Check for updates

AUTHORS:
Annika Kruger[1]
Ezette E. du Rand[1]
Christian W.W. Pirk[1]

AFFILIATION:
[1]Social Insects Research Group, Department of Zoology and Entomology, University of Pretoria, Pretoria, South Africa

CORRESPONDENCE TO:
Annika Kruger

EMAIL:
u25731808@tuks.co.za

DATES:
Received: 25 Sep. 2025
Revised: 20 Apr. 2026
Accepted: 20 Apr. 2026
Published: 29 July 2026

HOW TO CITE:
Kruger A, du Rand EE, Pirk CWW. Concentrations of pesticides in water and sediment in sub-Saharan Africa and the implications for honey bees. S Afr J Sci. 2026;122(7/8), Art. #23414. https://doi.org/10.17159/sajs.2026/23414

ARTICLE INCLUDES:
☒ Peer review
☒ Supplementary material

DATA AVAILABILITY:
☐ Open data set
☒ All data included
☐ On request from author(s)
☐ Not available
☐ Not applicable

EDITOR:
Teresa Coutinho

KEYWORDS:
Apis mellifera, water quality, bioindicator, biomonitoring, water monitoring

FUNDING:
South African National Research Foundation (SRUG2204062235, PMDS240617228299)



© 2026. The Author(s). Published under a Creative Commons Attribution Licence.

Concentrations of pesticides in water and sediment in sub-Saharan Africa and the implications for honey bees

The global challenge of inadequate access to clean and safe drinking water affects over a billion individuals, of whom more than 800 million are in sub-Saharan Africa. Evaluation of water quality is an integral part of effective and sustainable management of water sources that ensures its suitability for human consumption and environmental stability. Agrochemicals are a major source of surface water contamination. Long-term water quality monitoring is essential to track changes in water quality across time and space to make informed decisions regarding water management practices that protect the water sources in sub-Saharan Africa. In this study, we demonstrate the alarming fragmented nature and lack of long-term water quality monitoring data for sub-Saharan Africa by reviewing the level of contamination of water sources with pesticides that are widely used in the cultivation of the staple crop maize, specifically, atrazine, glyphosate, imidacloprid and metolachlor. Honey bees and beehive products are excellent indicators of environmental contamination and provide both qualitative and quantitative data. Long-term environmental monitoring programmes using managed honey bees as biomonitors have proven to be highly successful. We discuss the toxicity of atrazine, glyphosate, imidacloprid and metolachlor to honey bees and the feasibility of using honey bees as a bioindicator species for early detection of pesticide contamination of water sources in remote and rural areas in sub-Saharan Africa.

Significance:

Water is essential for life, yet millions of people across sub-Saharan Africa lack access to safe water. Long-term water quality monitoring is an essential part of water management practices that protect water sources and prevents deterioration of water quality. This review illustrates a lack of standardised and long-term water quality monitoring data in sub-Saharan Africa. Existing data provide a limited view of water quality in this region, potentially leading to an inaccurate perception of the true level of contamination. We suggest a low-cost, sustainable sampling model for remote, rural areas as part of developing an efficient, long-term water quality monitoring programme.

Introduction

Water is essential for life on earth. Not only is it the biological medium of life, but water is also at the centre of socio-economic development as it plays decisive roles in energy and food production, human health, ecosystem services and maintaining ecosystem health.[1] Of the 71% of the planet covered by water, only 2.5% is fresh water, of which less than 1% is accessible.[2] Global freshwater supplies are increasingly under pressure due to the growing demand driven by population growth, urbanisation, economic development (increasing industrial and agricultural activities etc.) and climate change.[1] The World Economic Forum has, since 2012, consistently listed water security as one of the top global risks in terms of impact.[3] The United Nations has long been addressing the issue of water security, with water security being one of the main goals of the United Nations' General Assembly's Sustainable Development Goals (SDG) that were adopted in 2015; SDG6 is "ensure availability and sustainable management of water and sanitation for all".[4]

Monitoring the water quality of water bodies (rivers, lakes and groundwater) in a country is an integral part of the United Nation's SDG6 Target 6.3 that seeks to halve the proportion of untreated wastewater discharged into water bodies to ensure good water quality that does not damage ecosystem function or human health.[4] In sub-Saharan Africa (SSA), about two thirds of monitored water bodies have good ambient water quality, but SSA also has some of the highest mortality rates attributed to unsafe water and inadequate sanitation. Nine of the ten countries with the worst access to clean water are located in SSA.[5] Agricultural activities and wastewater effluents are the two main stressors affecting the quality of fresh water in SSA.[1,6] With current water management practices, it is projected that SSA will become the new hotspot of surface water contamination globally.[7] Yet there is a lack of water quality monitoring data to track the expected changes in water quality across time and space in this region. While monitoring by itself will not solve the water quality crisis in SSA, it is an essential first step toward making informed decisions.

In this review, we highlight the fragmented nature of the water quality monitoring data available for SSA and the paucity of standardised and long-term monitoring of water quality in this region by using an example from the agricultural sector. Specifically, we review the occurrence and level of contamination of water sources with pesticides that are routinely used in the cultivation of a staple crop in SSA (maize) and we also discuss the feasibility and obstacles of using honey bees as a bioindicator species for early detection of low levels of contamination[8], including by pesticides, of water sources in remote and rural areas in SSA.

Level of pesticide contamination of water sources

Agriculture is the economic backbone of SSA. It is the primary source of livelihood for the majority of the population and a critical driver of the region's gross domestic product (GDP).[9] SSA's agriculture sector is the biggest consumer of water, with about 85% of freshwater withdrawals used for agricultural purposes[10], but it is also one of the

major sources of surface water contamination due to the extensive use of agrochemicals[11,12]. Small- and large-scale farmers rely on pesticides to protect their crops from pests and diseases to prevent crop losses. Annual pesticide use is estimated to be more than 200 000 metric tons.[13] While this accounts for only 2–4% of global pesticide consumption, the region has seen a significant upward trend in pesticide use since 1990.[13] Although these agrochemicals benefit the agricultural sector, indiscriminate and overuse contribute to polluting the environment and pose health risks to humans and other non-target organisms (for a review see ASSAf[14]).

Despite the risks, the use of pesticides is the most widely accepted method to ensure high crop yields in SSA.[15] In a region where food security can be precarious, pesticides are sometimes viewed as a form of crop insurance, especially for a major staple crop like maize.[15] More than 40 million hectares of land in SSA are used for maize production.[16] In 2025, the African Maize Market amounted to an estimated 44.17 billion US dollars.[17] Due to the increasing demand driven by human population growth, maize production will nearly triple by 2050.[18] The pesticides atrazine, glyphosate, metolachlor and imidacloprid are some of the most widely used pesticides in maize production in SSA (Table 1).[19] During the application of these pesticides to maize fields, drift contaminates surface water sources and other non-target areas.[20] Water is a primary pathway through which the pesticides are then transported from their site of first application to other environmental areas.[21]

Atrazine is used to control annual broadleaf weeds and grass in maize fields as either a pre- or post-emergence herbicide.[29] It was banned in the European Union (EU) in 2004 due to its persistent presence in groundwater above the allowable concentration for pesticides.[30] Since then, atrazine has been restricted or banned in more than 60 countries worldwide[30], with more countries expected to follow suite as a result of the World Health Organization's International Agency for Research on Cancer (IRAC) recently upgrading atrazine to a Group 2A compound ("Probably Carcinogenic to Humans").[31] However, it remains one of the most widely used herbicides in the USA, Australia and parts of SSA.[11,12] Glyphosate is a broad-spectrum herbicide used for vegetation and weed control post-emergent.[28] Unlike atrazine, despite facing public scrutiny due to health and environmental debates, glyphosate remains approved and widely used globally[30], with regulatory bodies such as the European Food Safety Authority and the US Environmental Protection Agency (EPA) emphasising low real-world risk for the general public.

Metolachlor is used as a pre-emergent herbicide to control annual grasses and broadleaf weeds. The original pesticide was a racemic product containing four stereoisomers, two 1'S-isomers and two 1'R-isomers.[32] Metolachlor has been replaced by S-metolachlor, which is enantiomerically enriched with the 1'S-isomers that have higher herbicidal activity. The names metolachlor and S-metolachlor are used interchangeably in most literature.[32] S-metolachlor has been banned in the EU since 2024 due to persistent groundwater contamination risks[33], but outside the EU its use is not heavily restricted in most countries, and it remains a popular herbicide for crops such as maize and soybeans. Imidacloprid is a neonicotinoid insecticide that is used to control sucking and piercing insects, termites and soil insects.[25] The EU implemented a near-total ban on imidacloprid and a number of other neonicotinoid insecticides in 2018, citing high toxicity to honey bees and other economically important pollinators; limited applications were permitted inside permanent greenhouse environments.[34] However, imidacloprid remains one of the leading neonicotinoid insecticides worldwide, holding a USD 1.7 billion share of the total global neonicotinoid market of USD 5.3 billion in 2024.[35]

We surveyed the available literature reporting the presence of atrazine, glyphosate, S-metolachlor and imidacloprid in water bodies, soil and sediment in SSA (Figure 1). Databases such as Web of Science, Google Scholar and Science Direct were searched using specific search terms: "pesticides in sub-Saharan African waters", "pesticides in South African* waters", "atrazine in South African* waters", "glyphosate in

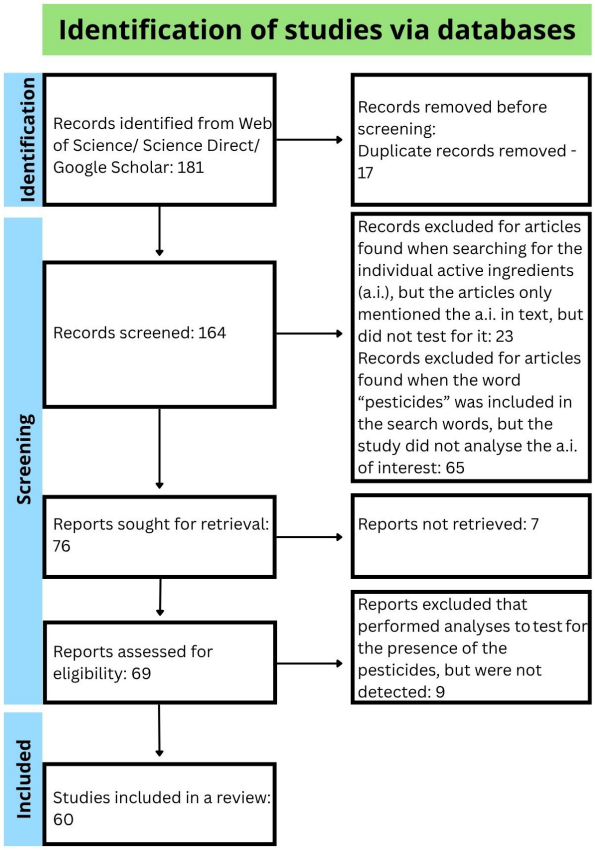

Figure 1: PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) flow diagram indicating the number of publications/reports that were found during the initial search, and the final number of publications/reports after removing the duplicates and exclusions. The number of reports/publications were identified using Web of Science, Google Scholar and Science Direct and the search terms "pesticides in sub-Saharan African waters", "pesticides in South African* waters", "atrazine in South African* waters", "glyphosate in South African* waters", "S-metolachlor in South African* waters" and "imidacloprid in South African* waters" (*South African was also substituted with the other countries of sub-Saharan Africa). No date limitations were applied.

Table 1: Four widely used pesticides in the production of maize in sub-Saharan Africa

Active ingredient	Water solubility (mg/L @ 20 °C)	Half-life in water (days)	Kow (log P)	Reference
Atrazine (herbicide)	30	41–231	2.61	22,23
Glyphosate (herbicide)	10 500	5 (pH 4, 5 & 9 (50 °C))	–3.40	24
Imidacloprid (insecticide)	610	4	0.57 (21 °C)	25,26
Metolachlor (herbicide)	530	>200	3.13	27,28

South African* waters", "S-metolachlor in South African* waters", "imidacloprid in South African* waters" (*South African was substituted with every country in SSA). No date limitations were applied, allowing for the inclusion of all available data up to the search completion date of 31 May 2025. Pesticide concentrations which were reported in sediment and soil were included to increase the number of data points included in the survey. Some of the earlier reports were not available online, but efforts were made to obtain the relevant information directly from the authors. For the purpose of this review, 49 countries were included as part of SSA in the search for data (Figure 2).

After removing duplicates and publications not mentioning atrazine, glyphosate, metolachlor/S-metolachlor or imidacloprid, a total of 60 publications and reports were analysed (Figure 1). A comprehensive table was compiled to summarise the reported atrazine, glyphosate, metolachlor and imidacloprid concentrations present in water, soil and sediment samples from across SSA as extracted from the peer-reviewed articles, dissertations and technical reports (see Supplementary table 1). Documented levels of atrazine, glyphosate, metolachlor and imidacloprid present in water, soil and sediment samples were available or accessible for only 17 out of the 49 SSA countries (i.e. only 35%); this proportion indicates a significant and concerning gap in water monitoring data in SSA. Noticeably, no records that included these four pesticides were available for the countries of central Africa (see Figure 2 and Table 2). Records for southern Africa were more readily available, with only four countries out of ten lacking water quality data pertaining to the specific pesticides. The concentrations of these pesticides in water bodies in southern Africa ranged from 0.0003 to 298.2 μg/L; 0.42 to 3.19 μg/L; not detected to 390 μg/L and 0.00019 to 120 μg/L for atrazine, glyphosate, imidacloprid and metolachlor, respectively (see Supplementary table 1). South Africa, the largest pesticide user in SSA[11], had by far the most records that included atrazine, glyphosate, imidacloprid and metolachlor in water quality monitoring data (see Table 2). The maximum reported concentration for atrazine in South Africa's water bodies of 298 μg/mL is 4–3000 times higher than that reported for any other SSA country. This value is also almost 150 times higher than the EU Environmental Quality Standard (EU EQS) of 2 μg/mL[36] or the 9.7 μg/mL recommended by the US EPA for atrazine in surface water[37]. The concentration vastly exceeds quality standards for drinking water, including the EU maximum residue level (EU MRL) for drinking water of 0.1 μg/mL[38], the US EPA's maximum contamination level (MCL) of 3 μg/mL[21] and the South African National Standard 241[39] of 100 μg/mL. Most of the concentrations reported for the other southern African countries are below the EU EQS, but exceed the EU MRL for drinking water. South Africa was the only country in the southern region of SSA for which reported levels of glyphosate (0.42 to 3.19 μg/L) and imidacloprid (not detected to 390 μg/L) in water bodies were available. These reported glyphosate concentrations are below the EU EQS of 398.6 μg/L for glyphosate[40] and the US EPA's MCL of 700 μg/L for drinking water[41], but exceed the EU MRL of 0.1 μg/L[37]. The imidacloprid levels in South Africa exceed the EU EQS value of 0.065 μg/L for imidacloprid and also exceed the EU MRL for drinking water of 0.1 μg/L.[42] The EU has extremely strict environmental water quality standards for imidacloprid due to the negative effects that this pesticide has on pollinators.[34] Levels for metolachlor were reported for only two of the nine countries in southern Africa; no EU EQS value is available for metolachlor, but the maximum reported concentrations exceed the EU MRL of 0.1 μg/L for drinking water[36] by 50 and 1200 times in Malawi and South Africa, respectively (see Table 2).

Records that reported levels of atrazine, glyphosate, imidacloprid and metolachlor in water bodies were available for only 7 of 18 countries in western Africa, with concentrations of 0.00015–0.938 μg/L, 0.00002–0.27 μg/L, 0.0008–0.3840 μg/L and 0.0001–0.0244 μg/L, respectively (see Supplementary tables 1 and 2). Only Ghana had a maximum reported atrazine concentration exceeding (double) the EU EQS of 2 μg/L in this region, but the concentration is still below the US EPA's recommended value of 9.7 μg/L. All the maximum reported atrazine levels in this region exceed the EU MRL for atrazine in drinking water (0.1 μg/L), with the levels in Ghana also exceeding the US EPA's MCL of 3 μg/L. Only two countries in this region (Nigeria and The Gambia) reported concentrations of glyphosate in water bodies. These reported concentrations are below the EU EQS of 398.6 μg/L and the US EPA's MCL of 700 μg/L for drinking water, with the glyphosate level reported in Nigeria exceeding the EU MRL of 0.1 μg/L for drinking water. Only three countries had records of imidacloprid levels in water bodies; the maximum reported concentrations from all three of these countries (Burkina Faso, Cameroon and Côte d'Ivoire) exceed the EU EQS value of 0.065 μg/L for imidacloprid, with one country (Burkina Faso) also exceeding the EU MRL for drinking water of 0.1 μg/L. Only one country from western Africa (Cameroon) had water quality data that included metolachlor levels.

Of the 15 countries in eastern Africa, only 4 had records reporting water quality that included atrazine, glyphosate, imidacloprid and metolachlor

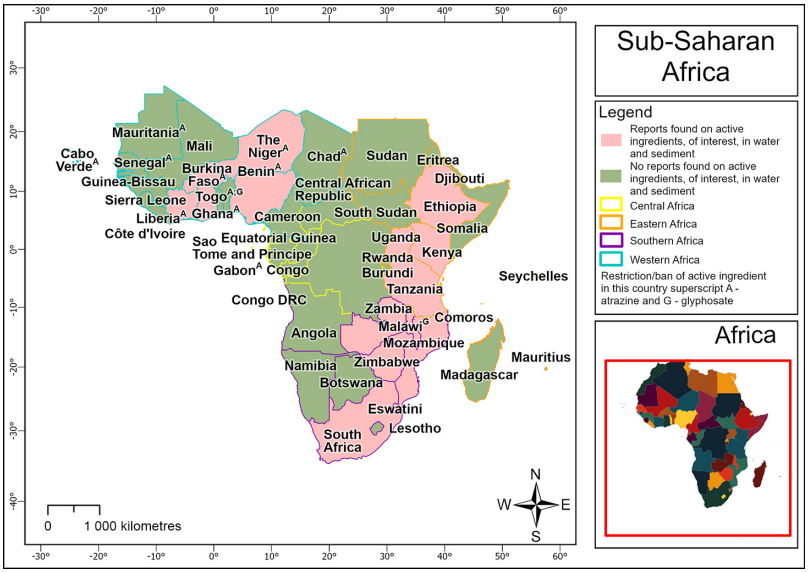

Figure 2: Map of the countries in sub-Saharan Africa, with pink indicating the countries for which water quality data were available/accessible and included levels of atrazine, glyphosate, imidacloprid or metolachlor. The use of atrazine is banned or restricted in Benin, Burkina Faso, Chad, Côte d'Ivoire, Gabon, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mauritania, Morocco, Niger, Nigeria, Senegal, Sierra Leone and Togo. The use of glyphosate is banned/restricted in Malawi and Togo. Carbo Verde is part of western Africa, Sao Tome and Principe form part of central Africa, while Comoros, Mauritius and Seychelles form part of eastern Africa. The map was created using ArcGIS® Pro.

Table 2: The maximum concentration of the pesticides reported to be present in water bodies in sub-Saharan countries. The number of reports/publications from which the data were extracted is also indicated.

Country	Maximum concentration reported in water bodies in sub-Saharan Africa (μg/L)				Number of publications/reports
	Atrazine	Glyphosate	Imidacloprid	Metolachlor	
Eastern Africa					
Ethiopia	6.6	–	0.3	–	3
Kenya	76.2	–	0.04	0.25	4
United Republic of Tanzania	0.52	0.05	–	–	2
Uganda	0.59	–	0.006	Detected	2
Southern Africa					
Eswatini	0.104	–	–	–	1
Malawi	2	–	–	5	1
Mozambique	0.2	–	–	–	2
South Africa	298.20	3.19	390	120	32
Zambia	0.13	–	–	–	2
Zimbabwe	6.15	–	–	–	1
Western Africa					
Burkina Faso	0.1808	–	0.384	–	1
Cameroon	0.4607	–	0.0771	0.0244	1
Côte d'Ivoire	–	–	0.062	–	1
The Gambia	–	<0.020	–	–	1
Ghana	4.02	–	–	–	2
The Niger	0.938	–	–	–	1
Nigeria	0.15	0.27	–	–	3

levels. The pesticide concentrations ranged from not detected to 76.2 μg/L, 0.035 to 0.05 μg/L, not detected to 0.3 μg/L and 0.002 to 0.250 μg/L, respectively (see Supplementary tables 1 and 2). Reported atrazine levels in all four countries exceeded the EU MRL for safe drinking water (0.1 μg/L), but the atrazine levels of two countries were still below US EPA MCL for drinking water (3 μg/L). The atrazine levels reported in Ethiopia and Kenya were 2–3 times and 25–38 times the EU EQS of (2 μg/L) and the US EPA's recommended level for surface water (3 μg/L). The levels of atrazine reported in the United Republic of Tanzania and Uganda were well below the environmental quality standards. Only one country in this region, United Republic of Tanzania, reported concentrations for glyphosate in water bodies. The reported glyphosate levels were below environmental and drinking water quality standards. Three countries in eastern Africa – Ethiopia, Kenya and Uganda – had records of imidacloprid levels in water bodies. The maximum reported concentration from Ethiopia exceeds the EU EQS (0.065 μg/L) and the EU MRL for drinking water (0.1 μg/L) for imidacloprid. Levels for metolachlor were reported for only 2 of the 15 countries in eastern Africa: Kenya and Uganda; one country reported 'detected' without specifying the concentration, while the other country's maximum reported concentration exceeded the EU MRL for drinking water (0.1 μg/L) for metolachlor by two and half times (see Table 2).

When evaluating these water quality data from SSA, it is important to keep in mind that, apart from South Africa, the number of water monitoring records for each country is extremely low (mostly one to four records per country), thus providing a limited view of water quality in each country that can result in an inaccurate perception of the true level of the contamination of water bodies in SSA.

Honey bees as a potential bioindicator species

Using honey bees (*Apis mellifera*; Hymenoptera: Apidae) for environmental monitoring is not a novel idea. Numerous studies have demonstrated the effectiveness of honey bees and their hive products as biomonitors for a range of environmental contaminants, such as heavy metals, persistent chemicals, agrochemicals, airborne particulate matter, and plant and pollinator pathogens, and even for antimicrobial resistance (reviewed in Cunningham et al.[43] and Smith et al.[44]). While foraging and collecting nectar, pollen and water, honey bees are constantly exposed to contaminants and pathogens in their environment which they carry back to the colony. At the colony, these containments and pathogens in or on the honey bees, pollen, honey or beeswax can be detected and quantified.[43] With an average foraging range of a 3 km radius[45], and a known life span and span of colony cycles, honey bees and their products provide insight into environmental contamination levels at defined spatial and temporal scales. International airports in Germany, Italy, Malta, Sweden and the Czech Republic have been running environmental monitoring programmes using honey bees to monitor air pollution levels for several years.[46-49] Some of these programmes that monitor the levels of heavy metals and polycyclic aromatic hydrocarbons around airports have been active since the late 1990s. Similarly, Italy has been using honey bees in environmental monitoring programmes to control the levels of agrochemicals in some areas since the 1980s.[50] Because honey bees are a managed pollinator

species, hives can be placed at specific locations where monitoring is required.

Honey bees are economically important pollinators that play a crucial role in both agricultural and natural ecosystems, increasing crop productivity and maintaining biodiversity.[51] Bayer Global reported that seasonal pollinators bring an annual worth of 235–577 billion US dollars in economic value to global food production.[52] Honey bees are considered eusocial insects because there are overlapping generations within a single colony, cooperative brood care and specialised castes with different tasks.[53] The two castes consist of the queen (responsible for reproduction) and the workers that are responsible for in-hive tasks and foraging. The worker bees' tasks depend on their age: newly emerged workers clean cells; 4–12-day-old workers feed the brood and younger and older adults, including the queen, and they spread her pheromones throughout the hive; 12–21-day-old workers have several tasks ranging from nest building to receiving nectar from foragers and processing it; and, lastly, workers that are 21 days and older are foragers and focus on collecting four resources (propolis, water, nectar and pollen) depending on the hive's needs.[53,54]

Honey bees require water for a variety of functions, including maintaining body fluid homeostasis, production of brood food, maintaining the humidity within the hive environment, and cooling of the hive.[55,56] A large portion of a colony's water needs are met by the nectar collected by the foragers, given that the bulk of nectar is water.[56] However, when ambient temperatures are high, honey bees use evaporative cooling to maintain a constant temperature of 35 °C in the brood area[57], which significantly increases the demand for water. The high demand stimulates water foragers to collect water and carry it back to the hive in their water impermeable crops. Upon arrival at the hive, the foragers unload this water to receiver bees that spread it around the hive or pass it on to hive mates to distribute within the hive.[58] Wing fanning is also employed not only to increase ventilation, but also to promote water evaporation. Visscher et al.[59] found that returning water foragers carry between 30 μL and 58 μL of water in their crops under arid conditions.

Increased water collection is also weather related: when the demand for brood food is high due to intensive brood rearing and nectar foraging is limited due to cool weather, nurse bees may require additional water to produce the protein-rich jelly which contains around 67% water.[60]

Surface water sources from which the foragers collect water may be contaminated with pesticides due to topical pesticide applications next to water sources or drift from such applications.[20,21] When a forager collects contaminated water, it is temporarily stored in the forager's water impermeable crop and carried back to the hive. It is therefore possible to catch returning water foragers at the entrance of the hive to analyse the water in their crops for the presence of pesticides. Detection of pesticides in the collected water could serve as an early warning sign of possible surface water contamination in the area where the hive is located. Catching returning water foragers is a well-established technique used in research studies and for which standard protocols exist.[58] Water foragers leave the hive with an almost empty crop, arriving at the water source with a minimal crop load.[59] During the flight back to the hive, the forager might regurgitate some water onto her tongue for evaporative cooling that may have a slight concentrating effect on the pesticides carried in the crop.[55] In contrast, absorption from the crop or the detoxification/breakdown of the pesticides may have a diluting effect on the amount of pesticide present in the crop that could limit the detection and/or quantification of the pesticide. Absorption from the crop is dependent on the chemical properties of the specific pesticide molecule. It is unlikely that significant amounts of pesticide are absorbed from the crop during the short period of the return flight due to the presence of the cuticular lining.[61] Nonetheless, *in vitro* studies have shown that the crop is permeable to unionised lipophilic pesticides to varying degrees.[62] The moderate to high lipophilicity of atrazine and S-metolachlor, based on their moderate to high log K_{ow} values, indicates that these pesticides have moderate to high potential to cross biological membranes[23,27], which may translate into some absorption from the crop in spite of the physical barrier formed by the cuticular lining. However, the extent of the crop's permeability to atrazine and S-metolachlor requires further investigation. Glyphosate and imidacloprid, on the other hand, are both highly water soluble[24,26] and it is unlikely that any significant amounts are absorbed from the crop, as illustrated by studies investigating the *in vivo* distribution and breakdown of imidacloprid in honey bees.[63] Suchail et al.[64] also found no evidence indicating that any breakdown or detoxification of imidacloprid takes place in the crop, which has subsequently been confirmed by other studies that found no direct evidence of detoxification of similar xenobiotics such as nicotine and acetamiprid in the crop.[65,66] However, additional studies are required to confirm these findings using a wider range of xenobiotics that exhibit a wider range of chemical properties.

Toxicity to honey bees

Apart from surface water, honey bees are exposed to pesticides through direct contact with residues on plants and through oral ingestion of pollen, nectar or guttation fluid that is contaminated due to topical pesticide application or systematic pesticides.[67] Exposure also occurs via contaminated hive products, such as the wax comb in which pesticides can persist, and through secondary routes such as dust or air particles.[67] Depending on the dose, pesticide exposure can be lethal, or it can be sublethal, affecting the cognitive function, physiology and behaviour of honey bees, which has a negative impact on the resilience and long-term survival of a colony.[67-70]

Of the four pesticides discussed in this review, the toxicity of imidacloprid to honey bees has received the most attention by far. Imidacloprid is highly toxic to honey bees, with an acute oral LD_{50} of 0.0037 μg/bee and acute contact LD_{50} of 0.081 μg/bee.[71] Ecologically relevant doses (0.02–0.30 ng/bee or 0.7–10 μg/L in nectar) generally do not have acute lethal effects[68], but these sublethal doses of imidacloprid significantly affect foraging activity and navigation, impair learning and memory, impair thermoregulation and reduce immunity, which lead to long-term colony decline (reviewed in Zhao et al.[67] and Cresswell[68]).

Glyphosate, in contrast, was first considered non-toxic or only slightly toxic to honey bees, with an acute oral LD_{50} of 100 μg/bee and acute contact LD_{50} of >100 μg/bee.[71] However, a growing number of studies have shown that glyphosate at ecologically relevant doses of 0.00013–0.0086 μg/bee can be lethal.[69] Studies that evaluated the sublethal effects of glyphosate on honey bees reported impaired development, reduction in intestinal microbiota, decreased ability to fly, decreased ability to absorb food, and impaired olfactory learning (reviewed in Battisti et al.[70]).

Atrazine is practically non-toxic to honey bees based on an acute oral LD_{50} of >100 μg/bee and acute contact LD_{50} of >100 μg/bee.[71,72] Although there are relatively few studies related to the sublethal effects of atrazine on bee physiology, there is increasing evidence that, at low doses, atrazine can negatively impact honey bee cognition[22], reduce pollen and sucrose consumption, disrupt immune system regulation[73], decrease locomotor activity, and cause detrimental changes to the midgut[74].

Metolachlor is considered non-toxic to honey bees, with an acute oral LD_{50} of >110 μg/bee and acute contact LD_{50} of >110 μg/bee.[71] Field realistic doses (around 20 ng/bee) do not cause mortality but have been shown to increase sugar syrup consumption and may alter systems regulating oxidative stress.[75] Even though metolachlor is one of the pesticides most frequently detected in hive products (pollen, honey and wax comb)[76], there is a significant lack of toxicological studies investigating the sublethal effects of metolachlor on honey bees.

Most of the studies investigating the effects of atrazine, glyphosate, metolachlor and imidacloprid on honey bees were conducted in Europe and North America. Only a handful of studies have investigated the effects of these pesticides at local ecologically relevant doses and under local conditions in SSA (see Supplementary table 2). A total of seven studies from five SSA countries evaluated survival, thermoregulation and flight efficiency after exposing honey bees to imidacloprid or glyphosate. There is a significant knowledge gap regarding the impacts of atrazine, glyphosate, metolachlor and imidacloprid on honey bees under local conditions in SSA, even though these four pesticides are widely used across SSA, as illustrated by the presence of the four pesticides in the water sources of several SSA countries (Figure 2 and Supplementary table 1). In addition, one or more of these pesticides were present in hive production, such as honey and pollen sampled from Côte d'Ivoire, Kenya, Niger, Mozambique, South Africa, Tanzania, Seychelles and Uganda,

confirming honey bees in SSA are exposed to these pesticides.[77-86] Concerningly, the number of studies investigating pesticide residues in hive products from SSA countries is also very limited.

Considering the maximum crop load of a forager (60 μL)[87] and the maximum pesticide concentrations detected in SSA water bodies (see Table 2), the pesticide dose in a single crop load of 60 μL contaminated water is well below the LD_{50} values of the four pesticides. Subsequently, it is unlikely that a single contaminated water load will cause the mortality of a forager.

Concluding remarks

Monitoring water quality is an important part of ensuring water bodies with good ambient water quality that are not detrimental to ecosystem and human health. In SSA, despite the widespread agricultural use of atrazine, glyphosate, imidacloprid and metolachlor, only 35% of countries have water quality monitoring data available that include levels of these pesticides. This figure illustrates a concerning lack of standardised and long-term water quality monitoring data in SSA, with the existing data providing a limited view of water quality in this region that could potentially lead to an inaccurate perception of the level of contamination. This in turn influences policies governing the level of regulations implemented to protect water quality across SSA and prevent its deterioration. Honey bees and beehive products are excellent indicators of environmental contamination, providing both qualitative and quantitative data. Long-term environmental monitoring programmes using managed honey bees as biomonitors have proven to be highly successful. Honey bees are easily kept and collected, relatively cheap to maintain and circumvent the use of complex sampling equipment and monitoring stations. Honey bees as biomonitors provide an ideal alternative sustainable sampling model for water bodies in remote and rural areas in SSA and could contribute to successfully implementing long-term water quality monitoring programmes.

Funding

C.W.W.P. (SRUG2204062235) and A.K. (PMDS240617228299) both received funding from the South African National Research Foundation.

Data availability

All the data supporting the results of this study are included in the article itself.

Declarations

We have no competing interests to declare. We have no AI or LLM use to declare.

Authors' contributions

A.K.: Investigation, writing – original draft, visualisation, writing – review and editing. E.E.d.R.: Formal analysis, writing – review and editing. C.W.W.P.: Conceptualisation, visualisation, writing – review and editing. All authors read and approved the final manuscript.

References

1. Nkiaka E, Bryant RG, Okumah M, Gomo FF. Water security in sub-Saharan Africa: Understanding the status of Sustainable Development Goal 6. WIREs Water. 2021;8(6), e1552. https://doi.org/10.1002/wat2.1552
2. US National Aeronautics and Space Administration. Total surface water [webpage on the Internet]. No date [cited 2026 Mar 09]. Available from: https://www.earthdata.nasa.gov/topics/terrestrial-hydrosphere/total-surface-water
3. World Economic Forum. Global risks report 2026. 21st ed. Geneva: World Economic Forum; 2026. Available from: https://www.weforum.org/publications/global-risks-report-2026
4. United Nations. Transforming our world: The 2030 agenda for sustainable development [webpage on the Internet]. c2015 [cited 2026 Mar 26]. Available from: https://sdgs.un.org/2030agenda
5. Reid K. 10 worst countries for access to clean water [webpage on the Internet]. c2024 [cited 2026 Mar 03]. Available from: https://www.worldvision.org/clean-water-news-stories/10-worst-countries-access-clean-water
6. United Nations Environment Programme. Progress on ambient water quality: Mid-term status of SDG indicator 6.3.2 and acceleration needs, with a special focus on health [webpage on the Internet]. c2024 [cited 2026 Mar 26]. Available from: https://www.unwater.org/publications/progress-ambient-water-quality-2024-update
7. Jones ER, Bierkens MF, Van Puijenbroek PJ, Van Beek LRP, Wanders N, Sutanudjaja EH, et al. Sub-Saharan Africa will increasingly become the dominant hotspot of surface water pollution. Nat Water. 2023;1(7):602–613. https://doi.org/10.1038/s44221-023-00105-5
8. Leuenberger V, Rausch J, Jaramillo D, Neururer C, Grobéty B. Heavy metal pollution from a shooting range revealed by honeybees. Environ Monit Assess. 2025;197(12), Art. #1384. https://doi.org/10.1007/s10661-025-14807-8
9. World Bank. Pathways to job creation in Africa. Africa's Pulse. 2025;32. Washington DC: World Bank; 2025. https://doi.org/10.1596/978-1-4648-2296-4
10. UN Food and Agriculture Organization (FAO). The state of food and agriculture 2020: Overcoming water challenges in agriculture. Rome: FAO; 2020. Available from: http://www.fao.org/3/cb1447en/cb1447en.pdf
11. Ansara-Ross TM, Wepener V, Van Den Brink PJ, Ross MJ. Pesticides in South African fresh waters. Afr J Aquat Sci. 2012;37(1):1–16. https://doi.org/10.2989/16085914.2012.666336
12. Curchod L, Oltramare C, Junghans M, Stamm C, Dalvie MA, Röösli M, et al. Temporal variation of pesticide mixtures in rivers of three agricultural watersheds during a major drought in the Western Cape, South Africa. Water Res X. 2020;6, Art. #100039. https://doi.org/10.1016/j.wroa.2019.100039
13. Urasa SJ, Dekker MC, Howlett WP, Mwezi RJ, Dorsey ER, Bloem BR. Parkinson's disease in sub-Saharan Africa: Pesticides as a double-edged sword. J Parkinsons Dis. 2024;14(3):437–449. https://doi.org/10.3233/JPD-230409
14. Academy of Science of South Africa (ASSAf). Neonicotinoid insecticides: Use and effects in African agriculture: A review and recommendations to policymakers. Pretoria: ASSAf; 2021. http://dx.doi.org/10.17159/assaf.2021/0069
15. Adeola A, Van Gestel CA, Doherty VF, Aneyo IA, Ajagbe F, Kasule F. Regional variations and determinants of pesticide use among farmers in southwestern Nigeria: Implications for sustainable agriculture. Front Agron. 2025;7, Art. #1503899. https://doi.org/10.3389/fagro.2025.1503899
16. Cairns JE, Chamberlin J, Rutsaert P, Voss RC, Ndhlela T, Magorokosho C. Challenges for sustainable maize production of smallholder farmers in sub-Saharan Africa. J Cereal Sci. 2021;101, Art. #103274. https://doi.org/10.1016/j.jcs.2021.103274
17. Mordor Intelligence. Maize production in Africa market size & share analysis – growth trends & forecasts (2025–2030) [webpage on the Internet]. c2025 [cited 2025 May 12]. Available from: https://www.mordorintelligence.com/industry-reports/african-maize-market
18. Van Ittersum MK, Van Bussel LG, Wolf J, Grassini P, Van Wart J, Guilpart N, et al. Can sub-Saharan Africa feed itself? Proc Natl Acad Sci USA. 2016;113(52):14964–14969. https://doi.org/10.1073/pnas.1610359113
19. Winfield® United. Crop production guide [webpage on the Internet]. c2025 [cited 2026 Apr 06]. Available from: https://portal.winfieldunited.com/getmedia/44197db4-13b2-45ea-821b-e2c11fabe990/2025-CPG-DIGITAL_Final_Secure.pdf?ext=.pdf
20. Dabrowski JM, Schulz R. Predicted and measured levels of azinphosmethyl in the Lourens River, South Africa: Comparison of runoff and spray drift. Environ Toxicol Chem. 2003;22(3):494–500. https://doi.org/10.1002/etc.5620220305
21. Polyrakis IT. Environmental pollution from pesticides. In: Costa R, Kristbergsson K, editors. Predictive modeling and risk assessment. Boston, MA: Springer US; 2009. p. 201–224. https://doi.org/10.1007/978-0-387-68776-6_11
22. Hu X, Xu Z, Xu J, Ma G, Pan Y, Cai M, et al. Impact of atrazine on sucrose sensitivity in honey bees. Insects. 2025;16(5), Art. #491. https://doi.org/10.3390/insects16050491
23. US National Center for Biotechnology Information. PubChem compound summary for CID 2256, atrazine. PubChem [webpage on the Internet]. No date [cited 2026 Apr 10]. Available from: https://pubchem.ncbi.nlm.nih.gov/compound/Atrazine

24. US National Center for Biotechnology Information. PubChem compound summary for CID 3496, glyphosate. PubChem [webpage on the Internet]. No date [cited 2026 Apr 10]. Available from: https://pubchem.ncbi.nlm.nih.gov/compound/Glyphosate

25. Gervais JA, Luukinen B, Buhl K, Stone D. Imidacloprid technical fact sheet. National Pesticide Information Center, Oregon State University Extension Services [webpage on the Internet]. c2010 [cited 2025 May 19]. Available from: https://npic.orst.edu/factsheets/archive/imidacloprid.html

26. US National Center for Biotechnology Information. PubChem compound summary for CID 86287518, imidacloprid. PubChem [webpage on the Internet]. No date [cited 2026 Apr 10]. Available from: https://pubchem.ncbi.nlm.nih.gov/compound/Imidacloprid

27. US National Center for Biotechnology Information. PubChem compound summary for CID 16760143, (S)-metolachlor ESA. PubChem [webpage on the Internet]. No date [cited 2026 Apr 10]. Available from: https://pubchem.ncbi.nlm.nih.gov/compound/S_-metolachlor-ESA

28. Rivard L, Branch EM. Environmental fate of metolachlor. Chem. 2003; 51218(45), Art. #42.

29. Du Preez LH, Van Rensburg PJ, Jooste AM, Carr JA, Giesy JP, Gross TS, et al. Seasonal exposures to triazine and other pesticides in surface waters in the western Highveld corn-production region in South Africa. Environ Pollut. 2005;135(1):131–141. https://doi.org/10.1016/j.envpol.2004.09.019

30. PAN International. Consolidated list of banned pesticides [webpage on the Internet]. c2024 [cited 2026 Mar 19]. Available from: https://pan-international.org/pan-international-consolidated-list-of-banned-pesticides/

31. Cattley RC, De Roos AJ, Mandrioli D, Pearce N, Pronk A, Soshilov A, et al. Carcinogenicity of atrazine, alachlor, and vinclozolin. Lancet Oncol. 2026; 27(1):11–12. https://doi.org/10.1016/s1470-2045(25)00702-8

32. Kabler AK, Chen S. Determination of the 1'S and 1'R diastereomers of metolachlor and S-metolachlor in water by chiral liquid chromatography–mass spectrometry/mass spectrometry (LC/MS/MS). J Agric Food Chem. 2006;54(17):6153–6158. https://doi.org/10.1021/jf061186+

33. European Commission, Directorate-General for Health and Food Safety. Commission implementing regulation (EU) 2024/20 of 12 December 2023 concerningthenon-renewaloftheapprovaloftheactivesubstanceS-metolachlor, in accordance with Regulation (EC) No 1107/2009 of the European Parliament and of the Council, and amending Commission implementing regulation (EU) No 540/2011. OJ L, 2024/20, 3.1.2024. c2024 [cited 2026 Apr 20]. Available from: http://data.europa.eu/eli/reg_impl/2024/20/oj

34. European Commission, Directorate-General for Health and Food Safety. Neonicotinoids [webpage on the Internet]. No date [cited 2026 Mar 12]. Available from: https://food.ec.europa.eu/plants/pesticides/approval-active-substances-safeners-and-synergists/renewal-approval/neonicotinoids_en

35. Global Market Insights. Neonicotinoid pesticide market opportunity, growth drivers, industry trend analysis, and forecast 2025–2034 [webpage on the Internet]. c2025 [cited 2026 Apr 04]. Available from: https://www.giiresearch.com/report/gmi1716589-neonicotinoid-pesticide-market-opportunity-growth.html

36. European Union. Environmental quality standards for priority substances and certain other pollutants [webpage on the Internet]. c2013 [cited 2025 May 19]. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02008L0105-20130913

37. United States Environmental Protection Agency. Atrazine [webpage on the Internet]. No date [updated 2025 Oct 07; cited 2026 Mar 18]. Available from: https://www.epa.gov/ingredients-used-pesticide-products/atrazine

38. European Union. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy (OJ L 327, 22.12.2000). c2000 [cited 2026 Apr 20]. Available from: http://data.europa.eu/eli/dir/2000/60/oj

39. South African National Standards 241-1. Drinking water. Part 1: Microbiological, physical, aesthetic, and chemical determinants. 2nd ed. Pretoria: SABS; 2015.

40. European Commission. Proposal for a directive of the European Parliament and of the Council amending directive 2000/60/EC establishing a framework for community action in the field of water policy, directive 2006/118/EC on the protection of groundwater against pollution and deterioration and directive 2008/105/EC on environmental quality standards in the field of water policy (COM(2022) 540 final; 2022/0344 (COD)). c2022 [cited 2026 Apr 20]. https://eur-lex.europa.eu/procedure/EN/2022_344

41. United States Environmental Protection Agency. Glyphosate [webpage on the Internet]. No date [cited 2026 Mar 18]. Available from: https://www.epa.gov/ingredients-used-pesticide-products/glyphosate

42. Scientific Committee on Health, Environmental and Emerging Risks. Scientific opinion on "draft environmental quality standards for priority substances under the water framework directive." Scientific Committee; 2021. Available from: https://health.ec.europa.eu/system/files/2022-08/scheer_o_021.pdf

43. Cunningham MM, Tran L, McKee CG, Ortega Polo R, Newman T, Lansing L, et al. Honey bees as biomonitors of environmental contaminants, pathogens, and climate change. Ecol Indic. 2022;134, Art. #108457. https://doi.org/10.1016/j.ecolind.2021.108457

44. Smith KE, Weis D, Amini M, Shiel AE, Lai VWM, Gordon K. Honey as a biomonitor for a changing world. Nat Sustain. 2019;2(3):223–232. https://doi.org/10.1038/s41893-019-0243-0

45. Badiou-Bénéteau A, Benneveau A, Géret F, Delatte H, Becker N, Brunet JL, et al. Honeybee biomarkers as promising tools to monitor environmental quality. Environ Int. 2013;60:31–41. https://doi.org/10.1016/j.envint.2013.07.002

46. Malta Today. Malta airport monitors air quality with 750,000 bees in airfield apiary [webpage on the Internet]. c2021 [cited 2026 Mar 27]. Available from: https://www.maltatoday.com.mt/environment/nature/109736/malta_airport_monitors_air_quality_with_750000_bees_in_airfield_apiary

47. Edwards L. Bees helping to monitor air quality at German airports [webpage on the Internet]. c2010 [cited 2026 Mar 27]. Available from: https://phys.org/news/2010-07-bees-air-quality-german-airports.html

48. Aeroporto di Bologna. Air quality biomonitoring [webpage on the Internet]. c2026 [cited 2026 Mar 26]. Available from: https://www.bologna-airport.it/en/innovation-and-sustainability/sustainability/sustainability-plan/air-quality-biomonitoring/?idC=62803

49. Munich Airport. Honey monitoring [webpage on the Internet]. c2026 [cited 2026 Mar 26]. Available from: https://www.munich-airport.com/honey-monitoring-264528

50. Porrini C, Ghini S, Girotti S. Use of honey bees as bioindicators of environmental pollution in Italy. In: Devillers J, Pham-Delegue M, editors. Honey bees: Estimating the environmental impact of chemicals. London: CRC Press; 2002. p. 186–247. https://doi.org/10.1201/9780203218655-14

51. Gizaw G, Kim Y, Moon K, Choi JB, Kim YH, Park JK. Effect of environmental heavy metals on the expression of detoxification-related genes in honey bee *Apis mellifera*. Apidologie. 2020;51:664–674. https://doi.org/10.1007/s13592-020-00751-8

52. Bayer Global. The value of pollinators to the ecosystem and our economy [webpage on the Internet]. c2025 [cited 2026 Apr 06]. Available from: https://www.bayer.com/en/agriculture/article/economic-value-pollinators

53. Pernal SF. The social life of honey bees. Vet Clin North Am Food Anim Pract. 2021;37(3):387–400. https://doi.org/10.1016/j.cvfa.2021.06.012

54. Johnson BR. Division of labor in honeybees: Form, function, and proximate mechanisms. Behav Ecol Sociobiol. 2010;64(3):305–316. https://doi.org/10.1007/s00265-009-0874-7

55. Nicolson SW. Water homeostasis in bees, with the emphasis on sociality. J Exp Biol. 2009;212(3):429–434. https://doi.org/10.1242/jeb.022343

56. Ostwald MM, Smith ML, Seeley TD. The behavioral regulation of thirst, water collection and water storage in honey bee colonies. J Exp Biol. 2016;219(14):2156–2165. https://doi.org/10.1242/jeb.139824

57. Human H, Nicolson SW, Dietemann V. Do honeybees, *Apis mellifera scutellata*, regulate humidity in their nest? Sci Nat. 2006;93(8):397–401. https://doi.org/10.1007/s00114-006-0117-y

58. Kühnholz S, Seeley TD. The control of water collection in honey bee colonies. Behav Ecol Sociobiol. 1997;41(6):407–422. https://doi.org/10.1007/s002650050402

59. Visscher PK, Crailsheim K, Sherman G. How do honey bees (*Apis mellifera*) fuel their water foraging flights? J Insect Physiol. 1996;42(11–12):1089–1094. https://doi.org/10.1016/s0022-1910(96)00058-3

60. Wongchai V, Ratanavalachai T. Seasonal variation of chemical composition of royal jelly produced in Thailand. Sci Technol Asia. 2015;7(2):1–8.

61. Crailsheim K. Regulation of food passage in the intestine of the honeybee (*Apis mellifera* L.). J Insect Physiol. 1988;34(2):85–90. https://doi.org/10.1016/0022-1910(88)90158-8

62. Conner WE, Wilkinson CF, Morse RA. Penetration of insecticides through the foregut of the honeybee (*Apis mellifera* L.). Pestic Biochem Physiol. 1978;9(2):131–139. https://doi.org/10.1016/0048-3575(78)90073-1

63. Suchail S, De Sousa G, Rahmani R, Belzunces LP. *In vivo* distribution and metabolisation of 14C-imidacloprid in different compartments of *Apis mellifera* L. Pest Manag Sci. 2004;60(11):1056–1062. https://doi.org/10.1002/ps.895

64. Suchail S, Debrauwer L, Belzunces LP. Metabolism of imidacloprid in *Apis mellifera*. Pest Manag Sci. 2004;60:291–296. https://doi.org/10.1002/ps.772

65. Du Rand EE, Pirk CW, Nicolson SW, Apostolides Z. The metabolic fate of nectar nicotine in worker honey bees. J Insect Physiol. 2017;98:14–22. https://doi.org/10.1016/j.jinsphys.2016.10.017

66. Brunet JL, Badiou A, Belzunces LP. In vivo metabolic fate of [14C]-acetamiprid in six biological compartments of the honeybee, *Apis mellifera* L. Pest Manag Sci. 2005;61(8):742–748. https://doi.org/10.1002/ps.1046

67. Zhao H, Li G, Cui X, Wang H, Liu Z, Yang Y, et al. Review on effects of some insecticides on honey bee health. Pestic Biochem Physiol. 2022;188, Art. #105219. https://doi.org/10.1016/j.pestbp.2022.105219

68. Cresswell J. A meta-analysis of experiments testing the effects of a neonicotinoid insecticide (imidacloprid) on honey bees. Ecotoxicology. 2011;20(1):149–157. https://doi.org/10.1007/s10646-010-0566-0

69. Battisti L, Potrich M, Sampaio AR, De Castilhos Ghisi N, Costa-Maia FM, Abati R, et al. Is glyphosate toxic to bees? A meta-analytical review. Sci Total Environ. 2021;767, Art. #145397. https://doi.org/10.1016/j.scitotenv.2021.145397

70. Battisti L, Potrich M, Lozano ER, Dos Reis Martinez CB, Sofia SH. Review on the sublethal effects of pure and formulated glyphosate on bees: Emphasis on social bees. J Appl Entomol. 2023;147(1):1–18. https://doi.org/10.1111/jen.13089

71. Pesticides Properties Database. A to Z list of pesticide active ingredients [webpage on the Internet]. c2006 [cited 2026 Apr 11]. Available from: http://sitem.herts.ac.uk/aeru/ppdb/en/atoz.htm

72. Fellows CJ, Anderson TD, Swale DR. Acute toxicity of atrazine, alachlor, and chlorpyrifos mixtures to honey bees. Pestic Biochem Physiol. 2022;188, Art. #105271. https://doi.org/10.1016/j.pestbp.2022.105271

73. Wang K, Cai M, Sun J, Chen H, Lin Z, Wang Z, et al. Atrazine exposure can dysregulate the immune system and increase the susceptibility against pathogens in honeybees in a dose-dependent manner. J Hazard Mater. 2023;452, Art. 131179. https://doi.org/10.1016/j.jhazmat.2023.131179

74. Dos Santos Araújo R, Viana TA, Botina LL, Bastos DSS, Da Silva Alves BC, Machado-Neves M, et al. Investigating the effects of mesotrione/atrazine-based herbicide on honey bee foragers. Sci Total Environ. 2023;898, Art. #165526. https://doi.org/10.1016/j.scitotenv.2023.165526

75. Helmer SH, Kerbaol A, Aras P, Jumarie C, Boily M. Effects of realistic doses of atrazine, metolachlor, and glyphosate on lipid peroxidation and diet-derived antioxidants in caged honey bees (*Apis mellifera*). Environ Sci Pollut Res. 2015;22(11):8010–8021. https://doi.org/10.1007/s11356-014-2879-7

76. Glinski DA, Purucker ST, Minucci JM, Richardson RT, Lin CH, Johnson RM, et al. Analysis of contaminant residues in honey bee hive matrices. Sci Total Environ. 2024;954, Art. #176329. https://doi.org/10.1016/j.scitotenv.2024.176329

77. Mitchell EA, Mulhauser B, Mulot M, Mutabazi A, Glauser G, Aebi A. A worldwide survey of neonicotinoids in honey. Science. 2017;358(6359):109–111. https://doi.org/10.1126/science.aan3684

78. Adeyinka GC, Mketo N. Occurrence and human health risk assessment of neonicotinoid residues and essential and non-essential metals in commercial honey obtained from stores in South Africa. Microchem J. 2025;219, Art. #115864. https://doi.org/10.1016/j.microc.2025.115864

79. Abafe O, Chokwe T. Determination and dietary risk assessment of neonicotinoid and insect growth regulators in honey. J Environ Expos Assess. 2022;1(1), Art. #3. https://doi.org/10.20517/jeea.2021.04

80. Ohoueu EJ, Iritie B, Eboua W, Elleingand E, Dembele A. Contamination of bee products by pesticides in Cote D'Ivoire. IMPACT: International Journal of Research in Applied. 2017;5:99–110.

81. Irungu J, Fombong AT, Kurgat J, Mulati P, Ongus J, Nkoba K, et al. Analysis of honey bee hive products as a model for monitoring pesticide usage in agroecosystems. J Environ Earth Sci. 2016;6(8):9–16.

82. Mulati P, Kitur E, Taracha C, Kurgat J, Raina S, Irungu J. Evaluation of neonicotinoid residues in hive products from selected counties in Kenya. J Environ Anal Toxicol. 2018;8(4), Art. #1000577. https://doi.org/10.4172/2161-0525.1000577

83. Lekduhur GJ, Onuwa PO, Eneji IS, Rufus SA. Analysis of selected pesticide residues and heavy metals in honey obtained from Plateau State, Nigeria. J Anal Sci Methods Instrum. 2021;11(1):1–13. https://doi.org/10.4236/jasmi.2021.111001

84. Dowell BF, Abadi GS, Daniel MW, Micah MM. Analysis of some physicochemical properties and dietary risks assessment of pesticide residues of local honey in Adamawa State, Nigeria. J Pharm Drug Dev. 2023;2(1). https://doi.org/10.58489/2836-2322/023

85. Muli E, Kilonzo J, Dogley N, Monthy G, Kurgat J, Irungu J, et al. Detection of pesticide residues in selected bee products of honeybees (*Apis mellifera* L.) colonies in a preliminary study from Seychelles archipelago. Bull Environ Contam Toxicol. 2018;101:451–457. https://doi.org/10.1007/s00128-018-2423-4

86. Amulen DR, Spanoghe P, Houbraken M, Tamale A, De Graaf DC, Cross P, et al. Environmental contaminants of honeybee products in Uganda detected using LC-MS/MS and GC-ECD. PLoS One. 2017;12(6), e0178546. https://doi.org/10.1371/journal.pone.0178546

87. Bourdon S, Mouillard-Lample L, Lemoine T, Lewin M, Guilbaud L, Barascou L, et al. How much nectar can wild bees carry? Allometric equations of nectar crop capacities for investigating bee nutrition and foraging ecology. J Insect Physiol. 2025;164, Art. #104840. https://doi.org/10.1016/j.jinsphys.2025.104840