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Honey Bees as Bioindicators of Air Pollution: A Narrative Review on Human Health Implications

Génesis Georgina García-Sánchez,[1] Martín Eduardo Ortíz-Acosta,[1] Ashuin Kammar-García.[2]*

[1]Escuela de Ciencias de la Salud. Universidad Autónoma de Baja California. Baja California, México. [2]Global Health and Population, Harvard T.H. Chan School of Public Health. Boston, United States of America.

RESUMEN

Abejas como bioindicadores de la calidad del aire: Revisión narrativa de sus implicaciones en salud humana.
La contaminación atmosférica representa una amenaza creciente para la salud ambiental y humana, particularmente en regiones densamente pobladas e industrializadas como Baja California (México) y California (Estados Unidos). Esta revisión narrativa, basada en una búsqueda estructurada de la literatura, explora el uso de las abejas melíferas (Apis mellifera) como bioindicadores de la calidad del aire y su relevancia para la vigilancia ambiental y de salud pública dentro del marco de Una Sola Salud (One Health). Se realizó una búsqueda sistemática de la literatura en PubMed/PubMed Central en mayo de 2025, sin restricciones de idioma o tipo de estudio, utilizando términos MeSH y palabras clave relevantes combinadas con operadores booleanos. Además, se efectuó una búsqueda manual de referencias clave. El proceso de selección incluyó la eliminación de duplicados, la revisión de títulos y resúmenes, y la evaluación de textos completos mediante criterios de inclusión predefinidos. La evidencia indica que las abejas acumulan contaminantes atmosféricos, incluidos metales pesados, pesticidas, material particulado y microplásticos, en diversas matrices como alas, polen y miel. Estas exposiciones desencadenan respuestas fisiológicas subletales, como estrés oxidativo y alteraciones enzimáticas, que reflejan mecanismos fisiopatológicos tempranos en humanos (por ejemplo, inflamación mediada por IL-6 y TNF-α). El biomonitoreo con abejas representa una herramienta rentable, sensible y escalable para identificar zonas de contaminación y exposición potencial humana. El uso de abejas como bioindicadores ambientales puede fortalecer la detección temprana de riesgos sanitarios asociados con la contaminación, especialmente en regiones con infraestructura

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*Autor para correspondencia:
Ashuin Kammar García, PhD, School of Public Health, 655 Huntington Ave, Boston, MA 02115, United States of America.
E-mail: akammar@hsph.harvard.edu
ORCID: http://orcid.org/0000-0002-3875-0945
https://revistabiomedica.uady.mx.

limitada de monitoreo del aire. La implementación de protocolos analíticos estandarizados y la cooperación binacional entre México y Estados Unidos podrían consolidar redes de vigilancia One Health y vincular la monitorización ambiental con estrategias preventivas de salud pública.

ABSTRACT

Air pollution is a growing threat to environmental and human health, particularly in densely populated and industrial regions such as Baja California (Mexico) and California (USA).This narrative review, informed by a structured literature search, explores the use of honey bees (Apis mellifera) as bioindicators of air quality and their relevance for environmental and public health surveillance within a One Health framework. A systematic literature search was conducted in PubMed/PubMed Central in May 2025, with no restrictions on language or study type, using MeSH terms and relevant keywords combined with Boolean operators. A manual search of key references was also performed. The selection process included duplicate removal, title and abstract screening, and full-text review using predefined inclusion criteria. Evidence indicates that bees accumulate atmospheric contaminants, including heavy metals, pesticides, particulate matter, and microplastics, across various matrices such as wings, pollen, and honey. These exposures trigger sublethal physiological responses, including oxidative stress and enzymatic alterations, paralleling early pathophysiological mechanisms in humans (e.g., IL-6 and TNF-α–mediated inflammation). Bee-based biomonitoring represents a cost-effective, sensitive, and scalable approach for identifying pollution hotspots and potential human exposure zones. The use of honey bees as environmental bioindicators can enhance early detection of pollution-related health risks, especially in regions with limited air quality infrastructure. Implementing standardized analytical protocols and fostering binational cooperation between Mexico and the United States could strengthen One Health surveillance networks. This integrative approach provides a practical model for linking environmental monitoring with preventive public health strategies.

INTRODUCTION

Air pollution remains one of the most pressing global threats to both environmental and human health. Exposure to airborne pollutants such as particulate matter (PM), volatile organic compounds (VOCs), heavy metals, and pesticides has been associated with increased risk of respiratory, cardiovascular, and neurological diseases (1-5). Although conventional air quality monitoring networks exist, they often have limited spatial coverage and may not accurately reflect biological exposure at the local level (6). In Mexico, air pollution remains a major public health concern. According to the National Air Quality Monitoring Network, the annual mean concentrations of $PM_{2.5}$ in cities such as Tijuana, Mexicali, and Mexico City exceed the limits recommended by the World Health Organization (5 $\mu g/m^3$), reaching values between 18 and 25 $\mu g/m^3$ (7, 8). These conditions highlight the magnitude of environmental risk and justify the need for complementary monitoring strategies based on biomonitoring approaches.

In this context, the use of biological indicators has emerged as a sensitive and cost-effective approach to complement traditional methods. Among these, the Western honey bee (*Apis mellifera*) has proven to be an effective bioindicator due to its wide foraging range, constant contact with air, soil, and vegetation, and its capacity to accumulate contaminants in its body and hive products such as honey, pollen, and wax (9-14).

Recent studies have reported the presence of heavy metals, pesticides, and microplastics in bees collected from urban and industrial environments, highlighting their utility as mobile samplers of airborne pollution. In regions such as Baja California (Mexico) and California (USA), where diverse pollution sources and semi-arid climates converge, bee-based monitoring can offer valuable spatial data on environmental exposure (15-18).

From a One Health perspective, acknowledging the interconnection between environmental, animal,

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and human health, bees not only provide ecological insights but also contribute to the early identification of health risks. This review aims to synthesize current evidence on the use of honey bees as bioindicators of air quality and explore their relevance for environmental and public health surveillance in the Baja California–California region.

METHODOLOGY

This article is designed as a narrative review informed by a structured search strategy.

A systematic literature search was conducted to identify studies on the use of honey bees (*Apis mellifera*) as bioindicators or biosamplers of environmental pollution, focusing on exposure to heavy metals, microplastics, pesticides, and airborne particulate matter. The search was performed in PubMed and PubMed Central, in May 2025, using a combination of MeSH terms and keywords (e.g., “Honey Bees,” “Airborne Particulate Matter,” “Heavy Metals,” “Pesticide Exposure,” “Microplastics,” “Biomonitoring”), combined with Boolean operators (“AND,” “OR”) to optimize sensitivity and specificity.

No restrictions were applied regarding study type, language, or publication date. The strategy included experimental, observational, and review articles. A manual search was also performed to include relevant articles cited in key references.

Selection occurred in multiple phases: duplicate removal, title/abstract screening by two independent reviewers, and full-text review using predefined inclusion criteria related to the use of bees or their products as indicators of exposure, bioaccumulation, or health/ecological impact. Some information was synthesized through conceptual figures and graphical summaries, which were created using BioRender.com under an academic license.

RESULTS

A total of 98 records were identified through the PubMed search. After screening titles and abstracts, 62 articles were excluded for not addressing the use of honey bees as bioindicators or for focusing on unrelated environmental contaminants. Thirty-six full-text articles were assessed for eligibility, and 25 studies met the inclusion criteria and were incorporated into the narrative synthesis. The search and selection process is summarized in **Figure 1**, which was prepared following the PRISMA 2020 guidelines (19) and adapted for the structure of a narrative review.

The reviewed literature revealed that honey bees (*Apis mellifera*) have been used to monitor a wide range of atmospheric pollutants, including particulate matter, heavy metals, pesticides, and microplastics. The matrices most frequently analyzed were wings, thorax, pollen, wax, and honey, using analytical techniques such as SEM-EDX, ICP-MS, GC-MS, and FTIR. These studies consistently reported bioaccumulation of pollutants, oxidative stress responses, and alterations in enzymatic or behavioral parameters, supporting the role of bees as effective environmental biomonitors. The information obtained from these studies is presented narratively in the following sections, organized by contaminant type and biological response, to provide an integrative synthesis of the available evidence and its implications for environmental and human health.

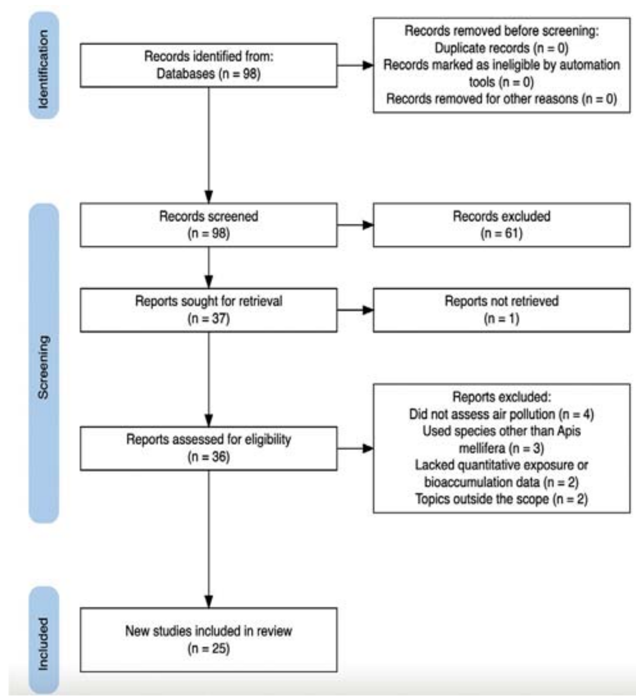

Figure 1. PRISMA Flowchart: study selection and exclusion. The figure was created using the PRISMA2020 Shiny App.

Atmospheric Pollution: Risks and the Need for Monitoring

Atmospheric pollution is a complex mixture of chemical compounds, solid particles, and liquid aerosols that impact not only natural ecosystems but also human health (6, 16). Among the most significant pollutants are fine particulate matter ($PM_{2.5}$ and PM_{10}), heavy metals (such as Pb, Cd, Zn) (12, 14), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs) (3, 13, 18), pesticides (5), and, more recently, airborne microplastics (9). Chronic exposure to these pollutants has been associated with an increased incidence of cardiovascular disease, with a reported relative risk (RR) of 1.64 for $PM_{2.5}$ concentrations of 217 µg/m³ over a 10–15-year follow-up (18, 20-22). Additionally, a 26% increase in ventricular arrhythmias has been observed for every 6 µg/m³ rise in $PM_{2.5}$ (20-22), and these pollutants have also been linked to respiratory, immunological, and neurological disorders (2, 18) **Table 1** summarizes the main health outcomes associated with different types and concentrations of particulate matter. Overall, the studies show a consistent link between exposure to $PM_{2.5}$ and PM_{10} and an increased risk of cardiovascular and respiratory diseases, including ischemic heart disease, stroke, and all-cause mortality. The magnitude of these associations tends to be stronger for fine particles ($PM_{2.5}$), especially in long-term exposure contexts. Evidence from multiple regions, such as China, Saudi Arabia, the United States, and areas affected by dust events, highlights that even modest increases in PM concentrations can contribute to significant health burdens (23, 25).

Table 1. Health effects associated with different types of particulate matter (PM) according to concentration.

Pollutant	Associated condition	Observed effect	Population	Reference
$PM_{2.5}$ (217 µg/m 3)	Cardiovascular disease	+64% (RR=1.64, 95%CI: 1.12-2.41)	China	Wei M *et al.,* 2024
$PM_{2\text{-}5\text{-}10}$(10 µg /m 3)	Cardiovascular disease admissions to the hospital.	0.5% to 1.1% increase incidence	Saudi Arabia	Saleem *et al.,* 2022
$PM_{2.5\text{-}10}$ (10 µg/m³)	All-cause mortality	RR = 1.046 (95% CI: 1.019–1.072) increment during dust events; pooled RR 2.87 in dust vs non-dust events	General population in dust-affected regions (Iran, Taiwan, Hong Kong, Sydney)	Pouri *et al.,* 2024
PM_{10} (10 µg/m³)	All-cause mortality	RR = 1.019 (95% CI: 1.011–1.028) increment on dust days; RR = 1.01 (95% CI: 1.004–1.016) on non-dust days	Same as above	Pouri *et al.,* 2024
$PM_{2.5}$	All-cause mortality	Non-significant on dust days: RR = 1.004 (95% CI: 0.958–1.049); significant on non-dust days: RR = 1.015 (95% CI: 1.003–1.028)	Same as above	Pouri *et al.,* 2024
$PM_{2.5\text{-}10}$ (10 µg/m³)	Cardiovascular mortality	RR = 1.085 (95% CI: 1.045–1.124) increment (dust events); same RR for non-dust events	Same as above	Pouri *et al.,* 2024
PM_{10} (10 µg/m³)	Cardiovascular mortality	RR = 1.022 (95% CI: 1.008–1.037) during dust events; RR = 1.011 (95% CI: 1.003–1.019) during non-dust events	Same as above	Pouri *et al.,* 2024

Pollutant	Associated condition	Observed effect	Population	Reference
$PM_{2.5}$ (10 µg/m³)	Cardiovascular mortality	Non-significant during dust events (RR = 1.055, 95% CI: 0.969–1.014); significant during non-dust events (RR = 1.026, 95% CI: 1.006–1.045)	Same as above	Pouri *et al.,* 2024
PM_{10} (10 µg/m³)	Respiratory mortality	RR = 1.018 (95% CI: 1.014–1.022) increment during dust events; RR = 1.020 (95% CI: 1.004–1.035) during non-dust events	Same as above	Pouri *et al.,* 2024
$PM_{2.5\text{-}10}$ (10 µg/m³)	Respiratory mortality	Not significant during dust events (RR = 1.071; 95% CI: 0.969–1.22); significant during non-dust events (RR = 1.056; 95% CI: 1.017–1.094)	Same as above	Pouri *et al.,* 2024
$PM_{2.5}$ (10 µg/m³)	Respiratory mortality	Not significant during dust events (RR = 1.103; 95% CI: 0.986–1.22); significant during non-dust events (RR = 1.023; 95% CI: 1.001–1.047)	Same as above	Pouri *et al.,* 2024
$PM_{2.5}$ (10 µg/m³)	Ischemic heart diosease	Increased RR = 1.18 (95% CI: 1.14–1.23)	USA	Brook *et al.,* 2010
$PM_{2.5}$ (10 µg/m³)	General cardiovascular mortality	Increased RR = 1.06 – 1.76 (95% CI: not specified)	USA	Brook *et al.,* 2010
PM_{10} (10 µg/m³)	Acute myocardial infarction	Increased risk of adverse events post-AMI RR = 1.08 (95% CI: not specified)	USA	Brook et al., 2010
$PM_{2.5}$ (10 µg/m³)	high blood pressure	+1.393 mmHg (systolic), +0.895 mmHg (diastolic) RR = not especified (95% CI: not specified)	Asia, América, Europa	Krittanawong *et al.,* 2023
$PM_{2.5}$ (10 µg/m³)	Diabetes mellitus	+25% risk (chronic exposure) RR = not especified (95% CI: not specified)	Asia, América, Europa	Krittanawong *et al.,* 2023
$PM_{2.5}$ (10 µg/m³)	Acute Myocardial Infarction (AMI)	Increased in long term risk RR = 1.08 (95% CI: 0.99–1.18)	USA	Alexeeff *et al.*, 2021
$PM_{2.5}$ (10 µg/m³)	Mortality from Ischemic Heart Disease (IHD)	Increased risk RR = 1.23 (95% CI: 1.15–1.31)	USA	Alexeeff *et al.*, 2021
$PM_{2.5}$ (10 µg/m³)	Cerebrovascular mortality	Increased in long-term risk RR = 1.24 (95% CI: 1.13–1.36)	USA	Alexeeff *et al.*, 2021
$PM_{2.5}$ (10 µg/m³)	Incident stroke	increase in long-term risk RR = 1.13 (95% CI: 1.11–1.15)	USA	Alexeeff *et al.*, 2021
$PM_{2.5}$ (10 µg/m³)	Cardiovascular mortality	increase in long-term risk RR = 1.14 (95% CI, 1.08–1.21)	USA	Alexeeff *et al.*, 2021

Pollutant	Associated condition	Observed effect	Population	Reference
$PM_{2.5}$ (10 µg/m³)	Acute Myocardial Infarction (AMI)	12 % increased risk RR = 1.12 (95% CI, 1.07–1.18)	USA (CA)	Alexeeff *et al.*, 2023
$PM_{2.5}$ (10 µg/m³)	Mortality from Ischemic Heart Disease (IHD)	21% increased risk RR = 1.21 (95% CI, 1.13–1.30)	USA (CA)	Alexeeff *et al.*, 2023
$PM_{2.5}$ (10 µg/m³)	Mortality from Cardiovascular Disease (CVD)	8 % increased risk RR =1.08 (95% CI, 1.03–1.13)	USA (CA)	Alexeeff *et al.*, 2023

In urban and industrial regions, such as parts of Baja California and California, the combination of mobile sources (e.g., vehicles), stationary sources (e.g., industries), and agricultural activities creates highly heterogeneous environments, complicating evaluation through fixed monitoring stations (6, 26-29).

Although traditional sensor-based systems provide valuable data, they have notable limitations: insufficient spatial coverage, lack of biological resolution, and reliance on high-cost technologies (1, 12, 30). As a result, the use of complementary biomonitoring approaches has been promoted, wherein living organisms are employed as passive or active integrators of environmental contamination (1, 10, 12). Biomonitoring offers several advantages: the capacity to accumulate pollutants over time, the potential to reflect actual biological effects, and the ability to provide more localized and sensitive assessments of environmental risk (3, 18). Lichens, mosses, mollusks, and more recently, pollinating insects such as bees have been used for this purpose, with the latter's physiology and ecological behavior making them particularly well-suited for assessing air quality (1, 12, 15).

In Mexico, particularly along the Baja California–California border corridor, air quality challenges include recurrent exceedances of $PM_{2.5}$ and ozone in urban and industrial microenvironments, influenced by traffic density, cross-border mobility, and semi-arid climatic conditions. Recent studies conducted in Mexico using bees and related biomonitoring approaches have documented fine particle deposition and composition across urban and rural settings, supporting the relevance of integrating biological and fixed-station data to improve spatial coverage (12, 29), national reports further contextualize these patterns and underline the need for locally tailored surveillance strategies (7).

Bees as Environmental Biomarkers

The use of honey bees (*Apis mellifera*) as environmental bioindicators has gained increasing attention in recent decades due to their unique ecological and physiological characteristics (17, 18). These insects exhibit highly active foraging behavior, with a flight range of approximately 2 to 5 kilometers from the hive, allowing them to interact with a variety of environmental matrices, including air, water, soil, and vegetation (17, 30, 31). This direct contact with the environment makes bees natural collectors of airborne pollutants and toxic compounds.

Thanks to their ecological behavior and specialized physiology, honey bees not only play a crucial role as pollinators within ecosystems but have also been firmly established as highly sensitive organisms for monitoring environmental pollution (2, 4, 15). Their constant interaction with the environment and their capacity to accumulate substances in both their tissues and biological products make them ideal biological vehicles for detecting contaminants present in air, water, and vegetation (31).

In this regard, numerous studies have demonstrated that bees are capable of collecting a wide range of atmospheric contaminants, enabling their use as integrated tools for environmental monitoring (1, 12, 32).

Physiologically, bees possess a dense coverage of body hairs that facilitates the adhesion of suspended particles, such as dust, heavy metals, and microplastics, during flight (11, 17). Moreover, contaminants can accumulate not only on their bodies but also in the products they produce, such as honey, pollen, and wax; thus, expanding the analytical possibilities for assessing environmental quality from multiple angles (3, 7, 10) (**Figure 2**).

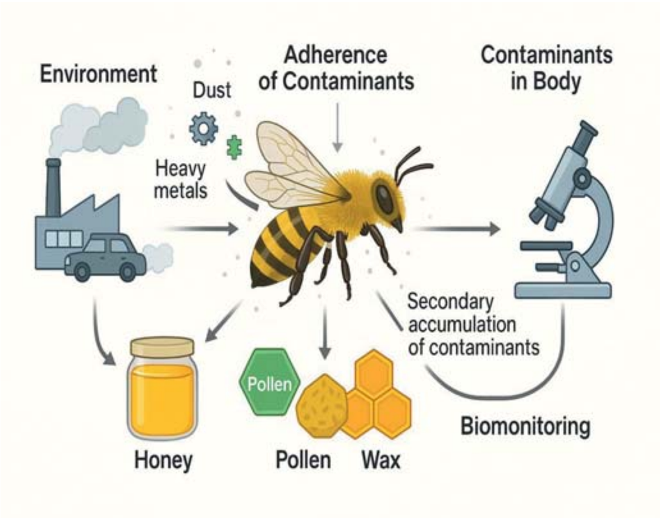

Figure 2. Mechanism of environmental contaminant uptake and biomonitoring potential in bees. This figure was created with BioRender.com and exported under a BioRender license.

A key advantage is their sensitivity to subtle environmental changes, which can manifest as physiological and behavioral responses even to low levels of contamination (17, 27). For instance, exposure to neurotoxic compounds, heavy metals, or ultrafine particles may impair their orientation, memory, and foraging efficiency (2, 16, 27). These effects not only compromise colony health (5) but also serve as early warning signals of environmental degradation in their habitat (2, 3, 16, 27).

Unlike other organisms traditionally used in biomonitoring, such as lichens or mollusks, bees can function as active bioamplifiers of the aerial environment; that is, as mobile organisms that integrate and reflect daily environmental exposure through their biological systems (12, 17). Their wide geographic distribution, ease of management by beekeepers, and exclusive reliance on natural resources for nourishment position them as exceptional bioindicators, particularly valuable in urban, agricultural, and industrial settings (10-12, 14).

Table 2. Summary of contaminants detected in honey bees (*Apis mellifera*).

Contaminant	Analyzed Matrix	Analytical Technique	Observed Effect / Outcome	Reference
Particulate matter ($PM_{2.5}$ / PM_{10})	Wings, thorax	SEM-EDX, XRF	Particle adhesion, oxidative stress, reduced flight performance	Meza-Figueroa *et al.,* 2024; Negri *et al.,* 2020
Heavy metals (Pb, Cd, Zn, Cu, Hg)	Whole body, honey, pollen, wax	ICP-MS, AAS	Bioaccumulation, enzyme inhibition (CAT, GPx), disorientation	Borsuk *et al.,* 2021; Demková *et al.,* 2024
Pesticides (neonicotinoids, organophosphates, pyrethroids)	Pollen, honey, wax	LC-MS/MS, GC-MS	Neurotoxicity, impaired foraging, immune suppression	Kast *et al.,* 2024; Wang *et al.,* 2024
Organic contaminants (PAHs, PCBs, phthalates)	Pollen, wax	GC-MS, HPLC	Genotoxicity, oxidative damage, colony weakening	Sari & Esen, 2022; Marcoccia *et al.,* 2024
Microplastics	Body surface, gut, honey	FTIR, Raman spectroscopy	Particle accumulation, digestive and immune alterations	Edo *et al.,* 2021; Al Naggar *et al.,* 2021

AAS, atomic absorption spectrometry; CAT, catalase; FTIR, Fourier-transform infrared spectroscopy; GC-MS, gas chromatography–mass spectrometry; GPx, glutathione peroxidase; HPLC, high-performance liquid chromatography; ICP-MS, inductively coupled plasma–mass spectrometry; LC-MS/MS, liquid chromatography–tandem mass spectrometry; PAHs, polycyclic aromatic hydrocarbons; PCBs, polychlorinated biphenyls; PM, particulate matter; $PM_{2.5}$, particulate matter ≤2.5 µm; PM_{10}, particulate matter ≤10 µm; ROS, reactive oxygen species; SEM-EDX, scanning electron microscopy with energy-dispersive X-ray spectroscopy; XRF, X-ray fluorescence.

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To provide an integrative overview of the evidence reviewed, **Table 2** summarizes the main contaminants detected in *Apis mellifera*, the biological matrices used for their analysis, the analytical techniques applied, and the physiological or ecological effects reported.

This synthesis highlights the methodological diversity among studies and the range of biological responses that validate the use of honey bees as sensitive environmental bioindicator. The following sections describe the main groups of pollutants identified in bees and their products, along with their environmental and public health significance.

Particulate Matter (PM_{10}, $PM_{2.5}$, and Ultrafine Particles)

Particulate matter (PM) is one of the primary components of air pollution and poses a direct threat to both human and environmental health (6, 34). $PM_{2.5}$ (≤2.5 μm in diameter) and PM_{10} (≤10 μm) can penetrate deeply into the respiratory systems of organisms and have been associated with chronic respiratory, cardiovascular, and neurological diseases (6, 35), as well as with environmental conditions that may be harmful to human health.

During flight and the collection of nectar and pollen, honey bees are constantly exposed to these particles, which adhere to their bodies, particularly the wings, abdomen, and thoracic hairs (6, 17). Due to this direct interaction, bees can serve as mobile biosensors of pollution in urban, agricultural, and industrial areas (12, 31, 32).

Recent studies have confirmed the utility of bees in mapping the spatial distribution of PM (12, 18). For instance, in two urban areas of Mexico, PM particles were identified on bee wings collected during different seasons using spectrometry and geochemical analysis techniques (SEM-EDX), revealing significant differences related to vehicular density and urban development (12). This study also demonstrated that bees in flight can capture particles from mobile sources such as cars and trucks, offering a valuable tool for monitoring high-traffic areas.

Moreover, the presence of materials such as silicon, iron, aluminum, and amorphous carbon on bee bodies has been interpreted as a direct reflection of air quality and its mineral composition, proving useful for environmental forensic investigations (6, 11). This particle-capturing ability enables the use of bees in settings where physical monitoring is limited or economically unfeasible, providing a sensitive, cost-effective, and eco-friendly alternative.

Heavy Metals (Pb, Cd, Zn, Cu, among others)

Heavy metals are among the most persistent and toxic atmospheric pollutants, primarily released by industrial activities, vehicular traffic, mining, and the combustion of fossil fuels (36, 37). These elements can be present in the form of fine airborne particles or settle onto soil and vegetation, from which they can be transferred to organisms interacting with those environments (11).

Bees are capable of collecting and accumulating heavy metals across various biological matrices (4, 12). These metals can adhere to their bodies during flight or be ingested through contaminated nectar, water, or pollen (17). Significant concentrations of lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), mercury (Hg), among others, have been detected in their tissues, as well as in honey, stored pollen, and wax (12, 15, 38).

Studies conducted in urban and industrial regions of Europe and Latin America have shown that bees can act as active samplers of airborne metal content (12, 15). Bees collected in polluted areas accumulate metals in proportions that accurately reflect the surrounding environment and exhibit excretory mechanisms to reduce internal load. Elevated levels of Pb and Cd have also been reported in pollen and honey, suggesting potential risks not only to colony health but also to human consumers of bee products (3).

Monitoring heavy metals through bees has thus become an effective strategy for assessing environmental risk zones, allowing for the estimation of bioaccumulation and contaminant transfer through the food chain. Moreover, this analysis is relatively simple, cost-effective, and provides a biological perspective on environmental quality that

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complements traditional physicochemical methods (11, 16).

Pesticides and Organic Contaminants

Pesticides, including insecticides, herbicides, and fungicides, as well as other persistent organic pollutants (POPs), represent a significant threat to both ecosystem and human health (1, 2, 14). These compounds disperse in the environment through agricultural application, rainfall, runoff, and volatilization, and can be transported through the air and deposited on flowers, leaves, environmental dust, and water bodies (1, 5, 39).

Due to their close relationship with floral resources and continuous environmental exposure, honey bees are particularly vulnerable to these contaminants (1, 13, 17). Studies have shown that bees can collect pesticide residues via nectar, pollen, and water, which accumulate in their bodies and hive products, especially wax, where lipophilic residues readily integrate (1, 2, 5, 9).

Recently, residues of organophosphates and pyrethroids were identified in wax and pollen samples from hives located in areas of intensive agriculture, reflecting direct exposure to pesticides used on nearby crops (2, 9). Moreover, exposure to neonicotinoid pesticides has been associated with sublethal effects in bees, including altered foraging behavior, disorientation, and immune suppression, which not only jeopardize colony viability (5, 14) but also position bees as early indicators of ecotoxicological risk (1, 16).

In addition to pesticides, bees may also incorporate organic contaminants such as polycyclic aromatic hydrocarbons (PAHs), phthalates, and polychlorinated biphenyls (PCBs), all of which have bioaccumulative potential and toxic effects for both bees and human consumers of their products (1, 2, 13, 40, 41). The detection of these compounds in honey and pollen collected in urban and industrial areas highlights the utility of bees as tools for integrated environmental monitoring (5, 14).

Microplastics

Microplastics (MPs), defined as plastic fragments smaller than 5 mm, have emerged as contaminants of growing environmental and public health concern (16). Initially studied in marine ecosystems, they have recently been detected in terrestrial and atmospheric environments, including in the air we breathe (2). Their presence in ambient air originates from multiple sources, such as tire wear, synthetic textiles, degrading plastics, and industrial emissions, allowing for deposition onto vegetation and soil, making them accessible to pollinators such as bees (6, 11).

Honey bees can collect microplastics passively during flight, as particles may adhere to their bodies via electrostatic forces or be indirectly ingested through contaminated pollen, nectar, or water (16). In a pioneering study, Edo *et al.*, 2021 (11) employed bees as mobile biosensors to detect microplastics in urban and industrial areas, identifying polystyrene, polyethylene, and polypropylene particles in different parts of their bodies using scanning electron microscopy and Fourier-transform infrared spectroscopy (FTIR). This finding confirmed that bees are not only sensitive to traditional chemical pollutants but also to emerging anthropogenic solid particles such as microplastics. Furthermore, the presence of microplastics varied according to land use, being more abundant in densely urbanized areas, further reinforcing the potential of bees for localized environmental monitoring.

Although the direct physiological effects of microplastics on bees remain poorly understood, there are concerns regarding chronic ingestion, accumulation, and potential interference with digestive, immune, and reproductive functions (16, 17). This concern also extends to bee products, such as honey, which may act as vehicles for human exposure (16).

Evidence of Exposure to Airborne Contaminants

The analysis of environmental contaminants in bees can be performed using various biological matrices from both the insect's body and its products (4). This analytical diversity allows for the evaluation of multiple exposure pathways and the accumulation of valuable information on environmental quality across broad spatial and temporal scales (2). The choice of matrix depends on the type of contaminant under study, the objective of biomonitoring, and the required analytical sensitivity (4).

The most commonly used bee body parts include the wings, thorax, abdomen, and the entire body (27). Wings, for example, are particularly useful for analyzing particulate matter (PM) and heavy metals due to their direct exposure to air and ease of non-invasive sampling (10). In contrast, the abdomen and soft tissues are more suitable for detecting internal bioaccumulation of lipophilic contaminants or ingested metals (1). Some studies also perform acid digestion of the whole body to quantify trace elements using spectroscopic techniques (1, 11).

Among hive products, the most frequently analyzed matrices are honey, pollen, and wax. Honey reflects exposure to soluble contaminants ingested during nectar foraging, such as pesticides and certain metals. Pollen acts as a concentrator of environmental contaminants and has been used to assess the presence of PAHs, PCBs, and microplastics. Wax, being a lipophilic and long-lasting matrix, serves as a historical archive of persistent organic pollutants such as pesticides and flame retardants (1-4, 7, 13).

The analytical methods employed vary by contaminant type. For PM and metals, techniques include scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDX), inductively coupled plasma mass spectrometry (ICP-MS), and X-ray fluorescence (XRF) (1, 33). For pesticides and organic contaminants, chromatographic methods such as HPLC, GC-MS, and LC-MS/MS are used, capable of detecting residues at trace levels (5, 11, 33, 42, 43). For microplastics, Fourier-transform infrared spectroscopy (FTIR) and Raman microscopy are the most common techniques (6,11).

The integration of these matrices and methods has enabled the construction of a more accurate picture of the type and degree of environmental contamination, overcoming the limitations of traditional physical monitoring systems. Additionally, combining external biological matrices (wings, wax) with internal ones (tissues, honey) provides a multiscale assessment that reflects both direct exposure and long-term contaminant accumulation (3, 4, 9).

Beyond their role as passive collectors of environmental pollutants, multiple studies have demonstrated that honey bees experience adverse biological effects due to exposure to heavy metals, pesticides, microplastics, and other airborne contaminants (1, 4, 5). These effects have not only ecological implications, compromising colony health, but also validate the use of bees as active biomarkers, given that their physiology responds measurably to changes in environmental quality (12).

One of the most widely documented mechanisms is oxidative stress, characterized by increased production of reactive oxygen species (ROS), lipid and protein damage, and alterations in antioxidant enzymes such as catalase and glutathione peroxidase (27). Ortega-Rosas *et al.* (29) demonstrated that bees collected in environments contaminated with fine particles and metals exhibited elevated levels of lipid peroxidation and genetic damage, indicating significant exposure to airborne pollutants.

From an ethological perspective, exposure to pollutants such as neonicotinoids, heavy metals, or ultrafine particles has also been linked to changes in foraging behavior, disorientation, reduced homing rates, and increased worker mortality (11, 16). Although often sublethal, these changes have cumulative effects that weaken the colony's social structure and may lead to progressive collapse (5).

Together, this body of evidence suggests that bees not only record the presence of environmental pollutants but also reflect their biological impact, positioning them as model organisms for aerial ecotoxicological studies. Their analysis thus offers a dual perspective: as environmental sensors and as indicators of biological effects in exposed organisms.

Field validations conducted in Mexico and other regions have provided consistent evidence supporting the feasibility of honey bees as atmospheric biomonitors. Studies performed in both urban and rural environments have demonstrated that *Apis mellifera* effectively traces fine particulate matter, heavy metals, and volatile organic compounds, revealing spatial contrasts associated with vehicular traffic, industrial activity, and urbanization gradients. These investigations have also documented significant associations between airborne particles and oxidative stress biomarkers in bees, as well as metal accumulation patterns that mirror anthropogenic emission sources. Collectively, this body of evidence confirms the ecological and methodological applicability of bee-based biomonitoring under Mexican environmental conditions and supports its integration into national strategies for environmental health surveillance (12, 29, 44, 45).

Implications for Human Health

The utility of bees as environmental biomarkers extends beyond ecological monitoring and has profound implications for human health, particularly within the One Health framework, which acknowledges the interconnection between ecosystem, animal, and human health (2, 8, 18 29). The detection of pollutants such as particulate matter, heavy metals, pesticides, and microplastics in bees and their products enables the identification of environmental exposures that also directly affect nearby human communities (2, 3, 6, 10).

Several contaminants identified in bees have been previously associated with adverse human health outcomes (3, 6, 18). $PM_{2.5}$ and PM_{10}, commonly found adhered to the wings of bees in urban and industrial areas, have been linked to increased incidence of respiratory, cardiovascular, and neurological diseases in humans, particularly among children, older adults, and individuals with chronic conditions (2, 6, 11). Pathophysiologically, $PM_{2.5}$ and PM_{10} trigger a range of interrelated mechanisms, including oxidative stress and systemic inflammation. Upon inhalation, $PM_{2.5}$ can reach the alveoli, inducing the production of reactive oxygen species (ROS) and activating inflammatory pathways such as NFκB, which stimulate the release of pro-inflammatory cytokines like interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNFα), resulting in both local and systemic inflammation.

Exposure to $PM_{2.5}$ has been consistently associated with increased cardiovascular morbidity and mortality via several pathophysiological pathways (44, 46). These include the induction of systemic inflammation and oxidative stress triggered by inhaled particles, which stimulate the release of IL-6, TNFα, and C-reactive protein (46). These inflammatory processes are closely linked to the development of endothelial dysfunction, evidenced by impaired flow-mediated vasodilation, and the elevation of procoagulant markers such as fibrinogen and von Willebrand factor, promoting a prothrombotic state (38). $PM_{2.5}$ also contributes to increased carotid intima-media thickness and the progression of subclinical atherosclerosis, both of which raise the risk of acute coronary events (45, 46). Studies in humans and animal models have shown that even short-term exposures can alter heart rate variability, induce arrhythmias, and provoke transient hypertension and vasoconstriction (46) (**Figure 3**).

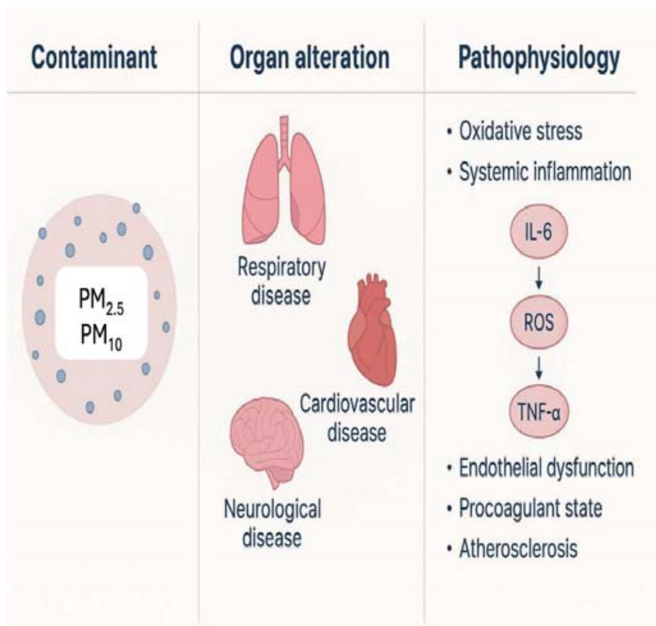

Figure 3. Pathophysiological mechanisms associated with exposure to airborne particulate matter ($PM_{2.5}$ and PM_{10}) and their impact on human health. PM refers to particulate matter, which includes airborne particles suspended in the atmosphere. PM2.5 consists of particles with aerodynamic diameters ≤2.5 µm; PM_{10} includes those ≤10 µm. This figure was created with BioRender.com and exported under a BioRender license.

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From a quantitative perspective, each 10 μg/m³ increase in $PM_{2.5}$ concentration has been associated with a 10–20% increase in the relative risk (RR) of acute myocardial infarction and an 8–12% increase in the risk of decompensated heart failure (24, 25, 46). At the population level, such exposure is also associated with a mean rise of 1.4 mmHg in systolic and 0.9 mmHg in diastolic blood pressure, contributing to the development of chronic hypertension (RR ≈ 1.13) (24, 25, 46). A relative risk of 1.12 has also been reported for atrial fibrillation in older adults exposed to high levels of particulate matter (46). These findings support a plausible causal relationship between $PM_{2.5}$ pollution and the increased incidence of cardiovascular events, even at exposure levels below current legal limits.

The detection of heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg) in bee tissues and collected pollen reflects their presence in the environment and their potential entry into the human food chain through contaminated honey or related products (2). These metals are neurotoxic and genotoxic, and chronic accumulation has been linked to renal and hepatic damage, cognitive impairments, and adverse effects on child development (3, 15).

Similarly, the presence of pesticide residues in honey, pollen, and wax poses risks to both consumers and beekeepers (3, 10, 18). Compounds such as neonicotinoids and organophosphates have been associated with neurotoxic effects, immunosuppression, and endocrine disruption in humans (10). Furthermore, the detection of microplastics in bee products raises new public health concerns, as these particles can serve as vectors for persistent organic pollutants and heavy metals, and may contribute to intestinal inflammation upon chronic ingestion, according to emerging evidence (16).

Integrating environmental monitoring with apicultural data represents a preventive strategy to identify health risk zones before adverse effects manifest clinically (29, 18). In regions with limited atmospheric monitoring, such as parts of Baja California, bees provide a reliable biological alternative for detecting pollution sources and anticipating harmful exposure scenarios, enabling early public health interventions. In summary, bees not only reflect the quality of the environments they inhabit but also serve as sentinels of environmental conditions that pose risks to human health.

DISCUSSION

This narrative review synthesized current evidence on the use of Apis mellifera as a bioindicator of air pollution and its relevance for environmental and public health monitoring within a One Health framework. These findings support their role as integrative sentinels of environmental quality. Moreover, experimental and field-based observations indicate that sublethal exposures in bees are accompanied by oxidative stress, enzymatic alterations, and metabolic disturbances that parallel early biological responses in humans.

The use of honey bees as bioindicators extends beyond ecological monitoring, representing a valuable translational tool for environmental and public health research. The accumulation of pollutants in bee tissues and products mirrors human exposure pathways through inhalation and ingestion, particularly in densely populated or industrialized areas. Moreover, alterations in oxidative and inflammatory biomarkers observed in bees resemble early molecular responses in humans exposed to air pollutants, including the activation of cytokines such as IL-6 and TNF-α and the overproduction of reactive oxygen species. Importantly, this biological parallelism supports the concept of bees as sentinel organisms capable of detecting environmental perturbations before the onset of clinically detectable effects in humans. The ability to identify subclinical alterations, such as oxidative stress and inflammation, positions bee-based biomonitoring as an early-warning system that strengthens preventive strategies within the One Health framework. Integrating these approaches could guide timely interventions and contribute to reducing the burden of pollution-related diseases in human populations. Future research should aim to standardize bee-based biomonitoring protocols and

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explore their integration into national air quality surveillance systems

The Baja California (Mexico) and California (USA) region shares a transboundary ecosystem marked by intense agricultural, industrial, and vehicular activity, semi-arid climate, and expanding urban centers such as Tijuana, Mexicali, San Diego, and Los Angeles. These conditions have led to persistent air pollution, including $PM_{2.5}$, ozone, heavy metals, and pesticide residues (44, 45, 47).

In this context, honey bees have emerged as practical bioindicators in areas lacking comprehensive air quality monitoring. Studies using bee wings have shown strong correlations between metal accumulation and proximity to traffic and industrial zones. Other approaches using bees in flight have detected differences in airborne particulate load between residential and high-traffic areas, identifying microzones of elevated human exposure.

From a One Health perspective, implementing bee-based biomonitoring in this border region provides a low-cost, non-invasive tool to inform environmental health policy, especially in vulnerable communities. Binational collaboration could enhance transboundary air quality management and support joint research on pollution-related health risks (47).

Strengthening policy translation requires concrete and collaborative actions. Establishing binational monitoring protocols between Mexico and the United States could enhance cross-border comparability of air quality data, particularly in regions such as Baja California, where industrial and urban emissions are highly interdependent. Likewise, implementing training programs for local and rural beekeepers focused on environmental health could expand monitoring networks while fostering community participation in pollution surveillance. These initiatives would not only bridge scientific and policy gaps but also promote sustainable and low-cost approaches to environmental governance within the *One Health* framework (7, 8). However, several limitations must be considered. Seasonality, variability in floral diets, and the absence of standardized protocols can affect the comparative interpretation of data. In addition, most current studies are observational in nature and require reinforcement through experimental or longitudinal designs that allow for more robust causal inferences.

The Baja California–California border region represents an area of high ecological and industrial connectivity, where atmospheric pollutants can disperse freely across jurisdictions. Integrating honey bee biomonitoring into existing environmental surveillance systems could provide a cost-effective complement to conventional stations. As a minimum standardized framework, we propose the use of bee wings, pollen, and honey as matrices for detecting particulate matter and heavy metals, collected monthly during active foraging seasons (March–October) (24, 25). Analytical methods such as SEM-EDX for particle characterization and ICP-MS for metal quantification are recommended due to their reproducibility and sensitivity. QA/QC procedures should include field blanks, replicate analyses, and standardized calibration against certified reference materials. Implementing such a protocol within a binational cooperation scheme (e.g., U.S.–Mexico Border 2025 Program) could enhance cross-border comparability and facilitate early detection of environmental risks relevant to human and ecosystem health.

CONCLUSIONS

Honey bees (*Apis mellifera*) represent a promising bioindicator for assessing air quality and its potential implications for human health. The available evidence suggests that bees accumulate atmospheric pollutants such as heavy metals, pesticides, particulate matter, and microplastics across different biological matrices, reflecting early physiological responses similar to those observed in humans. However, these findings should be interpreted as indicative associations that warrant further investigation through standardized and longitudinal designs. Advancing the development of harmonized sampling and analytical protocols, particularly within transboundary regions such as Baja California–California, could strengthen surveillance systems and foster collaborative *One Health* approaches that link environmental monitoring with preventive public health strategies.

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