A Systematic Review on Pesticide Residue Contamination of Groundwater Coupled with Human Health Risk Assessment in Africa

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Abstract

Background: Worldwide, agriculture has become dependent on the use of pesticides to boost production and meet the demand for farm products. However, pesticide use has raised concerns about their potential harm to both ecological and human health. Prompted by this concern, a systematic literature review was conducted to assess the magnitude of pesticide residue pollution of groundwater sources, coupled with health risk assessment, in Africa.

Methods: A thorough search using the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) format across multiple databases, including Science Direct, PubMed, and Google Scholar. Studies collected current data on groundwater pesticide residue contamination and human health risks between 2018 and September 2022.

Results: Four articles distributed at four study sites in three countries were identified. Pesticide residues were distributed as 53.2% organochlorines, 21.3% organophosphates, 17.0% pyrethroids, 4.3% carbamates, and 4.3% triazines from agricultural farms. Banned organochlorines pose both carcinogenic and non-carcinogenic risks to humans, thus indicating a public health concern. Research gaps were observed in investigating herbicides and fungicides and the absence of pesticide limits in national water quality guidelines.

Conclusion: The study concluded that banned organochlorine residues deteriorate groundwater quality and pose human health risks via ingestion. Therefore, there is a need for future research efforts to continue monitoring while prioritizing evaluating a wide range of pesticide residues and developing national standards for context-specific thresholds. Ultimately, sustainable agriculture is promoted, and sustainable development goals are met.

Keywords: Pesticide residues; ground drinking water; health risks; public health; Africa; toxicology

Introduction

Groundwater is a valuable natural resource crucial in sustaining life on Earth. The water is used for drinking, watering crops in agriculture, industrial processes, and maintaining ecosystems (Gowing et al., 2020). Furthermore, in African urban areas, groundwater helps

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meet the demands of growing populations (Twinomucunguzi et al., 2021). Despite its importance, groundwater is susceptible to contamination from various sources, including pesticide residues and human activities (Chaza et al., 2018). Pesticides, commonly used in agricultural practices, can leach into the soil and eventually reach groundwater reserves (Syafrudin et al., 2021). This contamination poses a significant risk to the water supply's quality and safety. Exposure to pesticide-contaminated groundwater can have adverse effects on human health, including increased risk of chronic diseases, developmental issues, and reproductive problems (Biosca-Brull et al., 2021; Panis et al., 2022; Pathak et al., 2022). The contamination of groundwater threatens human health, disrupts ecosystems, and affects the overall balance of the environment (Ganaie et al., 2023). Worth noting is that within most African countries, rural areas have no water distribution networks; hence, underground water is used as one of the main sources of drinking water (Masindi & Foteinis, 2021). Therefore, rural communities would face significant challenges in meeting their basic needs and sustaining their livelihoods without reliable groundwater sources.

Groundwater pollution is a severe public health problem in sub-Saharan Africa (Lopes-Ferreira et al., 2022; Röösli et al., 2022). Groundwater quality has recently been endangered by many factors, including natural and anthropogenic activities, which have caused severe deterioration and considerable threats to public health (Affum et al., 2018). Poor agricultural activities have caused widespread pesticide residue groundwater pollution in sub-Saharan Africa. Consequently, pesticide traces have been reported in the groundwater sources (Basopo & Muzvidziwa, 2020; Chow et al., 2023; Lapworth et al., 2017; Masindi & Foteinis, 2021; Ouedraogo & Vanclooster, 2021; Sishu et al., 2022).

While pesticide residues have been quantified in surface waters worldwide, few research studies have focused on groundwater detection and health risk assessment via oral ingestion in sub-Saharan African countries (Ohlander et al., 2020). Most research studies have focused on pollution by pesticides of environmental matrixes, including freshwater (Curchod et al., 2020; Horak et al., 2021; Twinomucunguzi et al., 2021); health risk due to dietary exposure (Illyassou & Schiffers, 2018; Wanjiku et al., 2022; Wumbei et al., 2019); on expertise, manner, and practice of users (Agmas & Adugna, 2020; Endalew et al., 2022; Mequanint et al., 2019); health risks due to occupational exposure for farmers and farmworkers (Afata et al., 2022); and susceptible groups, such as adult females and children (Fuhrimann et al., 2022). Therefore, a context-specific summary of outcomes across research studies from groundwater consumption and health risk is often absent.

This paper, therefore, provides an overview of current research on pesticide residues contaminating groundwater sources and human health risk assessment in the exposed population, as well as pointing out research progress and gaps in Africa. Therefore, a systematic literature review was conducted to find studies that gathered primary data on pesticide residue incidence in groundwater used for human consumption, health risk models used and risk categories in Africa. The following are the research questions: 1. What pesticide residues are detected in groundwater in sub-Saharan Africa? 2. How are the populations at risk exposed? 3. Which analysis methods are used to detect health risks? 4. What types of risks were studied? 5. Which population groups were studied? and 6. Which water guidelines were referenced?

Literature Review

In numerous sections of sub-Saharan Africa, there is constant and accelerated expansion of both urban and peri-urban settlements, thereby increasing demand for groundwater (Twinomucunguzi et al., 2021). In rural areas, groundwater is equally significant, if not more so. Apart from domestic uses, agriculture heavily relies on groundwater for irrigation, ensuring crop growth and productivity (Tudi et al., 2021). While groundwater is considered the most resilient source of drinking water across many sub-Saharan African countries, poor agricultural practices have contributed to the contamination of the groundwater sources by pesticide residues (Basopo & Muzvidziwa, 2020; Masindi & Foteinis, 2021; Sishu et al., 2022).

Crop cultivation not only helps to provide food for the increasing population (El-Nahhal & El-Nahhal, 2021; Gowing et al., 2020; Olisah et al., 2020), but also contributes to the achievement of certain sustainable development goals outlined by the United Nations (FAO, 2018). Approximately 3 million tons of agro pesticides, primarily herbicides, insecticides and fungicides, are utilized annually to improve agricultural output (Xu et al., 2018). Cultivation practice often entails an intensive and improper use of pesticides and fertilizers (Olisah et al., 2020). The pesticides are used by commercial farmers, but the smallholder farmer is not left out. Even though pesticide treatment is essential to achieve high and quality yields of products, its use has caused food and water contamination, incessant ecological damage (Olisah et al., 2020), and human health risks (Affum et al., 2018; Lehmann et al., 2017). Following application, over 95% of the pesticides sprayed are carried into environments other than the intended target (Tang et al., 2021). Gwimbi & Mundoga (2010), also asserted that pesticide application has been identified as one possible source of groundwater pollution, especially unprotected groundwater sources.

Contamination of ground drinking water with pesticide residues raises concerns over human exposure via daily water intake (El-Nahhal & El-Nahhal, 2021). As a result, prolonged exposure to these pesticides can adversely affect human health when ingested, inhaled, or encounter on the skin (Oyekunle et al., 2022). Given that context, Siviter et al. (2021), emphasized that exposure to pesticide residues in assortments can act cumulatively or synergistically.

Pollution of ground drinking water with pesticide residues has functional implications by imitating biological chemicals or intervening with their metabolic pathways (Lauretta et al., 2019). Pesticide residues such as insecticides, herbicides, and fungicides are the most problematic chemicals because they mimic hormones thereby leading to the causation of numerous non-communicable diseases such as low sperm count, diabetes, autism, and birth defects. In contrast, organochlorines are assumed carcinogens, which could harm vital organs (Gonsioroski et al., 2020). Furthermore, Stradtman and Freeman (2021), posited that the herbicide atrazine is an endocrine-disrupting compound, reproductive poison, and a neurotoxicant that impacts neurotransmission in humans.

As a result of human health risks due to pesticide residue exposure, water quality monitoring is imperative. Sjerps et al. (2019) argued that regularly monitoring groundwater quality, including pesticide residue levels, is crucial to identifying contamination early on. Furthermore, establishing monitoring programs and timely reporting of results ensure appropriate action, such as issuing advisories or implementing treatment measures (Ahmed et al., 2020; Altenburger et al., 2019; Demetillo et al., 2019).

Coupled with water quality monitoring, pesticide residues in groundwater sources adhere to a nation's water quality standards by meeting health-based limits. Such standards are, however, not available in most African countries. Such an irregularity was reflected in a review conducted by Li and Jennings (2017), which reported only ten countries in Africa including the East Africa Community, Egypt, Ethiopia, Morocco, Rwanda, South Africa, Sudan, Tanzania, Tunisia, and Uganda having regulatory specifications for some pesticide residues in water. Of the ten countries, four have only one pesticide listed in the national guidelines for water quality for drinking purposes. For example, the Republic of South Africa has only one pesticide, atrazine, listed in its drinking water guidelines (London et al., 2005; Department of Water Affairs and Forestry, 1996). Therefore, most African countries depend on the standards set by the World Health Organization (WHO, 2017) and water quality criteria provided in the European Union (EU) Water Framework Directive 2000/60/EC and EU Council Directive 98/83/EC (The European Parliament and the Council of the European Union, 2000).

The concentration of pesticide residues in groundwater obtained through monitoring is then used to calculate the levels of human exposure. Exposure to pesticide residues, even at minimal concentrations, causes a profound threat to human health (Ghasemnejad-Berenji et al., 2021). Several studies worldwide (Affum et al., 2018; Derbalah et al., 2019; Li, 2022; Zhai et al., 2017), employ hazard quotient approaches to estimate pesticide harm. Chronic pesticide residues exposure over a long period can have negative consequences and provide non-carcinogenic risks to humans (Huang et al., 2019), which can be more severe in vulnerable groups including the elderly, children, and infants (Dórea, 2021; Liu et al., 2015; Suwannakul et al., 2021).

Methodology

Search Strategy

A systematic literature review search was undertaken to produce a summary of research studies reporting on pesticide residues contaminating groundwater and the health risk of such in any of the countries located in Africa within the past 5 years (from January 2018 to 15 September 2022).

The evaluation took place following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009). Original research papers were investigated in the PubMed, Science Direct and Google Scholar archives without language restrictions. The search included different search terms for pesticides such as (pesticide residues, herbicide*, organochlorine, organophosphate, carbamate) African countries (names listed), groundwater, and risk assessment. Lastly, studies were excluded if they were exclusively on human health risk due to heavy metal exposure and fluorine, thereby reducing the number of titles to 1943. The complete search syntax is available in the supplementary materials.

Article Selection

Selecting articles for inclusion in the study involved screening titles and abstracts and conducting a full-text review. Peer-reviewed primary studies on pesticide residues in groundwater and human health risk assessment were included. Studies that were excluded comprised those from outside of Africa, reviews, described dietary risks, ecotoxicological risks and any other risk not due to pesticide residues in groundwater (e.g., Phthalate esters, bisphenol, and pharmaceutical products). The articles that were included underwent a screening process to determine eligibility. All selected articles were stored in Mendeley Reference Manager.

Data Extraction

The data presented here were gathered from all the studies that were identified:

Pesticide residues detected:

- Pesticide residues investigated in groundwater in each country, including degradation products detected (metabolites)

Human exposure pathways

- Ingestion or dermal contact

Health risk analysis techniques used:

- Regression models were used to assess exposure outcomes for example, descriptive reporting of outcomes or use of risk models.

At-risk population groups studied:

- Population age groups (i.e., infants, children, and adults)

Risk type studied:

- Cancer risk or non-carcinogenic risk

Water quality Guidelines referenced:

- National water quality guidelines, WHO guidelines or the European Union.

Analysis

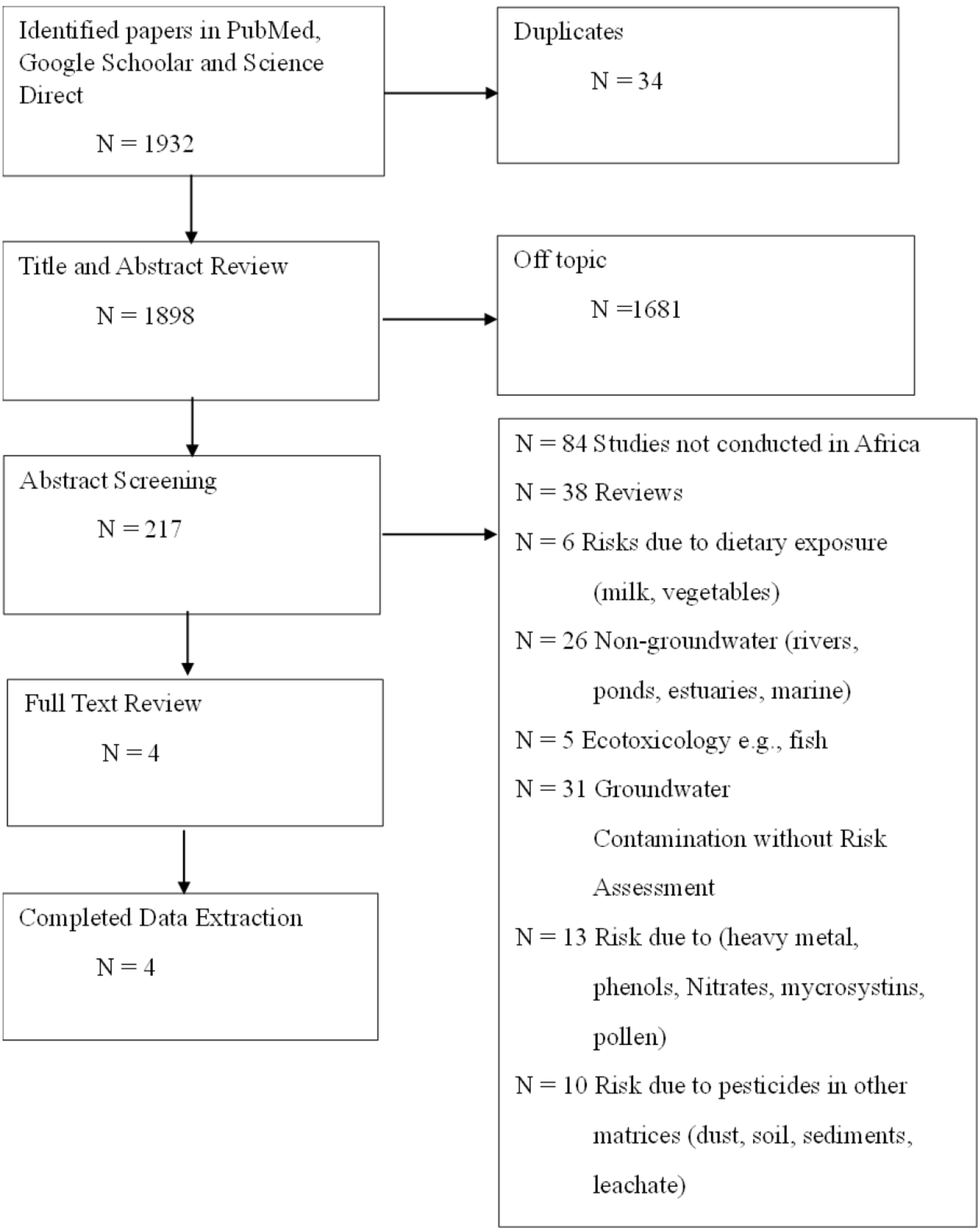
Gathered data was entered into a Microsoft Excel spreadsheet and analyzed using descriptive statistics, with the data and information presented in tables and graphs showing percentages, counts, or frequencies. To precisely identify the detected pesticide residues in groundwater, bar graphs were created showing the number and types of pesticide residues detected in groundwater in each nation where the study was carried out. Frequency tables were used to indicate the models and risk type studied.

Search Results

Figure 1 illustrates the process of conducting a literature review, including identifying relevant research articles and extracting data from them. The review in PubMed, Science Direct and Google Scholar yielded 1932 articles. Out of the total, thirty-four were found to be duplicates, allowing 1898 for title and abstract screening. The screening of titles and abstracts discarded 1681 research papers that were off-topic. Articles subjected to detailed review were 217. Out of this number, 213 articles were selected for a comprehensive review of their full texts. Research articles not selected in the review were grouped into the following groupings: studies not conducted in Africa (84), reviews on pesticide residues (38), dietary health risks (vegetables, milk, etc.) (6), non-groundwater sampled (river, dams, estuaries, etc.) (26), ecotoxicological risk e.g. fish (5), health risk due to other chemicals (heavy metals, phenols, nitrates, mycrocystins and pollen) (13), risk due to pesticides in other matrices (dust, soil, leachate, sediments) (10), and groundwater contamination without risk assessment (31). Ultimately, four papers met the inclusion criteria from which data was extracted.

Figure 1

Flowchart Depicting the Literature Review Process, Paper Identification and Data Extraction from Selected Research Articles.



Pesticide Residues Detected in Groundwater

Contamination of groundwater by pesticide residues in Africa was reviewed. As a result, one of the four research studies (25%) exclusively included an evaluation of organochlorine pesticide residues in groundwater. Different pesticide residues including organochlorines, organophosphates, pyrethroids and more, were investigated in 2 (50%) studies.

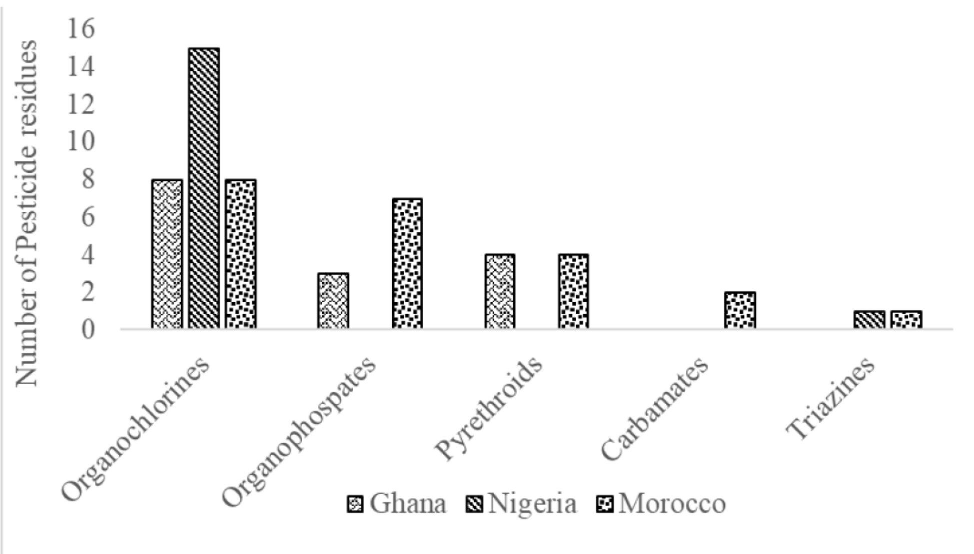
Common pesticide residues assessed in the three studies that measured organochlorine pesticide residues were dichlorodiphenyltrichloroethane (DDT), lindane, and its isomers. One article (25%) focused exclusively on triazine. Furthermore, organophosphates were the second dominant pesticide residue detected in the groundwater, up to 21.8%. Pyrethroids constituted 17.0% thus not so prevalent, carbamates were 4.3% and triazines 4.3%.

Figure 2 shows the number of pesticide residues investigated in each study and the countries where the studies were undertaken. The one (25%) study which concentrated on the investigation of organochlorines only also focused on the DDT and its metabolites, dichlorodiphenylethane (DDE) and dichlorodiphenyldichloroethane (DDD).

The results summarized in this review indicate that organochlorines (OCPs) were the most commonly found pesticide residues in groundwater samples taken from the African environment, reaching 53.2% (Figure 3). The African countries from which the organochlorines were analyzed include Ghana, Morocco, and Nigeria.

Figure 1

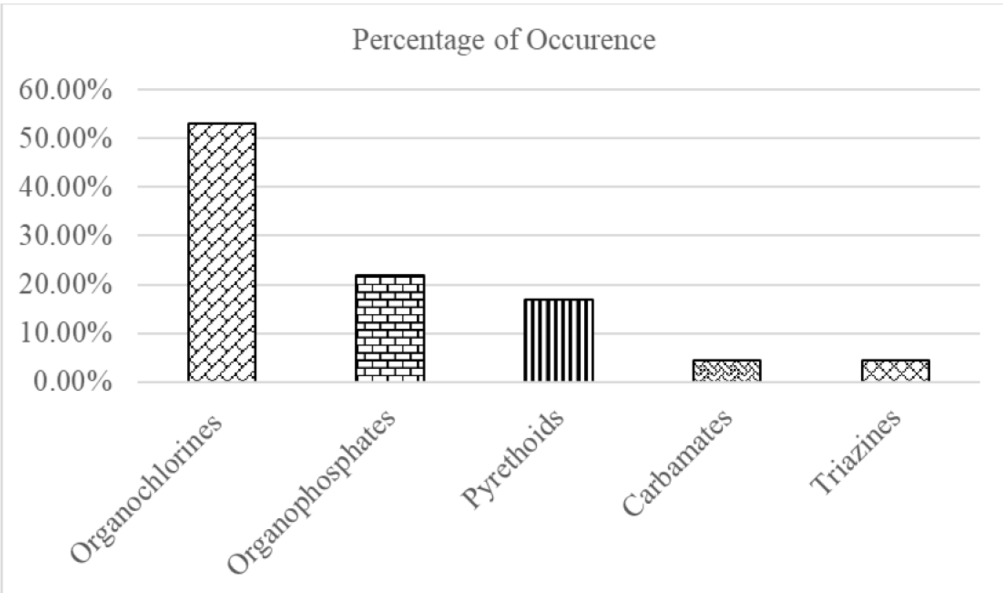
Number of Pesticide Residues Studied in Each Country.



In some cases, the concentrations of OCPs in the samples exceeded maximum residue levels (MRLs) of 0.02 ng/L) recommended by the European Union. Groundwater samples of Ile-Ife, Osun State, Nigeria reported dominant concentrations of heptachlor (14.60 μg/L) and methoxychlor (12.60 μg/L).

Figure 2

Percentage Incidence of Pesticides in Groundwater Resources from Locations in Africa.



Exposure Pathways

Ingestion and dermal exposure pathways were investigated in the reviewed studies. Ingestion exposure was singly examined in 3(75%) studies. To reflect the reality of health risks more objectively, dermal contact pathways and ingestion were considered in 1(25%) of the reviewed articles for adults and children.

Health Risk Analysis Techniques Used

Human health risk assessment plays a significant role in calculating the probability of adverse health risks from pesticide residues exposure in humans, thereby defining allowable bounds for contact (World Health Organization, 2021). Health risk analysis may be achieved using either of two approaches including deterministic and probabilistic approaches (Olisah et al., 2020). In this regard, all reviewed studies 4 (100 %) assessed human health risks posed by the pesticide residues detected in groundwater using the deterministic approach.

Human Population Groups at Risk

Humans of every age can be exposed to pesticide residues in groundwater through oral and dermal exposure. Therefore, to assess health risks in the published articles reviewed, the human receptors considered were divided into three population age groups: infants, children, and adults. Among the studies, 2(50 %) included children and adults while the other half 2(50%) investigated health risks in three age groups: adults, children, and infants.

Health Risks Measured

Health impacts investigated in these studies aimed at the effects of chronic exposure to the pesticide residues detected in the groundwater. Pesticide residues detected in the groundwater were assessed for both cancer and non-carcinogenic risks. All studies 4 (100 %) investigated both non-carcinogenic and cancer risks posed by the pesticide residues detected in groundwater. All studies articulated the Non-carcinogenic risk level as hazard quotient (HQ). The HQ value justifies the degree of non-carcinogenic risk in view of the day-to-day ingestion dose compared to the reference dose of target pesticide residue as described by WHO (2021). In adults, HQ values greater than 1 through ingestion emanated from 8 (17%) (Table 1) of the studied pesticide residues in Nigeria, Ile-Ife, and Osun State. HQs greater than 1 in children were also observed at the same locality due to 9(19, 2%) of the pesticide residues.

Table 1

Number of Pesticide Residues with Carcinogenic and Non-carcinogenic risk

	Adults	Children	Infants	Author & Country
Non-carcinogenic risk	8 (17 %)	8 (17 %)		Oyekunle et al., (2022) Nigeria
Carcinogenic risk	8 (17 %)	8 (17 %)		Oyekunle et al., (2022) Nigeria
		4 (8.5 %)	4 (8.5 %)	Berni et al. (2021) Morocco

Water Guidelines

Among the studies, half 2(50%) referred to the European Union (EU) directive 2013/39/EC only, while 1(25%) referred to both the EU directive 2013/39/EC and the World Health Organization. One (25%) study stated both Canadian Drinking Water Quality guidelines and the United States Environmental Protection Agency.

Discussion

The review considered the types of pesticide residues that contaminate groundwater, pathways through which humans are exposed, techniques for health risk determination and the water guidelines referenced in each study.

In line with the reported observations, underground water samples from Ile-Ife, Osun State, Nigeria were determined to be the most polluted from the reviewed articles due to the detected concentrations of organochlorines (OCPs) that exceeded the maximum residue limit (MRLs) of 0.03 µg/L for drinking water. Occurrence of these pesticide residues in the water was attributed to agricultural overflow, spray drift from pesticide application on crops, and inattentive disposal of pesticide containers (Berni et al., 2021; Sjerps et al., 2019). The two articles that reported groundwater contamination by organochlorines and other pesticide residues described concentration levels below the MRL. However, most of the studied OCPs included those that were globally banned, suggestive of either historical application of the pollutants for an extended period (Afata et al., 2022), or illegal and indiscriminate usage (Affum et al., 2018; Oyekunle et al., 2022); and high consumption (Owagboriaye et al., 2022). Despite being banned several years ago, some individual OCPs, such as p, p´-DDT, continue to control malaria vectors (Derbalah et al., 2019; Manyilizu, 2019). Another assertion for p, p´-DDT detection in groundwater in Saïss plain, Morocco, was attributed to its use in manufacturing dicofol, an organochlorine insecticide like DDT (Berni et al., 2021). Subsequently, DDT residues in dicofol can therefore be released into the environment. Owing to the p, p´-DDT discharge into groundwater adverse impacts on the ecosystems and humankind have become apparent. The reviewed research studies highlighted the importance of reducing human exposure and potentially expanding the scope of the Stockholm Convention to include vector control measures.

The pesticide residues detected in groundwater included OCPs and OPs which are insecticides while one pyrethroid and two triazines are used as herbicides. Thus, there is a significant research gap observed in the investigation of herbicides as well as fungicides, despite herbicides being the ten most imported pesticides in Africa, as reported by (Bertrand, 2019), with South Africa being on the lead and significantly using triazine and glyphosate-based herbicides (Horak et al., 2021). Further, herbicide use is on the rise in agriculture due to conservation farming (Manyilizu, 2019). While minimal acute toxicity was found in various herbicides and fungicides, they are frequently linked with causing endocrine disruption, neurotoxicity, reproductive disorders, and carcinogenic effects due to low-dose long-term exposures (Stradtman & Freeman, 2021). Of the examined studies, only one highlighted the health risks due to herbicides, particularly atrazine (Owagboriaye et al., 2022).

Detection of p′-DDE and heptachlor epoxide metabolites in two separate reviewed studies denotes the transformation of the parent compounds DDT and heptachlor, respectively (Syafrudin et al., 2021). This, therefore, increases the variety of toxicants to which the groundwater is exposed (Lushchak et al., 2018). In addition, toxicity may increase, as heptachlor is more toxic than the parent heptachlor (Oyekunle et al., 2022). The reviewed studies have revealed that agricultural activities have caused deterioration in their groundwater quality, thereby making the groundwater likely to pose health risks to the exposed.

Deterministic or probabilistic methods can assess human health risk (Kamarehie et al., 2019; Mohan & Sruthy, 2022). All the reviewed articles employed deterministic methods for health risk analyses of pesticide residues. This could be because of a few studies that were retried. Moreover, there is a lack of knowledge and skills to use the model or lack of partnership between researchers in the sub-Saharan African region and other knowledgeable investigators in developed countries (Kaur et al., 2020). Consequently, there is a need to use more realistic methods such as the probabilistic approaches to investigate potential health risks posed on the healthiness of humans by pesticide residues in ground drinking water (Kamarehie et al., 2019). To this end, academic partnerships are encouraged to conduct collaborative research and assist each other in understanding the health risk models. Once this is achieved, various approaches are used to determine health risks.

Health risk assessment is always undertaken after exposure to the pesticide residues. Since the pesticide residues enter the groundwater sources, the chief exposure routes are ingestion (drinking water) and dermal contact during bathing (Derbalah et al., 2019). Notably, chronic exposure to low doses of pesticide residues through water ingestion and dermal contact may result in chronic effects such as reduction of body immunity, hormonal imbalance, reduction in intelligence, particularly in children, and reproductive disorders as the compounds interfere with hormone action (Yilmaz et al., 2020). The severity of health risks may vary depending on the exposed age group (Liu et al., 2015).

Classifying the population into different age groups is vital as physiological and behavioral differences between infants and children compared to adults may considerably affect both external and internal exposure to pesticide residues and their effects on the body. Consequently, safe limits set for adults should ensure adequate protection for infants and children (Chidya et al., 2022; Derbalah et al., 2019).

Carcinogenic and non-carcinogenic risks reported signify that daily groundwater consumption from the study area has significant chronic health risks to adults and children. One study assessed non-oncogenic health risks through ingestion and dermal contact for children and adults according to atrazine concentrations detected. The results showed that the pesticide residue did not pose any risk since the HQ values for the age population were less than 1. Although such findings indicated groundwater safety for human consumption, the non-carcinogenic risk values for children through dermal contact exceeded those for adults. In such a scenario, dermal contact poses a higher risk for children compared to adults as per the findings of analyzed studies (Tudi et al., 2022).

On the other hand, the hazard index (HI) quantifies integrated health risk of the various pesticide residues in ground drinking water or the sum of HQs. Accordingly, two of the reviewed studies also reported HI for the human population who directly consume the groundwater. The HI values for all age groups were below 1, suggesting no considerable non-carcinogenic health risk when exposed to the pesticide residues through ingestion and dermal contact. On the other hand, infants and children were found to have the highest exposure to targeted pesticide residues compared to the adults, primarily due to their higher water consumption rates and greater absorption rates among the younger population as indicated by the reviewed research studies (Pascale & Laborde, 2020).

The carcinogenic health hazards were assessed using cancer risks (CR) accrued due to the ingesting of the groundwaters. According to the USEPA threshold for carcinogenic risk valuation, a cancer risk greater than 10^{-6} is significant. In this regard, cancer values greater than 1×10^{-6} in infants, children and adults were reported in the reviewed studies. Thus, the cancer-causing health risks posed to adults, children, and infants from ingesting the groundwater in Saïss Plain, Morocco; Ile-Ife, Nigerian; and Ankobra Basin, Ghana is significant. The carcinogenic health risks were posed by 12(25.5%) of the evaluated pesticide residues.

Both the oncogenic and non-oncogenic risks determined in the reviewed studies were observed for OCPs and those that were banned. Comparatively, the risks were greater at Ile-Ife, Osun State, Nigeria, and children and infants were exposed to higher levels of pesticide residues in contrast to adults. The findings support the claim that children and infants are more susceptible to the harmful effects of environmental poisons compared to other population groups. As alluded to earlier, this raised sensitivity was attributed to the increased intake rate and lesser body weight, which, taken together, result in an elevated dose of perilous substances per unit of body (Pascale & Laborde, 2020).

Daily ingestion of groundwater from the study area has significant chronic health risks to both adults and children. One study assessed the non-carcinogenic health risk associated with atrazine concentrations for both children and adults, considering ingestion and dermal contact. The results showed that the pesticide residue did not pose any risk since the HQ values for both population groups were less than 1. Although such findings indicated groundwater safety for human consumption, the HQ values through dermal contact for children were elevated compared to that for adults. Accordingly, children are likely to be at greater risk than adults in such a scenario.

The hazard index (HI) quantifies the integrated health risk of the various pesticide residues in ground drinking water or the sum of HQs. Accordingly, two of the reviewed studies also reported HI for the human population who directly consume the groundwater. The HI values for all age groups were less than one, indicating no significant non-carcinogenic health risk upon exposure to the pesticide residues through ingestion and dermal contact. On the other hand, the infants and children were exposed to the highest level of targeted pesticide residues in comparison to the adults because of the greater water consumption and high absorption rate by the early age population (Pascale & Laborde, 2020)

To denote MRL or maximum acceptable concentration (MAC) of investigated pesticide residues in the reviewed studies, measured values were compared to either EU directive 2013/39/EC or the World Health Organization in three studies, while in one study, a comparison was made to Canada and the Environmental Protection Agency of the United States of America. Similarly, risk (HQ and CR) was also compared to EU or US EPA standards. In these studies, reference was made to international regulatory pesticide standards in water because most African countries probably do not have their national legislative measures for pesticides (Li & Jennings, 2017). The lack of national regulatory standards for pesticides may be attributable to inadequate expertise in establishing maximum allowable levels of pesticides in drinking water (London et al., 2005). Another reason could be a shortage of partnerships between investigators in the African region and other investigators in advanced countries which may help African researchers to gain laboratory skills needed in pesticide analysis. In such a scenario whereby reference was made to international standards only, this may mean no contextual MRL/MAC or risk thresholds are available in any of the countries where the studies were undertaken or in Africa. Given that Africa uses pesticides indiscriminately (Olisah et al., 2020), and confirmed widespread groundwater pesticide residue contamination (El-Nahhal & El-Nahhal, 2021), this gap demands an appropriate policy response. There is a need therefore, to define context specific MRL/MAC and risk thresholds in the continent.

To realize national policies that regulate pesticides in drinking water within the African countries, various factors must be considered. First, human capacity must be increased; thus personnel training in the analysis of pesticides should be a deliberate effort by institutions and governments. Personnel with laboratory skills to analyze pesticides are few in most African countries. Second will be the provision of analytical equipment, including high-performance liquid chromatography, high-pressure liquid chromatography and gas chromatography. Third is reduction in the prohibitive costs of analyses. Once these factors are achieved, criteria set by analytical expertise can be imposed.

Nevertheless, African countries can still utilize international standards as templates for developing their own regulations regarding pesticides in drinking water.

The EU standards can serve as a basis for establishing the highest permissible levels of pesticides in drinking water, using the analytical detection limit for chlorine-based substances as a substitute for a zero-tolerance standard. The maximum allowable concentration for any pesticide is set at 0.1 micrograms per liter. In comparison, the limit for total pesticides is set at 0.5 micrograms per liter (The European Parliament and the Council of the European Union, 2020). Coupled with this, there is a need to register only environmentally safe pesticides that can be analyzed in the laboratory using the available capacity. Furthermore, African nations should consider the health and environmental consequences of pesticide use, expected conditions, and potential impacts. This assessment should also account for scientific unpredictability and encompass all possible pathways of pesticide residue exposure.

Finally, to establish the basis for policy and guidelines, the competence to monitor the sale, use, and environmental destiny of pesticides must be put in place. In line with this, pesticide exporters should provide adequate data on health or ecological risks, considering appropriate universal standards preceding exportation as spelled out in the Rotterdam Convention of 2004 (United Nations Environment Program, 2017). Such a convention allows for checking the selling of pesticides since most African countries export the chemicals. In addition, environmental policymakers should prioritise strengthening local capacity to manage environmental threats to human health effectively. This includes providing support and resources to communities and local governments, empowering them to address and mitigate these threats effectively. Furthermore, in Africa, regulatory controls should adequately address the growing international concerns regarding long-term adverse health and environmental impacts caused by the presence of pesticides in water from a public health perspective.

This study has two main strengths. Firstly, it thoroughly searched three databases, encompassing all pesticide research conducted in Africa. Additionally, the supplementary materials provided a comprehensive database, offering detailed information on each identified study, including the specific pesticide residues researched and the data collected. However, the study does have some limitations. These include a relatively brief period (5 years) of analysis, spanning only five years, resulting in a limited number of studies. Furthermore, the focus of the review was solely on groundwater contamination by pesticides and health risk assessment, neglecting other potential areas of concern.

Conclusion

The incidence of pesticide residues in the groundwater harms human health. Data from the reviewed searches on pesticide residues in groundwater in Africa disclosed that OCPs, OPs, pyrethroids and carbamates were particularly widely distributed in groundwater. Of concern are the banned OCPs, especially HCHs, DDTs, heptachlor, dieldrin, endrin, aldrin and endosulfan isomers. Such incidents might be because of the region's historical use of these contaminants for a long time. Even though barred twenty-two years past, OCPs like DDT are still in use for divergent functions. The recent review also found that the health risk to adults, children, and infants primarily stemmed from banned OCPs detected at high concentrations. In some samples, these concentrations exceeded the recommended daily intake limits set by organizations such as WHO, EU, USEPA or Canada. The elevated levels of these banned OCPs can be attributed to runoff from agricultural farmlands. Finally, this review has provided the current state of groundwater pesticide residue research in Africa.

Nevertheless, the sample size was small, which is a concern in terms of the quality and reliability of systematic reviews, which heavily rely on the size and representativeness of the sample included in the analysis. Worth noting was the limited availability of studies within the explored databases and the brief period of the search, resulting in a small sample size. Considering this, it is suggested that in future the search items be broadened to include additional databases or sources to capture a broader range of relevant studies. Furthermore, the search time was extended to include more studies and increase the sample size. In addition, unpublished studies, conference proceedings and reports are included to access additional information that may not be indexed in traditional databases. Finally, engaging with experts or researchers in the field to identify any missed studies that could contribute to the analysis. By implementing these strategies, researchers can enhance the likelihood of obtaining a more representative set of studies, which can improve the reliability and validity of their conclusion. The findings of such interventions may sufficiently inform risk reduction, develop contextual ground drinking water quality risk threshold standards, and promote sustainable agricultural production in meeting some 2030 sustainable development goals.

References

Afata, T. N., Mekonen, S., Shekelifa, M., & Tucho, G. T. (2022). Prevalence of Pesticide Use and Occupational Exposure Among Small-Scale Farmers in Western Ethiopia. *Environmental Health Insights*, *16,* 11786302211072950. https://doi.org/10.1177/11786302211072950

Affum, A. O., Acquaah, S. O., Osae, S. D., & Kwaansa-Ansah, E. E. (2018). Distribution and risk assessment of banned and other current-use pesticides in surface and groundwaters consumed in an agricultural catchment dominated by cocoa crops in the Ankobra Basin, Ghana. *Science of The Total Environment*, *633*, 630–640. https://doi.org/10.1016/j.scitotenv.2018.03.129

Agmas, B., & Adugna, M. (2020). Attitudes and practices of farmers with regard to pesticide use in NorthWest Ethiopia. *Cogent Environmental Science*, *6*(1), 1791462. https://doi.org/10.1080/23311843.2020.1791462

Ahmed, U., Mumtaz, R., Anwar, H., Mumtaz, S., & Qamar, A. M. (2020). Water quality monitoring: from conventional to emerging technologies. *Water Supply*, *20*(1), 28–45. https://doi.org/10.2166/ws.2019.144

Altenburger, R., Brack, W., Burgess, R. M., Busch, W., Escher, B. I., Focks, A., Mark Hewitt, L., Jacobsen, B. N., de Alda, M. L., Ait-Aissa, S., Backhaus, T., Ginebreda, A., Hilscherová, K., Hollender, J., Hollert, H., Neale, P. A., Schulze, T., Schymanski, E. L., Teodorovic, I., … Krauss, M. (2019). Future water quality monitoring: improving the balance between exposure and toxicity assessments of real-world pollutant mixtures. *Environmental Sciences Europe*, *31*(1), 12. https://doi.org/10.1186/s12302-019-0193-1

Basopo, N., & Muzvidziwa, A. (2020). Assessment of the effects of atrazine, dichlorodiphenyltrichloroethane, and dimethoate on freshwater fish (Oreochromis mossambicus): a case study of the A2 farmlands in Chiredzi, in the southeastern part of Zimbabwe. *Environmental Science and Pollution Research*, *27*(1), 579–586. https://doi.org/10.1007/s11356-019-06569-x

Berni, I., Menouni, A., el Ghazi, I., Godderis, L., Duca, R. C., & Jaafari, S. el. (2021). Health and ecological risk assessment based on pesticide monitoring in Saïss plain (Morocco) groundwater. *Environmental Pollution*, *276,* 116638. https://doi.org/10.1016/j.envpol.2021.116638

Bertrand, P. (2019). Uses and Misuses of Agricultural Pesticides in Africa: Neglected Public Health Threats for Workers and Population. In M. Larramendy & S. Soloneski (Eds.), *Pesticides - Use and Misuse and Their Impact in the Environment*. IntechOpen. https://doi.org/10.5772/intechopen.84566

Biosca-Brull, J., Pérez-Fernández, C., Mora, S., Carrillo, B., Pinos, H., Conejo, N. M., Collado, P., Arias, J. L., Martín-Sánchez, F., Sánchez-Santed, F., & Colomina, M. T. (2021). Relationship between Autism Spectrum Disorder and Pesticides: A Systematic Review of Human and Preclinical Models. *International Journal of Environmental Research and Public Health*, *18*(10), 5190. https://doi.org/10.3390/ijerph18105190

Chaza, C., Sopheak, N., Mariam, H., David, D., Baghdad, O., & Moomen, B. (2018). Assessment of pesticide contamination in Akkar groundwater, northern Lebanon. *Environmental Science and Pollution Research*, *25*(15), 14302–14312. https://doi.org/10.1007/s11356-017-8568-6

Chidya, R., Derbalah, A., Abdel-Dayem, S., Kaonga, C., & Sakugawa, H. (2022). Ecotoxicological and human health risk assessment of selected pesticides in Kurose River, Higashi-Hiroshima City (Japan). *Water Environment Research*, *94*(1), e1676. https://doi.org/10.1002/wer.1676

Chow, R., Curchod, L., Davies, E., Veludo, A. F., Oltramare, C., Dalvie, M. A., Stamm, C., Röösli, M., & Fuhrimann, S. (2023). Seasonal drivers and risks of aquatic pesticide pollution in drought and post-drought conditions in three Mediterranean watersheds. *Science of The Total Environment*, *858*, 159784. https://doi.org/10.1016/j.scitotenv.2022.159784

Curchod, L., Oltramare, C., Junghans, M., Stamm, C., Dalvie, M. A., Röösli, M., & Fuhrimann, S. (2020). Temporal variation of pesticide mixtures in rivers of three agricultural watersheds during a major drought in the Western Cape, South Africa. *Water Research*, *6,* 100039. https://doi.org/10.1016/j.wroa.2019.100039

Demetillo, A. T., Japitana, M. V., & Taboada, E. B. (2019). A system for monitoring water quality in a large aquatic area using wireless sensor network technology. *Sustainable Environment Research*, *29*(1), 12. https://doi.org/10.1186/s42834-019-0009-4

Department of Water Affairs and Forestry. (1996). *Water Quality Guidelines Field Guide Vol. 1: Domestic Water Use* (1st ed.). Department of Water Affairs and Forestry.

Derbalah, A., Chidya, R., Jadoon, W., & Sakugawa, H. (2019). Temporal trends in organophosphorus pesticides use and concentrations in river water in Japan, and risk assessment. *Journal of Environmental Sciences*, *79*, 135–152. https://doi.org/10.1016/j.jes.2018.11.019

Dórea, J. G. (2021). Exposure to environmental neurotoxic substances and neurodevelopment in children from Latin America and the Caribbean. *Environmental Research*, *192*, 110199. https://doi.org/10.1016/j.envres.2020.110199

El-Nahhal, I., & El-Nahhal, Y. (2021). Pesticide residues in drinking water, their potential risk to human health and removal options. *Journal of Environmental Management* 299, 113611. Academic Press. https://doi.org/10.1016/j.jenvman.2021.113611

Endalew, M., Gebrehiwot, M., & Dessie, A. (2022). Pesticide Use Knowledge, Attitude, Practices and Practices Associated Factors Among Floriculture Workers in Bahirdar City, NorthWest, Ethiopia, 2020. *Environmental Health Insights*, *16,* 11786302221076250. https://doi.org/10.1177/11786302221076250

Food and Agricultural Organization, (2018). More People, More Food, Worse Water? A Global Review of Water Pollution from Agriculture. *Water, Water, Land and Ecosystems (WLE) Program of the CGIAR*. International Water Management Institute. *http://www.fao.org/3/CA0146EN/ca0146en.pdf*

Fuhrimann, S., van den Brenk, I., Atuhaire, A., Mubeezi, R., Staudacher, P., Huss, A., & Kromhout, H. (2022). Recent pesticide exposure affects sleep: A cross-sectional study among smallholder farmers in Uganda.

Environment International, *158,* 106878. https://doi.org/10.1016/j.envint.2021.106878

Ganaie, M. I., Jan, I., Mayer, A. N., Dar, A. A., Mayer, I. A., Ahmed, P., & Sofi, J. A. (2023). Health Risk Assessment of Pesticide Residues in Drinking Water of Upper Jhelum Region in Kashmir Valley-India by GC-MS/MS. *International Journal of Analytical Chemistry*, *2023*, 1–16. https://doi.org/10.1155/2023/6802782

Ghasemnejad-Berenji, M., Nemati, M., Pourheydar, B., Gholizadeh, S., Karimipour, M., Mohebbi, I., & Jafari, A. (2021). Neurological effects of long-term exposure to low doses of pesticides mixtures in male rats: Biochemical, histological, and neurobehavioral evaluations. *Chemosphere*, *264*, 128464. https://doi.org/10.1016/j.chemosphere.2020.128464

Gonsioroski, A., Mourikes, V. E., & Flaws, J. A. (2020). Endocrine disruptors in water and their effects on the reproductive system. *International Journal of Molecular Sciences*, *21*(6), 1929. https://doi.org/10.3390/ijms21061929

Gowing, J., Walker, D., Parkin, G., Forsythe, N., & Tamiru, A. (2020). Groundwater for Sustainable Development Can shallow groundwater sustain small-scale irrigated agriculture in sub-Saharan Africa ? Evidence from N-W Ethiopia. *Groundwater for Sustainable Development*, *10*, 100290. https://doi.org/10.1016/j.gsd.2019.100290

Gwimbi, P., & Mundoga, T. (2010). Impact of climate change on cotton production under rainfed conditions: case of Gokwe. *Journal of Sustainable Development in Africa*, *12*(8), 59–69. http://www.jsd-africa.com.

Horak, I., Horn, S., & Pieters, R. (2021). Agrochemicals in freshwater systems and their potential as endocrine disrupting chemicals: A South African context. In *Environmental Pollution,* 268, 115718. https://doi.org/10.1016/j.envpol.2020.115718

Huang, F., Li, Z., Zhang, C., Habumugisha, T., Liu, F., & Luo, X. (2019). Pesticides in the typical agricultural groundwater in Songnen plain, northeast China: occurrence, spatial distribution and health risks. *Environmental Geochemistry and Health*, *41*(6), 2681–2695. https://doi.org/10.1007/s10653-019-00331-5

Illyassou, K. M., & Schiffers, B. (2018). First diet survey in Niger River valley and acute risk assessment for consumers exposed to pesticide residues in vegetables Agriculture represents in Niger the main economic sector and participates. *Tunisian Journal of Plant Protection,13*(2), 243-262.

Kamarehie, B., Jafari, A., Zarei, A., Fakhri, Y., Ghaderpoori, M., & Alinejad, A. (2019). Non-carcinogenic health risk assessment of nitrate in bottled drinking waters sold in Iranian markets: A Monte Carlo simulation. *Accreditation and Quality Assurance*, *24*(6), 417–426.

https://doi.org/10.1007/s00769-019-01397-5

Kaur, L., Rishi, M. S., & Siddiqui, A. U. (2020). Deterministic and probabilistic health risk assessment techniques to evaluate non-carcinogenic human health risk (NHHR) due to fluoride and nitrate in groundwater of Panipat, Haryana, India. *Environmental Pollution*, *259*, 113711. https://doi.org/10.1016/j.envpol.2019.113711

Lapworth, D. J., Nkhuwa, D. C. W., Okotto-Okotto, J., Pedley, S., Stuart, M. E., Tijani, M. N., & Wright, J. (2017). Urban groundwater quality in sub-Saharan Africa: status and implications for water security and public health. *Hydrogeology Journal*, *25*(4), 1093–1116. https://doi.org/10.1007/s10040-016-1516-6

Lauretta, R., Sansone, A., Sansone, M., Romanelli, F., & Appetecchia, M. (2019). Endocrine disrupting chemicals: Effects on endocrine glands. In *Frontiers in Endocrinology*, *10*, 00178. https://doi.org/10.3389/fendo.2019.00178

Lehmann, E., Turrero, N., Kolia, M., Konaté, Y., & de Alencastro, L. F. (2017). Dietary risk assessment of pesticides from vegetables and drinking water in gardening areas in Burkina Faso. *Science of the Total Environment*, *601*(602), 1208–1216. https://doi.org/10.1016/j.scitotenv.2017.05.285

Li, (2022). Prioritizing agricultural pesticides to protect human health: A multi-level strategy combining life cycle impact and risk assessments. *Ecotoxicology and Environmental Safety*, *242*, 113869. https://doi.org/10.1016/j.ecoenv.2022.113869

Li, & Jennings, A. (2017). Worldwide regulations of standard values of pesticides for human health risk control: A review. *International Journal of Environmental Research and Public Health,* 14(7), 4070826. MDPI. https://doi.org/10.3390/ijerph14070826

Liu, G., Peng, Z., Lan, T., Xu, X., Huang, G., Yu, S., Liu, G., & Li, J. (2015). Health risk assessment on pesticide residues in drinking water in Shenzhen. *Wei Sheng Yan Jiu Journal of Hygiene Research*, *44*(2), 264–269. https://doi.org/10.4236/odem.2018.64010

London, L., Dalvie, M. A., Nowicki, A., & Cairncross, E. (2005). *Approaches for regulating water in South Africa for the presence of pesticides*, 31(1), 53-60. http://www.wrc.org.za

Lopes-Ferreira, M., Maleski, A. L. A., Balan-Lima, L., Bernardo, J. T. G., Hipolito, L. M., Seni-Silva, A. C., Batista-Filho, J., Falcao, M. A. P., & Lima, C. (2022). Impact of Pesticides on Human Health in the Last Six Years in Brazil. *International Journal of Environmental Research and Public Health*, *19*(6), 3198. https://doi.org/10.3390/ijerph19063198

Lushchak, V. I., Matviishyn, T. M., Husak, V. v., Storey, J. M., & Storey, K. B. (2018). Pesticide toxicity: A mechanistic approach. *EXCLI Journal, 17*, 1101–1136. https://doi.org/10.17179/excli2018-1710

Manyilizu, W. B. (2019). Pesticides, anthropogenic activities, history and the health of our environment: lessons from Africa. In M. Larramendy & S. Soloneski (Eds.), *Pesticides – Use and Misuse and Their Impact in the Environment.* IntechOpen.

Masindi, V., & Foteinis, S. (2021). Groundwater contamination in sub-Saharan Africa: Implications for groundwater protection in developing countries. *Cleaner Engineering and Technology*, *2,* 100038. https://doi.org/10.1016/j.clet.2020.100038

Mequanint, C., Getachew, B., Mindaye, Y., Amare, D. E., Guadu, T., & Dagne, H. (2019). Practice towards pesticide handling, storage and its associated factors among farmers working in irrigations in Gondar town, Ethiopia, 2019. *BMC Research Notes*, *12*(1), 4754-6. https://doi.org/10.1186/s13104-019-4754-6

Mohan, S., & Sruthy, S. (2022). Human Health Risk Assessment due to Solvent Exposure from Pharmaceutical Industrial Effluent: Deterministic and Probabilistic Approaches. *Environmental Processes*, *9*(1), 18. https://doi.org/10.1007/s40710-022-00571-1

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Journal of Clinical Epidemiology*, *62*(10), 1006–1012. https://doi.org/10.1016/j.jclinepi.2009.06.005

Ohlander, J., Fuhrimann, S., Basinas, I., Cherrie, J. W., Galea, K. S., Povey, A. C., van Tongeren, M., Harding, A. H., Jones, K., Vermeulen, R., & Kromhout, H. (2020). Systematic review of methods used to assess exposure to pesticides in occupational epidemiology studies, 1993-2017. *Occupational and Environmental Medicine, 77*(6), 357–367. https://doi.org/10.1136/oemed-2019-105880

Olisah, C., Okoh, O. O., & Okoh, A. I. (2020). Occurrence of organochlorine pesticide residues in biological and environmental matrices in Africa: A two-decade review. *Heliyon, 6*(3), e03518. https://doi.org/10.1016/j.heliyon.2020.e03518

Ouedraogo, I., & Vanclooster, M. (2021). Challenges of groundwater pollution and management in transboundary basins at the African scale. *Proceedings of the International Association of Hydrological Sciences*, *384*, 69–74. https://doi.org/10.5194/piahs-384-69-2021

Owagboriaye, F., Oladunjoye, R., Aina, S., Adekunle, O., Salisu, T., Adenekan, A., Abesin, O., Oguntubo, J., Fafioye, O., Dedeke, G., & Lawal, O. (2022). Outcome of the first survey of atrazine in drinking water from Ijebu-North, South-West, Nigeria: Human health risk and neurotoxicological implications. *Toxicology Reports*, *9*, 1347–1356. https://doi.org/10.1016/j.toxrep.2022.06.012

Oyekunle, J. A. O., Adegunwa, A. O., & Ore, O. T. (2022). Distribution, Source Apportionment and Health Risk Assessment of Organochlorine Pesticides in Drinking Groundwater. *Chemistry Africa, 5*(4*),* 1115-1125. https://doi.org/10.1007/s42250-022-00370-z

Panis, C., Candiotto, L. Z. P., Gaboardi, S. C., Gurzenda, S., Cruz, J., Castro, M., & Lemos, B. (2022). Widespread pesticide contamination of drinking water and impact on cancer risk in Brazil. *Environment International*, *165*, 107321. https://doi.org/10.1016/j.envint.2022.107321

Pascale, A., & Laborde, Amalia. (2020). Impact of pesticide exposure in childhood. *Reviews on Environmental Health*, *35*(3), 221–227. https://doi.org/10.1515/reveh-2020-0011

Pathak, V. M., Verma, V. K., Rawat, B. S., Kaur, B., Babu, N., Sharma, A., Dewali, S., Yadav, M., Kumari, R., Singh, S., Mohapatra, A., Pandey, V., Rana, N., & Cunill, J. M. (2022). Current status of pesticide effects on environment, human health and it's eco-friendly management as bioremediation: A comprehensive review. *Frontiers in Microbiology*, *13,* 962619. https://doi.org/10.3389/fmicb.2022.962619

Röösli, M., Fuhrimann, S., Atuhaire, A., Rother, H. A., Dabrowski, J., Eskenazi, B., Jørs, E., Jepson, P. C., London, L., Naidoo, S., Rohlman, D. S., Saunyama, I., van Wendel de Joode, B., Adeleye, A. O., Alagbo, O. O., Aliaj, D., Azanaw, J., Beerappa, R., Brugger, C., … Dalvie, M. A. (2022). Interventions to Reduce Pesticide Exposure from the Agricultural Sector in Africa: A Workshop Report. *International Journal of Environmental Research and Public Health*, *19*(15), 19158973. https://doi.org/10.3390/ijerph19158973

Sishu, F. K., Tilahun, S. A., Schmitter, P., Assefa, G., & Steenhuis, T. S. (2022). Pesticide Contamination of Surface and Groundwater in an Ethiopian Highlands' Watershed. *Water*, *14*(21), 3446. https://doi.org/10.3390/w14213446

Siviter, H., Bailes, E. J., Martin, C. D., Oliver, T. R., Koricheva, J., Leadbeater, E., & Brown, M. J. F. (2021). Agrochemicals interact synergistically to increase bee mortality. *Nature*, *596*(7872), 389–392. https://doi.org/10.1038/s41586-021-03787-7

Sjerps, R. M. A., Kooij, P. J. F., van Loon, A., & Van Wezel, A. P. (2019). Occurrence of pesticides in Dutch drinking water sources. *Chemosphere*, *235*, 510–518. https://doi.org/10.1016/j.chemosphere.2019.06.207

Stradtman, S. C., & Freeman, J. L. (2021a). Mechanisms of neurotoxicity associated with exposure to the herbicide atrazine. *Toxics*, *9*(9), 207. https://doi.org/10.3390/toxics9090207

Suwannakul, B., Sapbamrer, R., Wiwattanadittakul, N., & Hongsibsong, S. (2021). Organophosphate Pesticide Exposures in Early and Late

Pregnancy Influence Different Aspects of Infant Developmental Performance. *Toxics*, *9*(5), 99. https://doi.org/10.3390/toxics9050099

Syafrudin, M., Kristanti, R. A., Yuniarto, A., Hadibarata, T., Rhee, J., Al-Onazi, W. A., Algarni, T. S., Almarri, A. H., & Al-Mohaimeed, A. M. (2021). Pesticides in drinking water-a review. In *International Journal of Environmental Research and Public Health,* 18(2), 1–15. MDPI AG. https://doi.org/10.3390/ijerph18020468

Tang, F. H. M., Lenzen, M., McBratney, A., & Maggi, F. (2021). Risk of pesticide pollution at the global scale. *Nature Geoscience*, *14*(4), 206–210. https://doi.org/10.1038/s41561-021-00712-5

The European Parliament and the Council of the European Union. (2000). 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. *Official Journal of the European Union*, 1–73.

The European Parliament and the Council of the European Union. (2020). Directive (EU) 2020/2184 of the European Parliament and of the Council16 December 2020 on the quality of water intended for human consumption. *Official Journal of the European Union*, 1–62.

Tudi, M., Li, H., Li, H., Wang, L., Lyu, J., Yang, L., Tong, S., Yu, Q. J., Ruan, H. D., Atabila, A., Phung, D. T., Sadler, R., & Connell, D. (2022). Exposure Routes and Health Risks Associated with Pesticide Application. *Toxics*, *10*(6), 335. https://doi.org/10.3390/toxics10060335

Tudi, M., Ruan, H. D., Wang, L., Lyu, J., Sadler, R., Connell, D., Chu, C., & Phung, D. T. (2021). Agriculture development, pesticide application and its impact on the environment. In *International Journal of Environmental Research and Public Health,* 18(3), 1–24). https://doi.org/10.3390/ijerph18031112

Twinomucunguzi, F. R. B., Nyenje, P. M., Kulabako, R. N., Semiyaga, S., Foppen, J. W., & Kansiime, F. (2021). Emerging organic contaminants in shallow groundwater underlying two contrasting peri-urban areas in Uganda. *Environmental Monitoring and Assessment*, *193*(4), 1–25. https://doi.org/10.1007/s10661-021-08975-6

United Nations Environment Program. (2017). *Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous*. United Nations.

Wanjiku Philip, S., Madadi Odongo, V., Wandiga, S. O., Omayio, D. G., & Okumu, M. O. (2022). Estimation and human health risk assessment of organochlorine and organophosphate pesticide residues in raw milk collected in Kenya. *F1000Research*, *11*, 14. https://doi.org/10.12688/f1000research.74748.1

World Health Organization, (2017). *Guidelines for drinking-water quality: fourth edition incorporating* *the first addendum*. World Health Organization.

World Health Organization. (2021). *WHO human health risk assessment toolkit: chemical hazards* (2nd ed). World Health Organization.

Wumbei, A., Issahaku, A., Abubakari, A., Lopez, E., & Spanoghe, P. (2019). Consumption Risk Assessment of Pesticides Residues in Yam Agriculture represents an important economic sector in Ghana, accounting for about 40% of the country's gross domestic. *Tunisian Journal of Plant Protection*, 49(2), 49-64.

Xu, X., Nie, S., Ding, H., & Hou, F. F. (2018). Environmental pollution and kidney diseases. *Nature Reviews Nephrology*, *14*(5), 313–324. https://doi.org/10.1038/nrneph.2018.11

Yilmaz, B., Terekeci, H., Sandal, S., & Kelestimur, F. (2020). Endocrine disrupting chemicals: exposure, effects on human health, mechanism of action, models for testing and strategies for prevention. In *Reviews in Endocrine and Metabolic Disorders,* 21(1), 127–147). https://doi.org/10.1007/s11154-019-09521-z

Zhai, Y., Zhao, X., Teng, Y., Li, X., Zhang, J., Wu, J., & Zuo, R. (2017). Groundwater nitrate pollution and human health risk assessment by using HHRA model in an agricultural area, NE China. *Ecotoxicology and Environmental Safety*, *137*, 130–142. https://doi.org/10.1016/j.ecoenv.2016.11.010.