Azpiazu et al., 2019).

Environmental contaminants pose a growing threat to our planet, creating an urgent need for effective biomonitoring tools. Traditional methods of environmental monitoring often require complex, expensive equipment and extensive sampling protocols such as gravimetric analysis, filtration and sedimentation of airborne or waterborne particulates, and core and grab samplers (Staniškienė et al., 2006). Honeybee merchandise was utilized in environmental research since at a minimum 1935, while Svoboda reviewed the outcomes of commercial pollution on honeybees. Since then, they were hired to display numerous contaminants, such as radionuclides after the Chornobyl catastrophe in 1986 and pesticide stages in agricultural areas. Their capacity to build up pollution from air, soil, and water makes them precious for assessing environmental quality (Mair et al., 2023).

Through bees' foraging activities, honey analysis provides an accessible and non-invasive method of monitoring environmental pollutants, indirectly revealing levels of contamination in soil, water, and air. Recent studies have detected heavy metals in honey bee products, certain honey samples had levels of Cd, Pb, Ni, and Cr above allowable limits (Herrero Latorre et al., 2017). The traditional method of environmental pollution monitoring and evaluation depends on sampling of air, water, soil, and plants. These methods are costly, time-consuming, and technically demanding. Also, the investigators need to collect samples from different areas to represent a certain geographic point. In contrast, honeybees cover vast areas and integrate pollutants into hive products. *A. mellifera* bee colonies are used as natural bio-samplers for monitoring the airborne human pathogen, SARS-CoV-2 (Cilia et al., 2022).

This review consolidated the role of honey as a bioindicator of environmental pollution. The mechanisms by which pollutants enter honey, the types of contaminants commonly detected, and analytical methods used for assessment have been discussed.

2. Honeybee Products Are Ideal for Monitoring Environmental Pollutants

Pollen, honey, and beeswax are excellent for monitoring environmental pollution (Mair et al., 2023). Because honeybees sample huge areas during their foraging trips, they are especially useful for monitoring environmental pollutants such as microplastics, pharmaceuticals, and industrial chemicals (dioxin and aromatic hydrocarbon). They collect toxins from different sources such as pesticide-treated crops, toxic plants, and varroa mite treatments then build up in hive products as they collect nectar, pollen, and other materials. This makes it easy to analyze these products for the occurrence of contaminants such as pesticides, antibiotics, and heavy metals. Their large foraging range of up to 12 km^2 gives them a good representation of the degree of pollution, and therefore they are inexpensive compared to traditional monitoring methods (Cho et al., 2021). Bees also respond to pollutants through physiological changes, which can be measured, and emerging approaches like gene expression analysis are enhancing their usefulness in terms of divulging emerging threats like climate change impacts (Catalano et al., 2024).

2.1. Advantages of Honeybees As Bioindicators Compared to Emerging Detection Technologies.

Technologies like paper-based biosensors, CRISPR-based tools, and machine-learning models show a lot of promise for detecting environmental pollutants and pathogens with speed and accuracy. However, they often depend on equipment, expertise, and infrastructure that are not available in many remote or low-resource areas. On the other hand, honeybees and their products are easy to access, affordable, and naturally integrated into the environment. Because they are constantly exposed to their surroundings, they can reflect long-term environmental pollution across wide regions without needing complicated systems to do so (Bromenshenk et al., 2015).

Honeybee colonies are relatively easy to care for and observe, which makes them ideal for long-term biomonitoring programs. Unlike biosensor systems that often need frequent calibration and maintenance, honeybees constantly interact with their environment with minimal human involvement beyond basic hive management. Moreover, because honey is already a common part of the human diet, analyzing it can offer direct insight into the potential health risks linked to the buildup of pollutants in the food chain (Girotti et al., 2020).

Honeybee products reflect the cumulative pollution of a given region over time, offering insights into chronic exposure trends that many rapid diagnostic tools cannot estimate. Traditional bioindicators like honeybees should not replace modern technologies they should work together. By combining both approaches, we get the best. Honeybee products represent pollution

Table 1: Pesticide residues in honey and health risks.

Pesticides	Residue Range in Honey (ppb)	Health Risks	References
Neonicotinoids (Imidacloprid)	2.3 – 16.9 (Field-collected honey in South Africa) (Abafe and Chokwe, 2021)	Neurotoxic and gastrointestinal symptoms	Mundhe et al. (2017); Wei et al. (2024)
Organophosphates (Chlorpyrifos)	860 ppb within a bee (Urlacher et al., 2016)	Hepatotoxicity and reproductive toxicity	Alipanah et al. (2022); Khalifa et al. (2025)
Carbamates (Carbaryl)	30.8 ppb (Colony Health in France) (Chauzat et al., 2009)	Cholinergic syndrome	APHIS (2020)
Pyrethroids (Deltamethrin)	No maximum residue limit (Dluhošová et al., 2024)	Neurobehavioral toxicity	Khalifa et al. (2022)

hotspots and long-term trends, while biosensors and molecular diagnostics provide rapid detection.

3. Accumulation and Detection of Pollutants in Pollen and Honey

3.1. Bioaccumulation

Pesticides can be deposited and accumulated by honeybees on plants, soils, or aquatic environments, along with foraging flights. Polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) accumulate in pollen and honey (Villalba et al., 2024). The tissues of honeybees typically collect metals (such as lead, cadmium, and zinc) (Goretti et al., 2023).

3.1.1. Pesticide bioaccumulation in honeybees and honeybee products:

Bioaccumulation occurs when honeybees absorb a toxic substance such as pesticides from the surrounding environment and accumulate in hive products at higher concentrations due to repeated exposure. The widespread use of pesticides such as neonicotinoids, organochlorines, organophosphates, and fungicides has resulted in significant bioaccumulation in hive products posing health hazards to bees and human health (Costa et al., 2025).

The ratio of pesticide concentration in hive products to that in the surrounding environment is quantified by bioaccumulation factors (BAFs). BAFs depend on the persistence, lipophilicity, and chemical properties of the pesticide (Blasco et al., 2003). DDT can concentrate in hive products and has a long environmental half-live (over 25 years in soil) so possesses high BAFs (Panseri et al., 2020). Around 17 pesticide residues were estimated in honey produced from Kenya and Ethiopia (two of Africa's largest honey producers), and malathion exceeds the maximum residue limits by two-fold (Irungu et al., 2016). Hazard indices were calculated and suggested health hazards of contaminated consumed honey linked to reproductive toxicity (El-Nahhal, 2020) (Table 1).

3.2. Sensitivity to Pollutants

Bees are extremely sensitive to harmful toxins, and their bodies may react by changing their behavior or increasing their mortality rate. When honeybees go for food, they gather contaminants from the earth, water, and air. Increased cumulative levels of dimethoate, imidacloprid, and chlorpyrifos in three apiaries near both agricultural areas and adjacent wildlands caused acute bee death episodes, especially between June 2016 and June 2018 (Calatayud-Vernich et al., 2019).

3.3. Advanced Detection Methods

The detection capabilities of honeybee monitoring are improved by new techniques such as sound analysis, automated hive tracking, and sensor-enhanced hives. Early detection of plant viruses, fungi, invasive species, and new threats like the effects of climate change and genes for antibiotic resistance is made possible by gene expression analysis, microbiome profiling, and high-throughput techniques like next-generation sequencing of pollen that has been stored (Techer et al., 2025).

3.4. Honey Can Reflect Regional Environmental Conditions

Heavy metals such as lead and cadmium emitted from industrial activity may accumulate in plants in this area and appear in honey. The mean levels of lead, cadmium, and nickel in the honey collected from the Lazio region (Italy) were lower than those found for honey gathered in other Italian locations. Also, chromium levels were lower than those of honey collected in six continents, higher than those of honey from different parts of Italy, and obviously lower than those of honey from southern Italy (Conti et al., 2018).

The drought in California has a domino effect on the amount of nourishment available to controlled bees in regions affected by drought. The decreased plant water availability does lower the nutritional value of nectar for bees. In comparison with bees reared on meals from plants with appropriate watering, bees grown on diets mimicking the nutrition generated by plants under low water conditions performed noticeably worse (Page, 2022).

4. Cost-Effectiveness and Accessibility

It is highly affordable and feasible to use honeybees for environmental monitoring, especially in areas with inadequate infrastructure.

4.1. Low-Cost

sampling hive requires no power supply, and sampling hive products like honey and pollen is simple, requiring minimal specialized equipment compared to expensive monitoring stations. This makes bees a low-cost, easily distributed environmental monitoring grid (Marcoccia et al., 2024).

4.2. Ease of Sampling and Analysis

Hive products are easy to collect and analyze, with no need for advanced technical skills beyond analytical interpretation. This accessibility has been leveraged globally, with historical applications dating back to the 1980s, such as monitoring radionuclide contamination following the Chornobyl disaster (Cunningham et al., 2022).

4.2.1. Sampling

samples include different types of honey (clover, corn, sunflower, anise, marjoram, caraway, and basil) from beekeepers and stationary apiaries. Samples were collected in dark plastic cubs using plastic gloves and wooden sticks and then stored at 4°C and -20°C (long-term) till analysis (Layek et al., 2020).

4.2.2. Analysis

- Pesticide residues are measured by chromatography (Radowan, 2024).
- Antibiotic residue analyzed by LC-MS/MS (Chan et al., 2022).
- Microbiological pathogens are quantified via qPCR (Smith and Osborn, 2009).
- Heavy metals concentration is evaluated by inductively coupled plasma mass spectrometry (Lewen et al., 2004).

4.3. Global Applicability

For environmental ecological monitoring, the honeybee (*Apis mellifera* L.) has proved itself to be a reliable and user-friendly biological indicator (Porrini et al., 2002). Many Mediterranean nations, including Spain, presently use honeybee-based biomonitoring (Gutiérrez et al., 2015). Due to the Mediterranean climate's favorability, honeybee activity can be exploited for the majority of the year in Italy (Perugini et al., 2018), Croatia (Barisic and Bromenshenk, 2002), France (Cotton et al., 2014), Greece (Kasiotis et al., 2014), Turkey (Yarsan et al., 2007), Iran (Sadeghi et al., 2012), and Egypt (Malhat et al., 2015).

5. Pathways of Pollutants Transfer from the Environment to Honeybee Products

Honeybees and their products act as sensitive bio-indicators of environmental pollution, with contaminants entering through multiple pathways linked to foraging behavior, airborne exposure, and hive dynamics. Here is how pollutants transfer from the environment to honeybee products:

5.1. Airborne Contamination

Bees encounter airborne pollutants during flight, including microplastics (MPs), microfibers (MFs), and particulate matter (PM). These contaminants adhere to bees' bodies or settle on flowers, which are later collected (Schiano et al., 2024).

- *Synthetic textiles*: Bees unintentionally collect MFs released into the air by synthetic textiles.
- *Traffic emissions*: Heavy metals like copper, zinc, and aluminum are deposited on plants by traffic pollutants, such as those from highways, and are then absorbed by pollen and wax.

- *Polytetrafluoroethylene (PTFE)* and *polyethylene (PE) MPs:* PE is widely used in agriculture, the effects of PTFE and polyethylene (PE) MPs on honeybees, *Apis mellifera*, and beehive products were investigated using Fourier transform infrared microspectroscopy (Schiano et al., 2024).

5.2. Foraging on Contaminated Flora

Bees collect nectar, pollen, and water from plants exposed to:

- *Pesticides* (e.g., carbamates) and fungicides are applied to plants, which are transferred to pollen and nectar (Zioga et al., 2020).
- *Heavy metals* (e.g., lead and cadmium) are absorbed by plants from polluted water or soil (Margaoan et al., 2025).
- *Acaricides (e.g. Amitraz), and antibiotics* used in hives or agriculture remain in floral resources (Johnson et al., 2013). Pollen is particularly vulnerable, often showing the highest contamination levels due to direct exposure in the field.

5.3. Soil and Water Transfer

Heavy metals found in the soil and water sources contaminated with pesticides or antibiotics are absorbed by plants and later detected in bee products (Mair et al., 2023).

6. The Impact of Climate Change on Honeybees

As shown by anecdotal communications obtained by Horizon scan experts, the summer heatwaves of 2022 in France had an impact on honey bee egg-laying during the Robinia pseudoacacia nectar flow, while the intense spring rainfall in Spain caused colony failure due to a shortage of forage supplies. In the near future, interactions between other drivers of decline and extreme climatic occurrences pose a serious concern (Willcox et al., 2023).

There will probably be a rise in migratory beekeeping as a result of more frequent droughts and extreme heat waves and increases in the percentage of hives moved (Martínez-López et al., 2022). The plant resources that bees and other animals rely on for nutrition may be impacted by extreme temperatures (35-40°C), humidity (<30% or >80%), and weather fluctuations (Sudden drops in winter temps (<10°C) and drought or floods). For instance, droughts and higher-than-normal summer temperatures can cause flower blooms to terminate early, which reduces the amount of pollen and nectar available for bees to consume (Flores et al., 2019).

In Egypt, the increase in temperature is expected in the spring to be like the current summer temperature in the future and this rise will be a problem for beekeepers by 2070 in Egypt. Bee workers outside the colonies will not be able to tolerate the temperature. The increase in CO_2 concentrations will affect food diversity with early or delayed flowering affecting honeybees' nutrition (Abou-Shaara, 2016).

7. Limitations in Using Honey As a Pollution Indicator

The composition of honey depends on bee species, the season, the composition of the water, air, soil, and types of plants making it difficult to differentiate between natural levels and anthropogenic levels of pollution (Varga et al., 2020). Another challenge is supplemental feeding such as syrup by beekeepers which introduces external contaminants.

8. Integrating Honey Monitoring into Environmental Policies

Honey is a low-cost regular bio sample that can be embedded in environmental policies. Incorporating honey monitoring into environmental regulations enhances temporal and spatial coverage, assists with regulatory compliance, and coordinates with comprehensive sustainability objectives, it enhances traditional monitoring. It can improve pollution monitoring, community involvement, and sustainable practices when incorporated into biodiversity plans, pesticide laws, and climate strategies. However, creating standardized procedures and resolving logistical issues is essential for success (Marcoccia et al., 2024).

9. Conclusion

Honeybees are active year-round in many regions, thus enabling continuous and long sightings. With great resilience, honeybee colonies can take up an unhealthy load of pollutants such as industrial chemicals, pesticides, and heavy metals, and bioaccumulate through the food chain, raising human health risks such as neurological, reproductive, and renal problems and harm to honeybees themselves (pollination and reduced colony health). To reduce environmental contamination, we need biomonitoring honeybee products for early detection of pollutants by using advanced analytical methods (e.g., GC-MS, LC-MS/MS, and ICP-MS), public awareness, and organic farming. For the Prevention: sustainable agriculture, buffer zones around hives, regulated pesticide use, industrial emission standards, and certificated honey safety can reduce contamination.

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