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A Systematic Review on Silent Pollution: Pesticides and Antibiotics in Bee Products and their Health Implications

Safia Ben Amor[1,*], Asma Abid[2], Maria Chikha[3,4], Ibrahim Elkhalil Behmene[1], Walid Boussebaa[2,5], Nour Elhouda-Mekhadmi[4,6], Samia Meliani[1] and Magda H. Abdellattif[7]

[1]Saharan Area Laboratory for Agricultural Modernization and Advancement (SALAMA - LAB) Higher School of Saharan Agriculture, El-Oued PB 90, El Oued 39011, Algeria

[2]Laboratory of Valorization and Promotion of Saharan Resources (VPRS), Faculty of Mathematics and Matter Sciences, University of Ouargla, Road of Ghardaia, 30000, Ouargla, Algeria

[3]Mohamed Cherif Messaadia University, Institute of Agricultural and Veterinary Sciences, BP 41000 Souk Ahras, Algeria

[4]Department of Biology, University of El-Oued, El-Oued, Algeria

[5]Scientific and Technical Research Center in Physico-Chemical Analysis, Headquarters Ex-Pasna Industrial Zone, Bou-Ismail CP, Tipaza 42004, Algeria

[6]Laboratory of Biodiversity and Applicationsof Biotechnology in the Agriculture Field, University of Chahid Hamma Lakhdar, El-Oued, Algeria

[7]Department of Chemistry, College of Science, Taif University, Al-Haweiah, P.O. Box 11099, Taif 21944, Saudi Arabia

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Abstract: Bee products such as honey, beeswax, propolis, and royal jelly are highly regarded for their nutritional, medicinal, and economic significance; however, they are increasingly impacted by "silent pollution" resulting from pesticide and veterinary antibiotic residues. Although many studies have documented individual contaminants within specific matrices, a comprehensive understanding of their simultaneous occurrence, transfer mechanisms, persistence, and implications for human and ecosystem health remains incomplete. This review offers a thorough and current synthesis of pesticide and antibiotic contamination in various bee products, with specific focus on matrix-specific accumulation, bioavailability, and long-term persistence within colonies. In contrast to prior evaluations, this study rigorously synthesizes global residue data with analytical techniques, sampling methodologies, regulatory standards, and exposure pathways to underscore systemic deficiencies in monitoring and risk evaluation. The review additionally assesses the cumulative and synergistic impacts of chemical mixtures, correlating residue profiles with risks to consumer health, pollinator well-being, and ecosystem stability. By presenting bee products as both essential food commodities and bioindicators of environmental contamination, this

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***Correspondence**
Safia Ben Amor
benamor.safia@esas-eloued.dz

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review emphasizes the critical importance of establishing standardized monitoring programs, enhancing regulatory supervision, and implementing effective residue mitigation strategies. These insights offer a new framework to promote safer apicultural practices and inform evidence-based policy formulation.

Key words: Silent pollution, bee products, honey residues, food safety and chemicals, veterinary antibiotics, pesticides.

Honey bees have become the main insect pollinators for many crops and ornamental plants because of their economic value to agriculture and horticulture, and hence their role in the environment (Khalifa *et al*., 2021). However, honey bee populations in various parts of the world is declining which is attributed to multiple interacting factors. Chemical products, particularly pesticides and veterinary antibiotics, are commonly used in agriculture and apiary practice against pests and diseases (Yang *et al*., 2023).

Pesticide and antibiotic residues occur in various bee products collected worldwide (Mullin *et al*., 2010) and highlight the need to monitor these products regularly yet oversight is limited. Studies conducted in France identified frequent chemical residues in beehive products originating from different landscapes (Lambert *et al*., 2013). In Canada, a thorough survey of wax conforming to parameter specifications on national and international markets nevertheless revealed multiple contaminants. Similar results emerged in Mexico, where honey collected from residue-free the agricultural landscape contained twelve pesticide residues (Ponce-Vejar *et al*., 2022). Comparable contamination results have also been documented in North Africa, where investigations of commercial honey from countries such as Egypt and Algeria revealed the presence of detectable residues of antibiotics and pesticides, despite existing legislative restrictions on veterinary treatments (Alla, 2020; Lynda *et al*., 2025). Similarly, studies conducted in Asia, including large-scale surveys of markets in China and the Middle East, have reported the frequent detection of residues of several classes of antibiotics and pesticide contaminants in honey, reflecting both environmental exposure and practices within apiaries (Wang *et al*., 2022).

For bee producers, contamination imposes a significant limitation on the sale of high-quality products and undermines consumer confidence (Bogdanov, 2006). Food safety and environmental protection policies often rely on monitoring and corroborated measurements of chemicals in food products to capture the magnitude and complexity of silent pollution (D'Amore *et al*., 2025). Monitoring regulated pesticides, antibiotic residues, and environmental contaminants in bee products is therefore essential for formulating relevant and effective governance frameworks (Al-Waili *et al*., 2012). Current policies governing pesticide usage and sales, mandatory identification and control technologies, and prescribing antibiotics address some areas but leave key aspects unregulated (Phan *et al*., 2023).

Honey bee products, including honey, wax, propolis, bee bread, and royal jelly, occupy a prominent position in human consumption globally (Fig.1). Global honey production is estimated at approximately 179,000 mt yr^{-1}, generating over $6 billion in revenue (Choudhary *et al*., 2023). The diverse demand stems from honey's taste and fragrance, cultural significance, medical properties, and role as a sweetening agent (Gaubert *et al*., 2023). Other bee products hold niche markets like bee wax for candles and emollients, propolis for immunity enhancement and inflammation reduction, and royal jelly for nutritional support (Simone-Finstrom *et al*., 2017).

Chemistry and pathways of contaminants

Hive-product contaminants affecting wax, honey, and propolis generally fall into agricultural, pharmaceutical, and environmental categories, entering colonies via contaminated pollen, nectar, water, plant-surface contact, or airborne exposure during foraging (Panseri *et al*., 2020; Ponce-Vejar *et al*., 2022; Krupke *et al*., 2012). In addition to widely documented pesticide inputs, African studies have reported organochlorine residues in honey consistent with both environmental contamination and in-hive accumulation processes, highlighting the persistence of legacy compounds in apicultural systems (Mukiibi *et al*., 2021). Pesticides remain the best-characterized agricultural contaminants, with many persisting in hive matrices for weeks to months depending on their chemical properties. Neonicotinoids (e.g.,

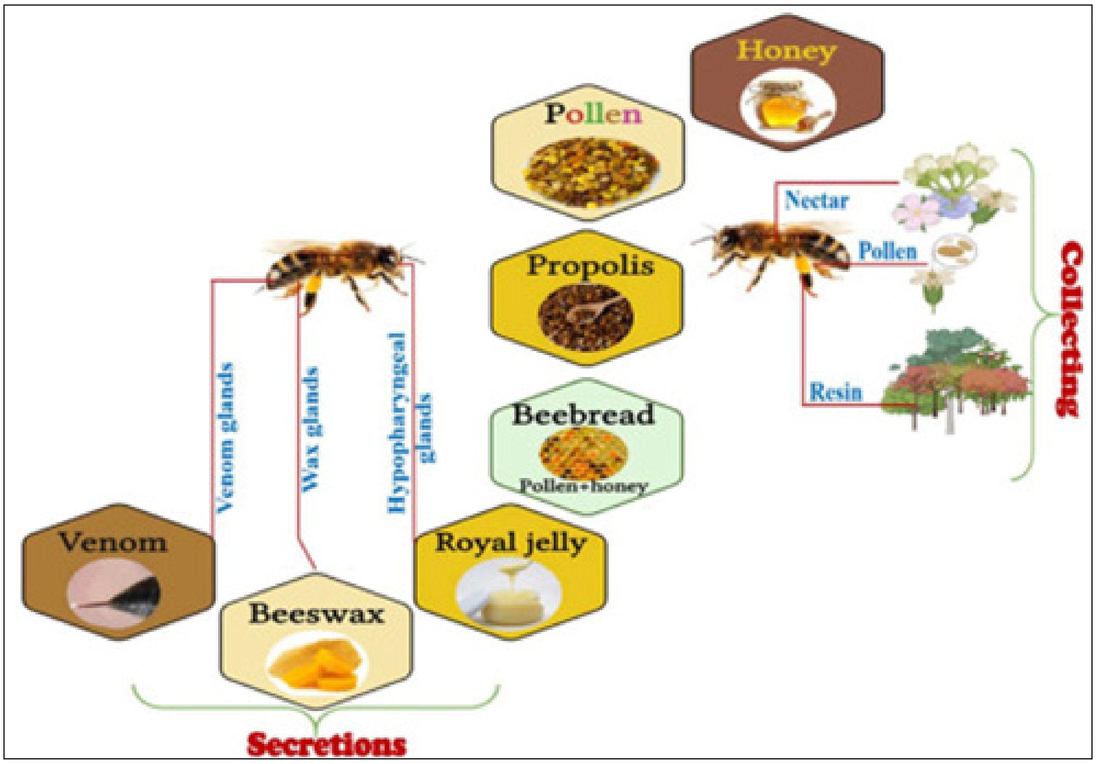

Fig.1. Origin and diversity of honeybee products (El-Didamony et al., 2024).

clothianidin, imidacloprid) are neurotoxic and can occur at concerning levels, while organophosphates and carbamates similarly disrupt acetylcholine signaling and impair bee neurological function (Margaoan *et al.*, 2024; Sadia *et al.*, 2024).Residue patterns differ by matrix: beeswax acts as a major sink for lipophilic compounds, accumulating insecticides and acaricides (including veterinary treatments such as coumaphos) and enabling long-term carryover from older comb and metabolite persistence (Bogdanov, 2006; Sadia *et al.*, 2024). Commonly detected and highly toxic residues across matrices include fipronil, teflubenzuron, fluvalinate, and amitraz, alongside increasing detection of herbicides, fungicides, and veterinary drugs. Less restrictive regulation and limited rules on wax collection/reuse may further contribute to ongoing, sometimes hard-to-detect contamination in hive products (Karazafiris *et al.*, 2011).

Pesticide residues in beeswax, honey, and propolis: Global agricultural pesticide use increased substantially from 1990 to 2023, nearly doubling from about 1.8 to 3.8 million tons, with the sharpest rise occurring after the early 2000s and only minor year-to-year fluctuations in recent years (Fig. 2). Many beekeepers typically apply pesticides for crop or plant protection and antiseptic medications to maintain beehive health (Devi *et al.*, 2021). The pollination services offered by colonies are critical to the production of numerous fruits, vegetables, nuts, and plant materials for tobacco or biofuels; thus, bees are widely considered essential for the global environment and food security (Richardson, 2023). However, even if producers do not treat their colonies overtly, the chance of partial contamination remains. The introduction of pesticide usage in the life cycle, the misregulated or unlicensed application of veterinary products, the feed designed for economic and productivity incentives, and the ingestion of nectar and pollen from areas with intensive agricultural practices cause the presence of pesticide residues in bee products (Xiao *et al.*, 2022).Various classes of pesticides can be detected in wax, honey, and propolis at levels numerous orders of magnitude below the upper limits stipulated by any international regulatory standards. Pesticide classification, persistence, and partitioning into matrixes help illuminate the contamination challenge (Mahmoudi *et al.*, 2014a; Panseri *et al.*, 2020).

Residue distribution between honey and wax depends partly on compound properties:

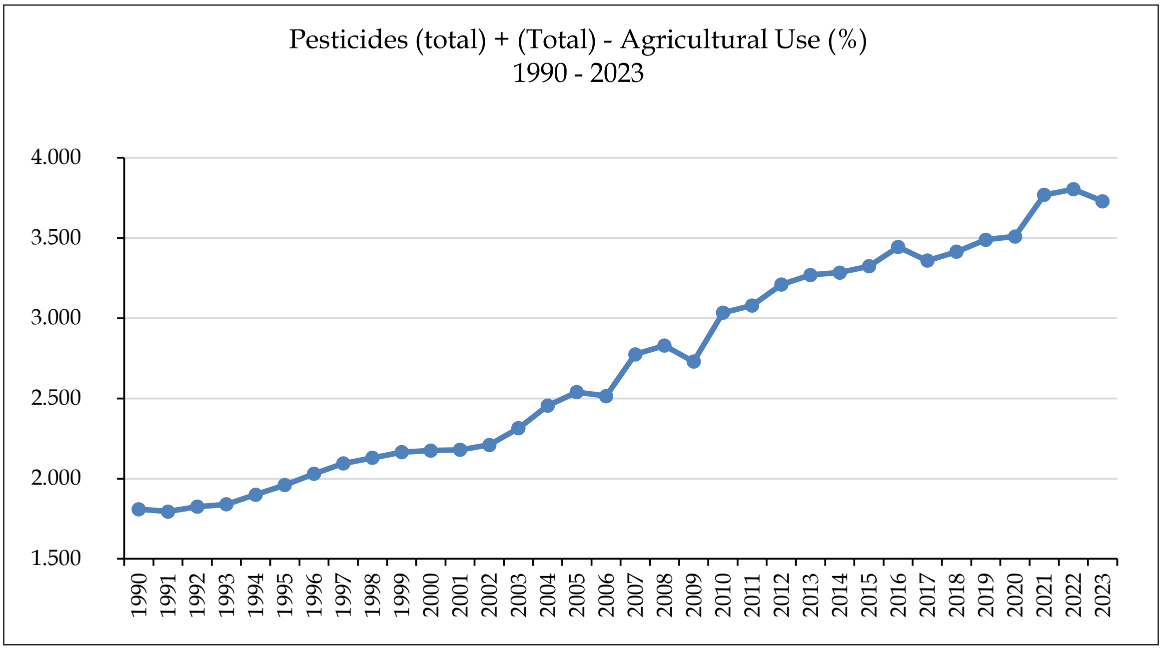

Fig. 2. Global Patterns of Pesticide Application in Agricultural Systems (1990-2023) (FAOSTAT, 2025).

lipophilic chemicals with low water solubility and high partitioning tend to concentrate in beeswax, making it a particularly sensitive biomonitor for persistent, low-volatility contaminants (Wilmart *et al.*, 2021). In Western France, a landscape survey found residues in 99% of beeswax, 60% of propolis, and 25% of honey samples, with chlorpyrifos, chlorpyrifos-methyl, diazinon, coumaphos, and tau-fluvalinate most frequently detected, highlighting hive matrices as valuable tools for monitoring pesticide and veterinary drug contamination (Lambert *et al.*, 2013). In Asia and Africa, beeswax is a long-term sink for lipophilic pesticides, while honey accumulates hydrophilic residues at lower concentrations. The Middle East and Asia have found agricultural pesticides and veterinary acaricides, including coumaphos and amitraz metabolites, in beeswax and honey (Calatayud-Vernich *et al.*, 2018; Kast *et al.*, 2021), while North Africa has found organophosphate residues in several hive matrices (Eissa *et al.*, 2014; Mahmoudi *et al.*, 2014b). These findings show that residue distribution is determined by chemical characteristics and hive matrix interactions, supporting multi-matrix monitoring methodologies in varied agroecological systems.

Antibiotic residues and co-occurring compounds: Antibiotics are typically used in apiculture to control or prevent the spread of bacterial diseases. However, their noncompliance with the Codex Alimentarius recommendation (1981) regarding the use of pharmaceutical products on honey bees, combined with the presence of their specific markers in honey, highlights the risk and the need to monitor the environment (Lambert *et al.*, 2013). In parallel, it has been shown that when honey samples are contaminated with antibiotics, they are often associated with the concomitant presence of pesticides (Mullin *et al.*, 2010). Several classes of antibiotics and other pharmaceuticals are regularly detected in commercial honey from countries with legislative constraints regarding the veterinarian treatment of honey bees, indicating that contamination is still an issue of concern (Alla, 2020; Lynda *et al.*, 2025). Priority should therefore be given to the analysis of those same compounds in bee products to obtain a better understanding of the risks and the contamination pathways that can lead to honey contamination (Végh *et al.*, 2023).

Analytical detection and monitoring: Detecting contaminant residues in bee products requires advanced analytical strategies to ensure safety and track long-term contamination trends. Instrumental techniques such as GC, HPLC, CE, and ESI–MS are widely used to identify and quantify pesticides, antibiotics, and their metabolites across different bee matrices (El Hawari *et al.*, 2024; Lynda *et al.*, 2025). Sample preparation typically relies on solid–liquid extraction followed by cleanup with SPE or dSPE, and may include derivatization to improve detectability during analysis (Badawy *et al.*, 2022).

Quality assurance is meticulously achieved through the consistent use of internal standards and quality-control samples, while method validation has focused extensively on critical parameters such as specificity, linearity, limits of detection (LOD), repeatability, recovery rates, and the effects brought about by different matrices in analytical results. It is essential that these comprehensive practices contribute to maintaining the highest safety standards for products derived from bees (Lambert *et al.*, 2013).

Analytical challenges remain regarding the accuracy of quantification, uncertainties around LODs and recovery values, and the comparability of results across laboratories. Inter-laboratory studies are scarce, highlighting the need for harmonized protocols to facilitate comparability and trend analysis (Ponce-Vejar *et al.*, 2022). Enhanced coordination and comparable validation studies could support efforts toward standardized analytical approaches for measuring pesticide residues in bee products (Carrera *et al.*, 2024).

Sampling strategies and quality assurance: Sampling is the foundation of bee-product quality assessment because it enables evaluation of defined lots, guided by quality assurance systems and standardized, product-specific protocols for honey, beeswax, propolis, and royal jelly (Mohamadzade Namin *et al.*, 2023; Arfa *et al.*, 2021). Sampling plans should be aligned with analytical objectives and confidence requirements, with screening used for rapid preliminary checks (Milojković-Opsenica *et al.*, 2022; Arfa *et al.*, 2021).

A combination of screening and confirmatory analyses is used to detect hazards and contaminants and demonstrate regulatory compliance, including immunoassays for pesticide residues and monitoring required under EU controls for mycotoxins and heavy metals (Astolfi *et al.*, 2020; Zeghoud *et al.*, 2021). Standard physicochemical methods support integrity assessment, while conventional and targeted analyses address authenticity, traceability, and contaminant load that inform acceptance decisions and post-hive management (Akash and Rehman, 2025; Kotsanopoulos and Exadactylos, 2022; Madukasi *et al.*, 2025). Residue profiles especially pesticides also shape market access, shelf-life, packaging and processing choices, and overall product value, alongside compositional and nutritional quality evaluation (Lengai *et al.*, 2022; Artjoki and Laari, 2025; Wojtacka, 2024; Pedrosa *et al.*, 2021).

Data interpretation and benchmarking: Statistical methods are essential for interpreting large monitoring datasets and evaluating the significance of results, often through characterizing population distributions and estimating representative mean levels (Lambert *et al.*, 2013). National and international benchmark reference values help identify potentially critical situations, and their derivation should, where possible, use the full range of available data and distribution-based approaches to ensure representativeness. However, as monitoring methods are being developed for a fungus, a virus, and associated chemical compounds in bee matrices, full characterization of the relevant dataset is still pending (Cunningham *et al.*, 2022).

In the absence of parcel-specific information, residue data on pesticides and veterinary drugs in honey and wax from 2018 onward provide a practical basis for establishing relevant benchmarks, since these matrices have the largest and still-growing datasets. The current analysis uses wholesale data from 646 honey and 387 wax samples, covering 29 pesticides and 19 veterinary drugs, while data collection for other bee products is still ongoing (Ponce-Vejar *et al.*, 2022). The adopted sampling strategy supports representativeness, and recording sample origins aids the development of geographical reference frameworks (Durazzo *et al.*, 2021).

Exposure Pathways, Bioaccumulation and Health Implications

Routes of exposure and transfer through the food chain: The contamination of bee products directly links environmental pollution to consumer exposure and ecosystem transfer. Pesticides from agricultural runoff and wastewater treatment, as well as antibiotics from veterinary applications and effluents, infiltrate apicultural systems through several interrelated routes (Bargańska *et al.*, 2016). Contamination initiates at the hive and disseminates via the food chain, with environmental reservoirs facilitating contamination beyond local habitats (Carter *et al.*, 2020).

Honey, pollen, beeswax, and propolis form successive matrices of transmission. Honey can contain residues from nectar and honeydew, whereas wax and propolis can collect pollutants due to extended exposure to treated surroundings and recycled hive materials (Kebede *et al.*, 2024). Encapsulation or amalgamation of products maintains unique residue profiles, frequently uncovering previously unnoticed contamination pathways (Raimets *et al.*, 2021). The spatial and botanical diversity of pollen broadens the potential for contamination across different landscapes and seasons (de Oliveira *et al.*, 2016; Xiao *et al.*, 2022).

Transfer also transpires via discarded hive remnants, deceased bees, and contaminated pollen that infiltrate terrestrial food webs, affecting insectivorous animals and the overall integrity of ecosystems. Drift from treated crops and habitat alteration exacerbate these pathways, whereas cumulative and unintentional exposures result from chemicals not considered in risk assessments, indicating misuse or legacy contamination (Mullin *et al.*, 2010). The finding of residues in colonies experiencing abrupt mortality highlights the insufficient comprehension of the transfer processes between parent matrices and hive products (Lambert *et al.*, 2013).

Bioaccumulation and cumulative exposure: Various exposure pathways result in concurrent contamination of honey, wax, and bee pollen, facilitating bioaccumulation within the hive ecosystem (Bava *et al.*, 2024). Wax serves as a long-term reservoir for lipophilic insecticides and antibiotics, enabling their recurrent redistribution into many matrices (Raimets *et al.*, 2021). Routine monitoring frequently focuses on restricted groups of compounds, neglecting seasonal variations, transformation products, and synergistic effects (Nassar *et al.*, 2024).

Non-targeted and multi-residue screening methodologies more effectively encompass authentic exposure scenarios, incorporating metabolites and degradation products of significance (Wang *et al.*, 2020). Global surveillance data consistently indicate cumulative exposure to pesticide mixtures,

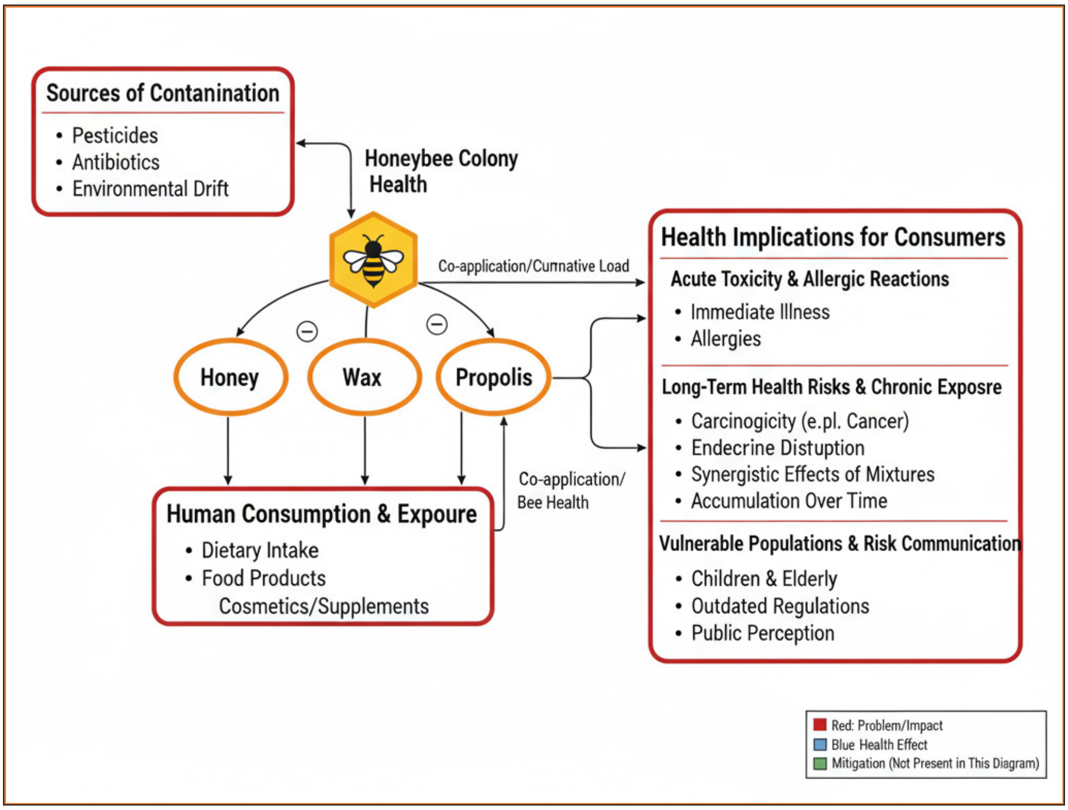

Fig. 3. Consumer health risks from contamination in bee products.

including neonicotinoids and fungicides, across various agricultural systems, highlighting the necessity for integrated monitoring strategies that encompass colony status, management practices, and landscape context (Mullin *et al.*, 2010).

Health implications for consumers: Pesticide residues are regularly evaluated in primary crops; however, honey and other bee products are relatively under-examined, permitting persistent pollutants to stay undiscovered (Lambert *et al.*, 2013) (Fig. 3). Conservative exposure calculations indicate that contamination from wax and comb may already reach or surpass toxicological thresholds, especially when accounting for cumulative inputs from several hives and co-application techniques.

Residue profiles in honey and wax offer chemical “fingerprints” that facilitate the identification of primary contamination sources and their related health hazards. These profiles indicate agricultural cycles, home chemical application, and sublethal environmental pollution, frequently demonstrating consistent patterns across geographically diverse locations (Glinski *et al.*, 2024; Swiatly-Blaszkiewicz *et al.*, 2025). Acute health impacts may encompass allergic reactions, whereas chronic exposure raises issues pertaining to carcinogenicity and endocrine disruption (Wu *et al.*, 2011).

Long-term dangers are exacerbated by synergistic effects from chemical mixes, such as combinations of pesticides and antibiotics that can produce harmful by-products (Hesketh *et al.*, 2016). Residues lasting beyond one month may signify prolonged exposure routes and heightened health risks, especially when mixes surpass legal limits (Végh *et al.*, 2023; Swiatly-Blaszkiewicz *et al.*, 2025).

Vulnerable populations and risk communication: Bee products are commonly regarded as natural and beneficial for health; nevertheless, evidence of “silent pollution” undermines this belief (Pamminger *et al.*, 2018). Vulnerable populations, such as children, frequent consumers, and individuals utilizing bee-derived products, may be disproportionately impacted by prolonged low-dose exposure. Residues have been identified in honey, wax, pollen, and propolis years post-regulatory prohibitions, indicating persistence and bioaccumulation within hives (Ostiguy *et al.*, 2019; Zioga *et al.*, 2020).

Antibiotic residues accumulate despite their low environmental persistence, underscoring the hive’s function as a contamination reservoir (Mahmoudi *et al.*, 2014; Lima *et al.*, 2020). Simultaneously, honey bees function as efficient indicators of environmental pollution, hence facilitating their application in comprehensive monitoring and clear risk communication systems (Mosca *et al.*, 2025).

Impact on bee health and ecosystems: Pesticides and antibiotics pose problems not only for human health via contaminated food but also for the health of pollinators, especially the honeybee, *Apis mellifera*, whose role is well documented (T O’Neal *et al.*, 2018). Pollinator health, in turn, is essential both for agricultural yields and for the basic stability of ecosystems. Surviving colonies affected by residue exposure exhibit sublethal physiological and behavioral alterations, including effects on foraging, learning, feeding, immunity, and pheromonal recruitment, which increases the risk of colony collapse. The proportion of crop species pollinated by honeybees ranges between 28% and 70% of all food consumed by humans, depending on the country. Loss of the honeybee and other pollinators would have wide-ranging impacts on agricultural output and on ecosystem biodiversity, with fundamental implications for stability and resilience (Lambert *et al.*, 2013) (Fig. 4).

Sublethal effects on bee physiology and behavior: Pesticide residues in honey and wax, even below regulatory limits, can cause sublethal impacts on honey bees, affecting cognition, foraging, orientation, immunity, and overall colony dynamics. Evidence from laboratory, field, and RFID studies shows that neonicotinoids and fipronil impair olfactory and visual learning, while sublethal neonicotinoid exposure disrupts foraging and navigation. Dietary exposure to sublethal clothianidin or imidacloprid can also alter bee body weight and metabolism, indicating disruption of nutritional regulation (Renzi, 2013).

Mixtures of pesticides in nectar/pollen and pesticide–fungicide co-occurrence in wax may cause cumulative or synergistic effects, even when honey residues are not detected (**Karise** *et al.*, 2018). Sublethal exposure is commonly

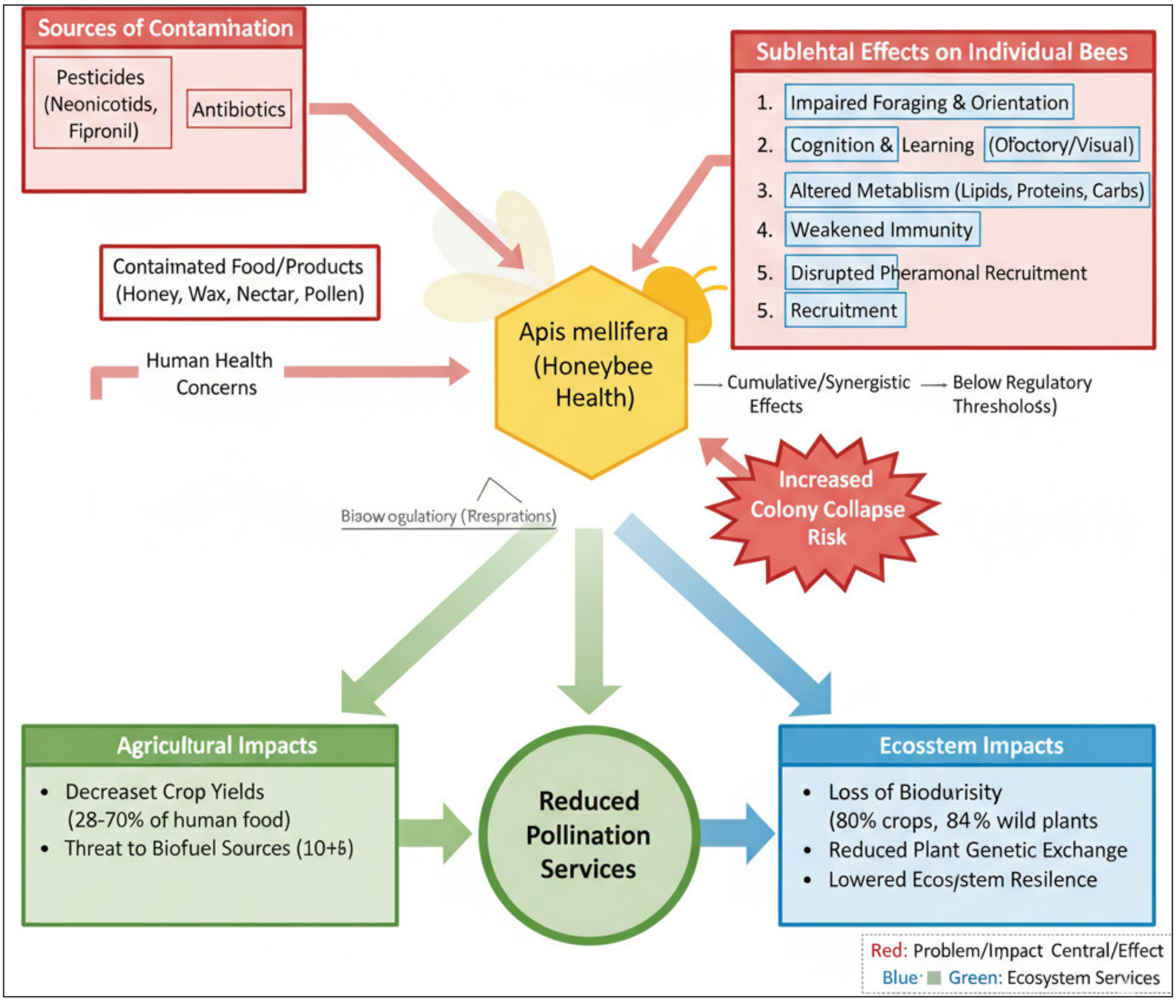

Fig. 4. Conceptual framework: impact of pesticides and antibiotics on honeybee health and ecosystem services.

defined as <1/10 of the LD50 and depends strongly on exposure duration (Chmiel *et al.*, 2020; Ahsan *et al.*, 2025). Neonicotinoids are most studied, with evidence of impaired learning and disorientation, though colony impacts are difficult to confirm due to buffering at the colony level (Van der Sluijs *et al.*, 2013; Paoli and Giurfa, 2024). Biomonitoring approaches, including biochemical assays and non-lethal respiration measurements, can help track these effects (Di Noi *et al.*, 2021; Orčić *et al.*, 2022; Mokkapati *et al.*, 2022).

Implications for colony health and pollination services: Colony health is intricately linked to the capacity of pollinators to deliver ecosystem services and agricultural production. The decline of managed honey bee colonies raises concern for biodiversity conservation and the stability of food crop yields, with a particular focus on the role of alien pollinators in biotic pollen delivery (T O'Neal *et al.*, 2018). In Europe, approximately 80% of crops and 84% of flowering plants directly benefit from animal pollination, highlighting the reliance of native flora on pollinator activities. Furthermore, more than 10% of the world's biofuel energy sources depend on animal-mediated pollination, underlining the importance of this service for renewable energy supplies (Christen, 2023). Pollinators as keystone species are critical to maintaining biodiversity and facilitate genetic exchange between flowering plants, thereby enhancing metapopulation resilience to climate-induced local extinctions. Pollinator-mediated reproduction of wild plants ultimately contributes to biotic resilience within climate-affected ecosystems (Gérard *et al.*, 2020). The continued stable metabolism of pollinators within agricultural systems and ecosystems operating under natural law remains to be demonstrated and documented. Such stability underpins the resilience of pollinator services and facilitates symbiotic interactions between flowering plants and animal pollinators and the conservation of wild plants. Given the importance of pollinator-mediated ecosystem services for biodiversity and resilience of stabilized agricultural systems, it is imperative to assess to what extent the extensive chemical contaminations of bee products remain tolerated by the pollinators (Potts *et al*., 2016).

Global standards and permissible levels: Current legislation generally requires honey to comply with pesticide and veterinary drug residue limits aligned with Codex Alimentarius guidance, where acceptable levels are set nationally using exposure and toxicity evidence under FAO/WHO specifications. However, Codex still lacks maximum residue limits (MRLs) for some pesticides that are repeatedly detected in honey, and monitoring is often implemented through bilateral trade agreements alongside broader international food safety checks (Al-Waili *et al*., 2012).

In Europe, honey falls under the Official Control framework (EU) 2017/625, supported by rules for organizing official food controls and EU reference laboratory/centre systems for detecting and monitoring chemical residues and contaminants, including capacity-building for advanced analytical methods (European Food Safety Authority (EFSA) *et al*., 2024). These systems promote state-of-the-art techniques (e.g., mass spectrometry and multiplex approaches) that also apply to honey, propolis, and beeswax (Wang *et al*., 2021). Despite honey's recognized vulnerability to residues and its dietary importance (including for infants), routine control of pesticides and antibiotics is still not fully integrated into regular official control practice, and ongoing detection of residues continues to raise long-term health and ecological concerns (Panseri *et al*., 2020; Rodrigues *et al*., 2024).

Monitoring, Mitigation and Best Practices

Monitoring programs and enforcement: National and regional monitoring systems for pesticide residues in honey and beeswax are established, especially in Europe, where comprehensive multi-residue screening programs have shown contamination with 20-25 chemicals per sample, many of which are hazardous to honey bees (Mullin *et al*., 2010). Nevertheless, regulatory frameworks frequently omit pre-harvest wax treatments and hive management methods, so

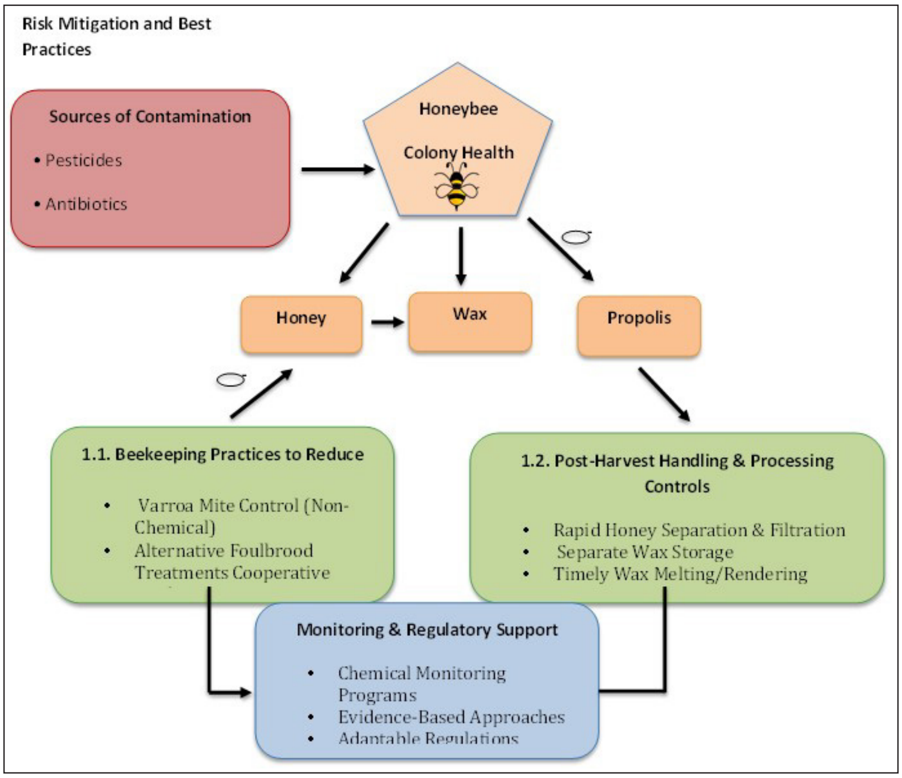

Fig. 5. Risk mitigation strategies for chemical residues in bee products.

constraining their efficacy in diminishing total residue levels (Lambert *et al*., 2013).

Enhanced regulatory oversight, alongside expanded compound coverage and unified enforcement, is crucial, especially in places with active beekeeping that produce honey for export.

Risk mitigation and optimal practices: Evidence-based beekeeping procedures can markedly diminish pesticide and antibiotic residues in hive products (Fig. 5). After successful varroa management, synthetic miticide residues diminish within weeks, whereas alternative treatments reduce residual buildup in wax, honey, and propolis (Graham *et al*., 2022). Collaborative production strategies are essential, as pollutants accumulate over time and disperse throughout hive matrices.

Post-harvest management and processing constitute further contamination risks. Cleaning apparatus, segregation of treated and untreated wax, expedited rendering, filtering, and regulated storage mitigate residue transfer and buildup (Végh *et al*., 2023; Evran *et al*., 2024). While post-harvest mitigation cannot completely eradicate residues, it diminishes contamination levels and enhances monitoring measures (Luo *et al*., 2021; Lucas *et al*., 2023).

Alternative Treatments and Reduced-Residue Practices

Pesticides and antibiotics have been used extensively in agriculture and livestock production, respectively, to improve both crop and animal protection, and therefore production. They may end up present in foods and food products through different routes (El-Seedi *et al*., 2022). Honey bee products, such as honey, beeswax, propolis, and royal jelly, are also part of the human food chain and have also been found containing a variety of pesticides and antibiotics. Three spontaneously derived products from these same food products, namely, contaminated honey, corn syrup (from corn), and sugar syrup (from cane), have been reported to cause an important proportion of contamination in the hives. Beekeepers still struggle to find effective and fast-acting treatments for different bee diseases. Even if restricted to the commonly published treatment regimens, liquid antibiotic residues are easily accumulated at detectable levels and may be taken up directly through oral ingestion.

The contamination of honey and other bee products with pesticide and antibiotic residues is therefore an important topic that has been recently investigated throughout the world and deserves more attention also within the national territory. The fingerprints left reveal when and where those products were used and their subsequent fate. Non-chemical control strategies would preserve the honey bee products and reduce the risks linked to chemical treatments. In very severe cases, targeted chemical treatments should be preferred to broad-spectrum ones. The use of antibiotics should also be avoided whenever possible. Treatments directed against the development of the disease at the pest or predator stage, such as for Varroa destructor, should be applied first (Bogdanov, 2006).

Conclusions

Silent pollution from pesticide and veterinary antibiotic residues in bee products poses significant risks to pollinator health, ecosystem stability, and long-term human well-being. Beeswax, propolis, and other hive products act both as consumable commodities and as bioindicators of environmental contamination, reflecting cumulative chemical exposure across agricultural and natural landscapes. This review shows that lipophilic pesticides preferentially accumulate in beeswax, whereas hydrophilic antibiotics are more commonly detected in honey, resulting in prolonged and interconnected exposure pathways within colonies.

Despite increasing research, critical knowledge gaps persist. Chronic low-dose exposure, mixture toxicity, and residue transfer across hive matrices and trophic levels remain poorly characterized due to fragmented study designs and methodological heterogeneity. In particular, the synergistic effects of pesticide–antibiotic mixtures, their associations with antimicrobial resistance markers, and their sublethal impacts on pollinators are insufficiently understood, limiting robust risk assessment and weakening regulations that rely mainly on single-compound thresholds.

These findings emphasize the need to move from isolated residue testing toward standardized, multi-residue monitoring frameworks covering major bee products. Harmonized analytical methods, expanded surveillance in underrepresented regions, and inclusion of mixture toxicity in risk assessment are essential for effective regulation. For apicultural practice, reducing in-hive pharmaceutical use, adopting integrated pest management, and improving traceability are key priorities.

Addressing silent pollution in bee products requires coordinated action across agricultural, environmental, and public health sectors to protect consumers, sustain apiculture, and preserve ecosystem resilience.

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