Heliyon 10 (2024) e28054

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

DDT contamination in water resources of some African countries and its impact on water quality and human health

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A R T I C L E I N F O

Keywords:
Dichlorodiphenyltrichloroethane (DDT)
Water sources
Drinking water
Indoor residual spraying (IRS)
Toxicity and cancer risk

A B S T R A C T

Dichlorodiphenyltrichloroethane (DDT) usage has been prohibited in developed nations since 1972 but is exempted for use in indoor residual spraying (IRS) in developing countries, including African countries, for malaria control. There have been no previous reviews on DDT residues in water resources in Africa. The study aimed to provide a review of available research investigating the levels of DDT residues in water sources in Africa and to assess the consequent human health risks. A scoping review of published studies in Africa was conducted through a systematic electronic search using PubMed, Web of Science, EBSCO HOST, and Scopus. A total of 24 articles were eligible and reviewed. Concentrations of DDT ranged from non-detectable levels to 81.2 μg/L. In 35% of the studies, DDT concentrations surpassed the World Health Organization (WHO) drinking water guideline of 1 μg/L in the sampled water sources. The highest DDT concentrations were found in South Africa (81.2 μg/L) and Egypt (5.62 μg/L). DDT residues were detected throughout the year in African water systems, but levels were found to be higher during the wet season. Moreover, water from taps, rivers, reservoirs, estuaries, wells, and boreholes containing DDT residues was used as drinking water. Seven studies conducted health risk assessments, with two studies identifying cancer risk values surpassing permissible thresholds in water sampled from sources designated for potable use. Non-carcinogenic health risks in the studies fell below a hazard quotient of 1. Consequently, discernible evidence of risks to human health surfaced, given that the concentration of DDT residues surpassed either the WHO drinking water guidelines or the permissible limits for cancer risk in sampled drinking sources within African water systems. Therefore, alternative methods for malaria vector control should be investigated and applied.

1. Introduction

Dichlorodiphenyltrichloroethane (DDT) is an insecticide that was originally used to effectively combat malaria and other insect-borne human illnesses [1]. Having been extensively utilized on a global scale, DDT was phased out for agricultural use in most

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https://doi.org/10.1016/j.heliyon.2024.e28054
Received 1 August 2023; Received in revised form 13 January 2024; Accepted 11 March 2024
Available online 20 March 2024
2405-8440/

Abbreviations

DDT	Dichlorodiphenyltrichloroethane
DDE	Dichlorodiphenyldichloroethylene
DDD	Dichlorodiphenyldichloroethane
IRS	Indoor Residual Spraying
POPs	Persistent Organic Pollutants
OCPs	Organochlorine Pesticides
HQ	Hazard Quotient
CR	Carcinogenic Risk

developed regions in 1972 (US EPA, 2017), and for malaria control in 1996 [1,2]. In response to these developments, 152 nations approved and signed the Stockholm Convention in 2001, marking a global commitment to cease the utilization of persistent organic pollutants (POPs) [3]. Notwithstanding, nations dependent on DDT as a less costly method for controlling malaria were accorded exemptions. Subsequently, in September 2006, the WHO approved the use of Indoor Residual Spraying (IRS) with DDT in African nations, where malaria remains a severe health burden, outlining that the benefits of DDT outweigh the environmental and human health risks as a cost-effective method to control malaria (WHO, 2006).

Residents living in areas where IRS is performed face an increased susceptibility to elevated levels of DDT exposure. This heightened risk stems from inherent lipophilic properties of DDT, coupled with its enduring presence in the environment [4]. Physical contact, inhalation of indoor sprays, and ingestion of contaminated water and food are the main modes of exposure. In its dissolved or particulate remnant form, DDT has the potential to infiltrate surface water sources, which can affect the quality of water, jeopardize aquatic life, and be a source of exposure to humans via recreational and drinking resources [5]. As a result, there is growing concern around the effects of DDT on the health of humans and the environment [6,7].

The application of DDT through spraying processes can pollute bodies of water globally as a nonpoint source of waste, contaminating the drinking water supply [8]. This is especially true in nations that manufacture DDT, such as India, China and Korea [9]. Additionally, DDT pollution also affects countries that have and still use DDT, such as South Africa, Mozambique, Ethiopia, Sudan, Zambia and Zimbabwe —all of which are situated in Africa [9]. Data from India, Brazil, South Africa, and Mexico suggest that DDT levels in soil or water samples are higher in regions where DDT residual spraying occurs, when compared to areas without spraying [9].

Organochlorine pesticides infiltrate water sources via several pathways, including drainage pollution from agricultural areas where pesticides are used, pesticide dust or droplets during application processes like IRS, pesticide containers, and from cleaning agricultural machinery [10]. Freshwater contamination is a major concern worldwide, as inland waters are contaminated with chemical pollutants from mines and other manufacturing operations, including pesticides from crop runoff [11].

Pilot experiments investigating environmental pollution with DDT in the Limpopo Province of South Africa, have raised questions about water quality and estrogenic activity in water bodies where DDT spraying takes place. Employing different animal species as environmental pollution indicators, the results of this research indicated that chickens, two fish species, and sea birds were all contaminated [12]. Another pilot analysis conducted in northern South Africa observed high concentrations of DDT and metabolites in numerous aquatic and terrestrial biota in a DDT-sprayed area [13]. Hence, a comprehensive investigation into the presence of DDT in water bodies is crucial, especially in light of its potential adverse effects on human health. Safe drinking water is critical for long-term human health, socioeconomic progress, and maintaining a reasonable standard of living. Additionally, there is also a requirement for developing nations to fulfil the Sustainable Development Goal (SDG) addressing access to adequate sanitation and clean water by the year 2030 [14]. The presence of pesticides such as DDT, even at low concentrations in water sources, especially when those sources are used for drinking, can compromise human health and water quality [15]. The WHO [54] has set a guideline value of 1 μg/L for DDT in drinking water.

Existing epidemiological data demonstrates that DDT exerts multifaceted effects on human biological systems, yielding various health implications. These encompass endocrine disruption leading to adverse impacts on both female and male reproductive systems, influence on neurological development and behavior, negative immunological effects, manifestations of asthma, susceptibility to cancer and ramifications for child development and growth [16–19].

No previous reviews have been conducted specifically investigating DDT contamination in water sources in Africa. Two reviews which were done in China found that DDT levels were high enough in seafood samples to have negative effects on human health [20]. These reviews also established DDT as the primary matrix for assessing environmental risk in aquatic organisms [21]. Additionally, a review conducted in South America found that DDT was more prevalent than other organochlorine pesticides (OCPs) in all environmental matrices [22]. There is therefore a lack of regional data globally pertaining to the occurrence of DDT in water sources, notably portable water, especially in countries with significant DDT usage. This knowledge gap is especially important in Africa, where DDT is used for malaria vector control, and whose population is particularly vulnerable to environmental hazards [23]. Continuous monitoring of chemical contaminants in water bodies in developed nations has served as a foundation for policy formation and pollution management, with the aim of achieving clean water bodies. This highlights the need for regional evaluation of hazardous chemicals, notably POPs, in water bodies, particularly in Africa [23].

Previous research has also not comprehensively evaluated the human health risks posed by DDT water contamination regionally. Consequently, the goal of this study was to ascertain the existing evidence of DDT contamination in water sources and evaluate its potential health risks for individuals exposed to DDT-contaminated water in Africa. This study holds the potential to catalyse further research on the impact of DDT on water quality, particularly in numerous African countries where DDT is still widely used. It furthermore serves as a crucial tool for informing policy decisions, recognizing that despite DDT being a low-cost and cost-effective antimalarial chemical, the environmental and human health risks from IRS exposure must be carefully considered against the benefits of DDT's usefulness in malaria prevention – especially now, given the reality that a malaria vaccine is likely to be on the market.

The study was set out to perform a comprehensive scoping review of existing research concerning the presence and concentrations of DDT in various water sources across Africa, and to analyse the potential human health implications arising from DDT exposure due to water contamination. The specific objectives were as follows: (a) to conduct a systematic assessment of research by critically analysing the available literature related to the occurrence and levels of DDT within water sources across the African continent, (b) to characterize the types of water sources where DDT residues were commonly found and (c), to summarize and consolidate the existing research on the potential risks to human health resulting from exposure to DDT-contaminated water resources in Africa.

2. Methods

2.1. Study design

A systematic scoping review using the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocol (PRISMA-P) guidelines was conducted. Original studies in peer-reviewed journals containing empirical data on DDT levels in African water resources between 2010 and 2023 were targeted. The review involved developing a search strategy, screening of identified articles, application of inclusion and exclusion criteria and data extraction.

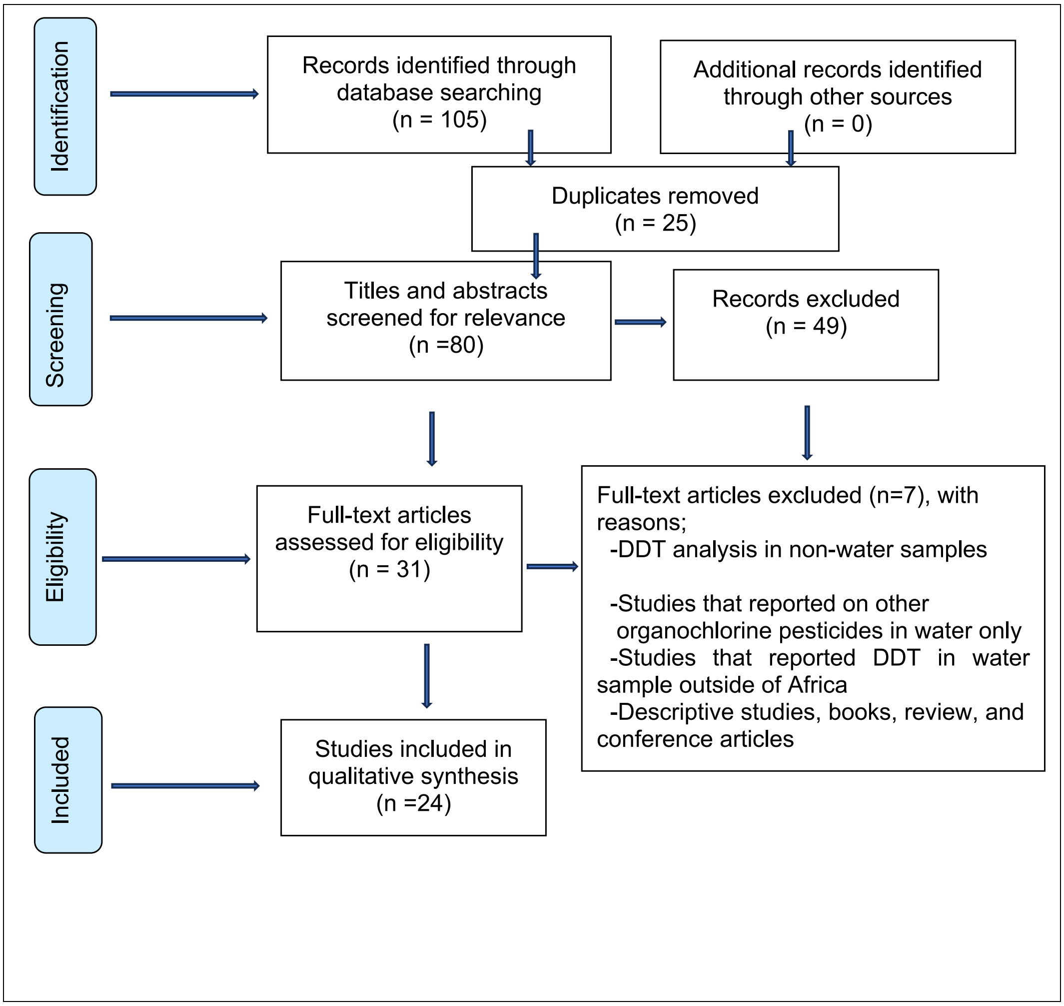

Fig. 1. PRISMA flow chart of studies screened.

Table 1
Studies reporting DDT levels in South African water resources.

No	References	Location & Country	No of Sampling sites & size	Sampling period and season	Water Media	Contamination of water sources	Uses of water media	[a]DDT levels (μg/L)	Summary of human health risk assessment
South Africa									
1	[24]	Eastern Cape, South Africa	5 sites 400 samples	Oct 2017–Sept 2018. (All seasons)	Surface water; Sundays (SDE) & Swartkops Estuaries (SWE)	Discharge of various solid & industrial pollutants, no known recent DDT applications	Agricultural and domestic use (drinking & bathing)	Mean DDT in wet season: 0.02 Mean DDT in Pre-dry season: 0.1 Mean DDT in Dry season: 0.02 Mean DDT in Pre-Wet season:0.01 Max DDT: 0.133	Risk assessment ratio in SDE 2.54×10^{-7} (drinking water), and 1.10×10^{-9} (bathing water) for carcinogenic risk 3.38×10^{-3} (drinking water) and $1{,}47 \times 10^{-5}$ (bathing water) for non-carcinogenic risk Risk assessment ratio in SWE 6.63×10^{-7} (drinking water) and 2.89×10^{-9} (bathing water) for carcinogenic risk 8.84×10^{-3} (drinking water) and 3.85×10^{-5} (bathing water) for non-carcinogenic risk
2	[25]	KwaZulu Natal, South Africa	9 sites	16–17 July (dry season) and 25–26 Sept 2013 (pre-wet season)	Surface water (Msunduzi river)	Various anthropogenic activities, no known recent DDT applications	Major source of water for the area	Max p.p-DDT in dry season: 19.95 Max p.p-DDD in pre-wet season: 81.15	N/A
3	[26]	Eastern Cape, South Africa	6 sites	Dec 2015 (wet season) – May 2016 (dry season)	Surface water (Buffalo River)	Various household & industrial pollutants, no known recent DDT applications	Domestic & Agricultural purposes	Mean DDT in wet season: 1.43 Mean DDT in dry season: 0.45 Max DDT: 0.5	Non- cancer risk: Hazard Quotient (HQ) for different age groups 4,4-DDE: ($14{,}751 \times 10^{-6}$), (8741×10^{-6}) and (2950×10^{-6}) for age groups 0–6, 7–17 and adults, respectively 4,4-DDD: (8306×10^{-6}), (4922×10^{-6}) and (1661×10^{-6}) for age groups 0–6, 7–17 and adults, respectively 4,4-DDT: (12×10^{-6}), (7×10^{-6}) and (2×10^{-6}) for age groups 0–6, 7–17 and adults, respectively

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Table 1 (*continued*)

No	References	Location & Country	No of Sampling sites & size	Sampling period and season	Water Media	Contamination of water sources	Uses of water media	[a]DDT levels (μg/L)	Summary of human health risk assessment
4	[27]	Limpopo, South Africa	2 sites 12 samples	Feb 2008 (wet season)-summer	Tap water	IRS with DDT	Used for drinking and other domestic purposes	Max DDT: 7.6 (wet season)	N/A
5	[28]	Limpopo, South Africa	3 sites	Not stated	Surface water (Luvuhu river)	IRS with DDT	_	Max DDT: Survey 1: 0.12 Survey 2: 0.7 Survey 3: 2.3 Survey 4: 2.2	N/A

[a] Not all studies reported on mean/median DDT concentrations.

2.2. *Literature search strategy*

A systematic electronic search was conducted using PubMed, Web of Science, EBSCO HOST and Scopus. The search strategy included keywords related to DDT AND water contamination. The search was limited to articles written in English and published between 2010 and June 2023. The starting year for the review was 2010 because recent studies would be able to reflect on the most current DDT levels in water sources. Search terms used for each database are shown in the supplementary information (Table S1).

The initial search, using four databases, identified a total of 105 articles. After removing duplicates, 80 articles were screened by their titles and abstracts. After this first phase of screening, 49 articles were excluded, and the remaining 31 underwent full-text screening. Seven further articles were excluded after full-text screening, leaving 24 eligible articles for review (See Fig. 1). The 24 eligible studies were categorised by location in eleven African countries, including: South Africa (5), Nigeria (4), Ghana (2), Kenya (2), Mozambique (1), Ethiopia (2), Zambia (1), Tanzania (2), Egypt (2), Morocco (2) and Tunisia (1).

2.3. *Selection of studies*

Eligibility criteria were developed before the study was conducted to help determine publications to be included for the review. The primary investigator (LM) reviewed the articles, and two other reviewers (AA or AD) were consulted in situations of doubt about inclusion. After a thorough discussion, consensus was reached.

A study was deemed eligible if it met the following inclusion criteria.

- Studies published in English.
- Studies done based on water samples from Africa.
- Studies that analysed DDT in water sources.
- Studies published from 2010 until June 2023.

A study was deemed ineligible if it met the following exclusion criteria.

- Studies published in languages other than English.
- Studies with incomplete data.
- Studies focusing on DDT exposure of animals, especially aquatic animals, which have no direct link to adverse health effects of humans and exposure.
- Studies where DDT levels were measured using samples other than water samples.

3. Results

This review included evidence from 24 studies conducted in 11 African countries on DDT levels detected in different water sources and where available, health risk assessments (7). The countries in which the studies were conducted included South Africa (n = 5), Nigeria (n = 4), Ghana (n = 2), Kenya (n = 2), Mozambique (n = 1), Ethiopia (n = 2), Tanzania (n = 2), Zambia (n = 1), Egypt (n = 2), Morocco (n = 2) and Tunisia (n = 1).

Table 2
Studies reporting DDT levels in West African water resources.

No	References	Location & Country	No of Sampling sites & size	Sampling period and season	Water Media	Contamination of water sources	Uses of water media	DDT levels (μg/L)	Summary of human health risk assessment
Nigeria									
1	[29]	Ilorin Kwara State, Nigeria	6 Samples	Sampling season not mentioned	Surface water (Asa Dam River)	Personal care products being discharged in this water body	Drinking water supply	Max DDE: 0.007 Max DDD: 0.005	Carcinogenic risk: O, P DDD = 0.0004 for children and 0.00005 for adults); O, P DDE = 0.0001 for children and 0.00001 for adults); P, P DDE = 0.0003 for children and 0.00004 for adults) HQ: O.P DDD = 0.454 for children and 0.2763 for adults) O, P DDE = 1.188 for children and 0.1584 for adults); P, P DDE = 4.377 for children and 0.5836 for adults)
2	[30]	Edo State, Nigeria	72 Samples	Jan 2012 to June 2013 (Covered all the seasons)	Surface water (Owan River)	Flow of agrochemicals from cocoa plantations, no known recent DDT applications	Agricultural use	Mean DDT: 0.12 (all seasons)	N/A
3	[31]	Edo State, Nigeria	216 Samples	Jan 2012 to June 2013 (Covered all the seasons)	Surface water (Illushi River)	Acts as a drainage system for the area's rice fields, no known recent DDT applications	Used for drinking & domestic purposes	Mean DDT: 0.09 (all seasons)	Non-cancer risk: HQ = 0.0158 (Children) HQ = 0.0046 (Adults)
4	[32]	Iwo, Nigeria	1 site	Nov–Dec 2012 (dry season-winter)	Surface water (Aiba man-made reservoir)	Contamination from fishing, farming, cleansing of household goods and autos, no known recent DDT applications	Used to preserve drinking water	Mean DDT in dry season: 0.12 DDT detected in 37% of water samples	N/A
Ghana									
5	[15]	Western region of Ghana	11 sites 88 Samples	Aug–Oct 2016 (wet season-summer)	Surface water (Ankobra basin, Peme River & streams) Ground water (boreholes)	Agricultural runoff from cocoa fields, no known recent DDT applications	Used for drinking purposes	Mean DDT in Surface: 0.08 (wet season)	Cancer risk: p, p′-DDT = (infants: 5.1×10^{-6} to 1.28×10^{-5}; children: 1.56×10^{-6} to 2.55×10^{-6}); p, p′-DDD = (infants: 1.8×10^{-5}; children: 3.6×10^{-6}); p, p′-DDE (infants: 2.6×10^{-6}; children: 2.6×10^{-6})
								Mean DDT in Ground water: 0.06 (wet season) Max DDT: 0.11	Cancer risk: p, p′-DDT= (infants: 2.8×10^{-5}; children: 1.5×10^{-6}) and (infants: 7.7×10^{-6};

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Table 2 (*continued*)

No	References	Location & Country	No of Sampling sites & size	Sampling period and season	Water Media	Contamination of water sources	Uses of water media	DDT levels (μg/L)	Summary of human health risk assessment
									children: 5.6 × 10^{-6})
6	[33]	Western Brong-Ahafo, Ghana	4 sites 64 samples	Dec 2014–Feb 2015 (dry season-winter)	Hand dug wells	Runoff from cocoa farms, no known recent DDT applications	Used for drinking and domestic purposes	Mean DDT: 0.04 (dry season) DDT detected in 31.6% of water samples	N/A

3.1. DDT residue levels in Southern Africa's waterways

Within the context of Southern African nations (Table 1), studies exclusively emanate from South Africa. A total of five studies were conducted in this region, encompassing two investigations in the Eastern Cape [24,26], two in Limpopo [27,28] and one in Kwa-Zulu Natal [25]. Four studies [24–26,28] detected DDT residues in surface water (from four rivers and one estuary), and one study detected DDT residues in drinking water from taps [27]. DDT residues in the five studies were detected throughout the year but varied seasonally and peaked in different seasons in the different areas. The provinces in which the studies were conducted (Limpopo, Kwa-Zulu Natal, and the Eastern Cape) have similar microclimates, with rainy summers and dry winters.

In most of the sampling sites, as discerned in the studies conducted by Adeyinka et al. [25] during the wet and pre-wet seasons, Yahaya et al. [26] in the wet season, Van Dyk et al. [27] during the wet season and Barnhoorn et al. [28] (season not explicitly specified), DDT concentrations surpassed the WHO drinking water guideline of 1 μg/L. This included samples sourced from tap water designated for consumption [27]. The highest DDT concentration, quantified at 81.15 μg/L, was recorded in the Msunduzi River during the pre-wet season [25].

Only the two studies in the Eastern Cape - Olisah et al. [24], encompassing all seasons and Yahaya et al. [26], spanning both dry and wet seasons - conducted a health risk assessment. In the study by Olisah et al. [24], both the carcinogenic and non-carcinogenic risks for DDTs in Sundays and Swartkops estuaries were found to be below an acceptable lifetime risk in drinking and bathing water.

3.2. DDT residue levels in West Africa's waterways

In West Africa, studies were conducted in Nigeria and Ghana (Table 2). Four studies in Nigeria investigated DDT levels in surface water from three rivers and a reservoir. A study by Adeyinka et al. [29] carried out during the dry and pre-wet season found DDT metabolites at very low concentrations (DDE: 0.007 μg/L and DDD: 0.005 μg/L). A study by Olutona et al. [32] was carried out during the dry season and had the lowest DDT concentrations (ranging from 0.03 μg/L to 0.05 μg/L). Higher DDT levels of 0.12 μg/Land 0.09 μg/L were found in the studies by Ogbeide et al. (2015[a]) and Ogbeide et al. [31] respectively, conducted throughout all seasons. DDT levels in all of these studies were below the WHO drinking water guideline threshold of 1 μg/L, including in the Aiba reservoir [32] and Illushi River basin [31], which are used to provide drinking water. Notably, human risk assessments were only conducted by Ogbeide et al. [31] and Adeyinka et al. [29]. Ogbeide et al. [31] found no non-cancer effects as the hazard quotients (HQs) were lower than one. In contrast, Adeyinka et al. [29] identified potential non-cancer and carcinogenic risks in children compared to adults, as their HQs exceeded one and the carcinogenic risk (CR) values surpassed the permissible guideline of 1×10^{-6}, respectively.

Two studies by Affum et al. [15] and Fosu-Mensah et al. [33] were conducted in western Ghana and explored the levels of OCPs in surface and groundwater sources. Affum et al. [15] found DDT concentrations of 0.08 μg/L and 0.06 μg/L during the wet season in water samples obtained from groundwater (boreholes) and surface water (rivers). In contrast, Fosu-Mensah et al. [33] sampled groundwater during the dry season, revealing a lower concentration of 0.04 μg/L. In both studies, the DDT concentrations did not vary much and were all below the WHO drinking water guideline threshold of 1 μg/L for drinking water. When assessing risk, Affum et al. [15] reported cancer risk values for children and infants that exceeded the permissible guideline (1×10^{-6}) based on the US-EPA standard (2005).

3.3. DDT residue levels in East Africa's waterways

In East Africa, studies were undertaken in Kenya, Mozambique, Ethiopia, Zambia, and Tanzania (Table 3). In Kenya, two investigations were conducted by Musa et al. [35] and Muendo et al. [34] in wet and wet-light rain seasons. These studies involved the collection of water samples from various rivers. In both studies, higher DDT concentrations were found during the wet season; with Muendo et al. [34] measuring a concentration of 1.36 μg/L, slightly exceeding the WHO guideline, whereas in the study by Musa et al. [35], a concentration of 0.36 μg/L was measured during the wet season. In Mozambique, one study involved the assessment of DDT levels in drinking water samples from the Manhiça district, collected during the dry season and a total DDT residue level of 0.03 μg/L was found, which was below the WHO drinking water guideline [36].

Table 3
Studies reporting DDT levels in East African water resources.

No	References	Location & Country	No of Sampling sites & size	Sampling period and season	Water Media	Contamination of water sources	Uses of water media	[a]DDT levels (μg/L)	Summary of human health risk assessment
Kenya									
1	[34]	Bungoma district, Kenya	_	Aug 2008 (wet period) & Dec 2008 (light rain period)	Surface water (River kuywa)	Runoff from sugarcane farms, no known recent DDT applications	Used for drinking purposes	Max DDT in wet season:1.36 Max DDT in light rain season: 0.17	N/A
2	[35]	Victoria Basin, Kenya	7 sites	Jan–March 2009 (dry season) Oct–Dec 2009 (wet-light rain season)	Surface water (Nyando Sondu-Miriu Basin)	Contamination by agricultural pesticides & insecticides, no known recent DDT applications	Source of water for residential, irrigation, industrial and power generation	Mean DDT in Wet season: 0.36 Wet-light rain season: 0.29 Max DDT: 0.2	N/A
Mozambique									
3	[36]	Manhica district, Mozambique	20 sites	July 19th & 25th 2018 (dry season)	Ground water (boreholes) Surface water (Wells & build fountains)	DDT runoff from IRS	Serves as sources of drinking water	Mean DDT in dry season: 0.03 Max DDT: 0.013	N/A
Ethiopia									
4	[37]	Ethiopia	43 water samples at 8 sites	April 2018 (dry season) and September 2019 (wet season)	Surface water: Lake, tributary rivers, and wetlands	Pesticide runoff from farms	Serves as a source of water consumption and provides valuable ecosystem services (e.g., fisheries and water for crop cultivation)	Mean DDT in Wet season: not detected. Dry season: 0.24	HQ: River-(Infant = 0.63; children = 0.42; adults = 0.14) Wetland-(Infant = 0.42; children = 0.28; adults = 0.09) Lake-(Infant = 0.16; children = 0.11; adults = 0.04)
5	[38]	Central rift valley, Ethiopia	12 sites	March, May & July 2015; July 2016	Tap water and surface water (rivers)	DDT contamination through IRS.	Agricultural and drinking purposes	Not detected	N/A
Zambia									
6	[39]	Zambia	3 sites	July 2012 (dry season)	Surface water (shallow wells & open streams) & taps	DDT contamination through IRS	Sources of drinking water	Mean DDT in dry season: 0.77 Max DDT: 0.51	N/A
Tanzania									
7	[40]	Mainland Tanzania	20 sites	Not mentioned in the study	Surface water (Lakes and reservoirs)	Contamination by the organic micropollutants	The lakes are precious water resources and	Mean DDT = 0.001	N/A

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Table 3 (*continued*)

No	References	Location & Country	No of Sampling sites & size	Sampling period and season	Water Media	Contamination of water sources	Uses of water media	[a]DDT levels (μg/L)	Summary of human health risk assessment
						and organochlorine pesticides (OCPs)	stunning wildlife habitats		
8	[41]	Tanzania	12 sites	Sept–Oct 2009 (dry season); March–April 2010 (rainy season); Jan–Feb 2011 (pre-rainy season)	Surface water (Pangani River & tributaries)	Agrochemical pollution linked to fast-growing floriculture. Small-scale farmers around the river basin cultivate a range of fruits and vegetables near to water sources, threatening river water quality. No known recent DDT applications	Drinking and domestic uses, also used by cattle, hydropower generation & industries	Max DDT in dry season: 0.002 DDT detected in 58% of water samples	N/A

[a] Not all studies reported on mean/median DDT concentrations.

Two studies were conducted in Ethiopia. One study investigating DDT levels in surface water samples from agriculture, effluents from floriculture and taps for drinking water, found no detectable DDT residues in any of the samples [38]. Conversely, the study by Abera et al. [37] in which sampling was conducted during the dry and wet season, detected DDT only during the dry season at a mean concentration of 0.25 μg/L. A human health risk assessment was performed in this study revealing HQs below permissible levels, with elevated values noted for infants, followed by children, while adults exhibited the lowest values.

In Zambia, a study investigating DDT levels in various samples, including drinking water, was conducted during the dry season in three regions, including a control region where no DDT spraying occurred [39]. In the control region, DDT residues were not detected, but in regions where DDT was applied, the highest concentration of DDT found was 0.77 μg/L [39], which was below the WHO drinking water guideline for DDT.

Lastly, in Tanzania, one study investigated DDT levels in surface water used for drinking and recreational purposes [41] throughout all seasons and detected DDT in 58% of water samples. The highest concentration found was 0.002 μg/L for total DDT during the dry season, which was below the WHO drinking water guideline for DDT. Another study by Zhao et al. [40] which sampled DDT in lakes and reservoirs also identified a low DDT mean concentration of 0.001 μg/L.

3.4. *DDT residue levels in North Africa's waterways*

In North Africa, studies from Egypt, Morocco and Tunisia were found (Table 4). Two studies were conducted in Egypt in the vicinity of three intensive agricultural and industrial areas along the Nile in one study [42] and a large lake in the other study [43]. The highest concentrations of DDT were found by Dahsan et al. (2016) who sampled during the dry season, whilst Kamel et al. [43] sampled during both the dry and wet seasons, and found slightly higher concentrations during the wet season. In both studies, the total DDT concentrations recorded during the different seasons were greater than 3 μg/L surpassing the WHO drinking water guideline for DDT. Nevertheless, no definitive evidence suggests that the water was used for drinking, as according to Dahshan et al. [42] the water sampled from the Nile River was used for agricultural and industrial purposes, and according to Kamel et al. [43] the water from Manzala Lake was used for recreational purposes such as fishing. Interestingly, both studies revealed p, p'-DDT as the predominant DDT metabolite, indicating recent DDT application.

Two studies were conducted in Morocco: Lakhlalki et al. [45] conducted a study throughout all seasons, and Berni et al. [44] performed investigations during both the wet and dry seasons. Lakhlalki et al. [45] collected water samples from a lagoon receiving agricultural and industrial effluent and run-off, while Berni et al. [44] sampled groundwater from wells used for drinking and agriculture in a rural area. The highest concentration observed in the latter study was found during the dry season. Importantly, the highest total DDT concentrations found in these studies were well below the WHO drinking water guideline threshold of 1 μg/L.

A health risk assessment conducted by Berni et al. [44] identified cancer risk values for infants (DDT & DDE = 1.8×10^{-5}) and children (DDT-1.6×10^{-6}; DDE-1.4×10^{-6}) exceeding the US-EPA standard of 1×10^{-6} (2005) for the carcinogenic risk assessment. Thus, despite DDT concentrations in the water samples falling below the WHO guidelines, the risk assessment indicated the water was not safe for use by infants and children. Additionally, for the non-carcinogenic risks, HQs of 1×10^{-2} (infants), 3×10^{-3} (children) and 1.4×10^{-3} (adults) were determined, which are below the permissible guideline.

Lastly, in Tunisia, Zaghden et al. (2022) conducted sampling in surface water in autumn during the wet-light rain season and found a low maximum DDT concentration of 0.0132 μg/L. Notably, no health risk assessment was undertaken in this study.

Table 4
Studies reporting DDT levels in North African water resources.

No	References	Location & Country	No of Sampling sites & size	Sampling period and season	Water Media	Contamination of water sources	Uses of water media	[a]DDT levels (μg/L)	Summary of human health risk assessment
Egypt									
1	[42]	Egypt	20 sites 60 samples	Summer 2013 (dry season)	Surface water (Nile River)	Sources of contamination not mentioned in the study and no known recent DDT applications	Main source of drinking water	DDT = 5.62 (dry season) Mean DDT = 2.3	N/A
2	[43]	Egypt	4 Sites	Oct 2012 (dry season) and March 2013 (wet seasons)	Surface water (Manzala lake)	Meeting place for several contaminated water supplies, no known recent DDT applications	Recreational use (fishing)	DDT in dry season = 3.23 DDT in wet season = 3.36 (wet season)	N/A
Morocco									
3	[44]	North-central Morocco	22 sites 84 Samples	Summer 2017 (dry season) Winter 2018 (wet season)	Ground water (wells)	Contamination from earlier use of technical DDT	Utilized for drinking and agricultural purposes	DDT in dry season = 0.06 DDT in wet season = 0.03 Max DDT = 0.03	Carcinogenic risk values: DDT 1.8×10^{-5} (infants); 1.6×10^{-6} (children) & 2.4×10^{-7} (adults). DDE 1.8×10^{-5} (infants); 1.4×10^{-6} (children) & 2.2×10^{-7} (adults). Non-carcinogenic risk values (HQ): DDT 1×10^{-2} (infants); 3×10^{-3} (children) 1.4×10^{-3} (adults)
4	[45]	El Jadida & Safi, Morocco	5 sites	May 2015–April 2016 (all seasons)	Surface water (Oualidia lagoon)	Receives saltwater, exposed to agricultural and grazing land, polluted by runoff from septic tanks, no known recent DDT applications	Used for oyster & cereal farming	Mean DDT = 0.000023 (all seasons)	N/A
Tunisia									
5	[46]	Tunisia, Southern Mediterranean Sea	27 water samples at 27 sites	October 30 to November 3, 2017 (Autumn-wet-light rain season)	Surface water	High anthropogenic activities, including industrial, agricultural, and domestic activities, as well as atmospheric transport	Supports various economic activities, including fishing and agriculture	Max DDT = 0.0132	N/A

[a] Not all studies reported on mean/median DDT concentrations.

Table 5
Summary of the type of water sources in which DDT was detected in the different African countries.

African Countries	Types of water sources
South Africa	Rivers, estuaries and tap water
Nigeria	Rivers and a reservoir
Ghana	Hand-dug wells, boreholes, and rivers
Kenya	Rivers
Egypt	River and a lake
Morocco	Lagoon and wells
Ethiopia	Rivers, Lake, wetlands and tap water
Mozambique	Boreholes, wells and build fountains
Tanzania	River, Lakes, reserviors and tributaries
Zambia	Shallow wells, open streams and tap water
Tunisia	Sea water

3.5. Water sources sampled in the reviewed studies

Table 5 shows that the water resources in which DDT was detected in this review of 24 studies and 11 countries, included several surface water sources, reservoirs, groundwater and tap water. The sites included those providing water used for drinking, agricultural purposes and recreational activities.

3.6. DDT levels during the wet and dry seasons

Fig. 2 below illustrates DDT concentrations in four studies that compared DDT levels during the wet and dry seasons. Yahaya et al. [26] in South Africa and Kamel et al. [43] in Egypt, reported higher total DDT concentrations across all sites during the wet season than in the dry season. In contrast, the study by Berni et al. [44] in Egypt found a total sum of 0.03 μg/L for DDT concentrations during the wet season, a value lower than the total sum of 0.06 μg/L found during the dry season. Similarly, the study by Abera et al. [37] conducted in Ethiopia did not detect any DDT in the wet season but found a DDT mean concentration of 0.24 μg/L during the dry season.

Table 6 illustrates the mean DDT concentrations detected in various studies that sampled water during either the dry or wet seasons. Affum et al. [15] and Van Dyk et al. [27] exclusively conducted sampling during the wet season, revealing a mean DDT concentration of 3.84 μg/L. In contrast, Olutona et al. [32]; Fosu-Mensah et al. [33]; Villanueva et al. [36]; Munyinda et al. [39]; Hellar-Kihampa et al. [41], and Dahshan et al. [42] sampled in the dry season, reporting a mean DDT concentration of 1.1 μg/L. The observed mean DDT concentration during the wet season across these studies surpasses that recorded during the dry season although the standard deviations indicate that the difference in the means is within their variability.

4. Discussion

4.1. Overview of main results

This comprehensive scoping review incorporates findings from 24 studies undertaken across 11 African nations, focusing on the

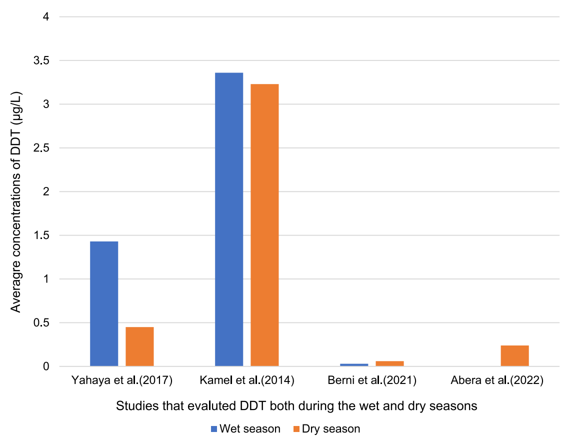

Fig. 2. Comparison of DDT levels found in the 4 studies that evaluated DDT both during wet and dry seasons.

Table 6
Table Comparison of mean DDT levels (μg/L) found in studies that investigated DDT in either the wet season or dry season only.

Season	Mean (SD) DDT concentration
Wet season	3.84 (5.28)
Dry season	1.1 (2.23)

detection of DDT levels in diverse water sources and, wherever feasible, includes health risk assessments. It is noteworthy that a majority of these investigations were conducted in South Africa. The prevalence of DDT-related research in South Africa surpasses other African nations for a variety of reasons. Primarily, South Africa has a long history of DDT use for malaria control, with some areas having implemented indoor residual spraying (IRS) for over 80 years [47]. This long-term use of DDT has raised concerns about its impact on human health and the environment, subsequently leading to increased research in the country [48]. Additionally, South Africa's diverse ecosystems and rich biodiversity make it an important region to study the ecological risks associated with DDT [49]. Furthermore, South Africa has dedicated resources and funding available to conduct research and monitoring, including a dedicated malaria surveillance unit. Overall, the combination of historical DDT use, ecological significance, and external/dedicated funding has likely contributed to the higher level of research on DDT in South Africa compared to other African countries.

4.2. Types of water sources in which DDT was detected

Table 5 indicates that the studies reviewed found the presence of DDT residues in samples from several water sources used formally for drinking water. In contrast, evidence from reviews of studies conducted in other regions highlights limited data on DDT residues in drinking water. For instance, a review by Sarker et al. [50], which studied four South Asian countries (India, Pakistan, Nepal, and Bangladesh), included studies investigating DDT residues from rivers and lakes used to provide freshwater mostly for agricultural and industrial purposes, with some used by surrounding communities for domestic purposes. The review presented limited data on DDT residues in drinking water sources. Similarly, Zhang et al. [20] conducted a review in South China, encompassing studies that collected water samples from rivers, ponds, a harbour, a bay, and the sea - sources used mainly for fishing, not drinking. Additionally, another review by Girones et al. [22] in South America explored evidence of DDT exclusively in coastal waters and sea surface water, without any indication of its presence in drinking water sources.

This review does not provide sufficient data for a feasible comparison of DDT levels in different water sources. However, rivers have been identified as particularly vulnerable due to receiving direct discharges from industrial and agricultural activities (Wang et al., 2013), the presence of organic matter such as sediments and suspended solids to which DDT binds [51] and the ongoing release of DDT through IRS into the outdoor environment, including rivers, through dust and air [52].

4.3. Seasonality of the DDT detections

Four of the 24 studies included in this review were conducted across both wet and dry seasons. In reference to Fig. 2, higher DDT concentrations were identified during the wet season in studies conducted by Yahaya et al. [26] and Kamel et al. [43], surpassing the [53] drinking water guideline threshold of 1 μg/L. In contrast, the studies by Berni et al. [44] and Abera et al. [37] reported slightly higher DDT concentrations during the dry season, but these concentrations remained below the [53] drinking water guideline threshold of 1 μg/L. The slightly higher DDT levels observed during the dry, summer season in the study by Berni et al. [44] are likely attributed to DDT application on fruit trees in Morocco during this period, potentially resulting in heightened groundwater concentrations [44]. Abera et al. [37] did not provide specific reasons for higher DDT levels in the dry season, but similar factors may be at play.

As illustrated in Table 6, other studies conducted sampling either during the wet or dry seasons. The mean DDT concentration during the wet season (3.84 μg/L) exceeded that for the dry season (1.1 μg/L) and surpassed the WHO drinking water guideline threshold of 1 μg/L. The higher DDT concentrations in water systems during the wet seasons may be attributed to the runoff of residues from previously sprayed areas, facilitated by rainfall, into the different water bodies [55]. DDT levels are higher during rainy seasons due to factors such as increased application of DDT for malaria control; for example, in countries like South Africa mosquitos are more prevalent during summer, which is a wet season in many malaria-endemic South African areas, hence application of DDT in this season may be high. This implies that the timing of DDT application may affect the levels of DDT and its metabolites in water bodies [56].

The analysis of malaria transmission under future climate change factors with regard to changes in temperature and rainfall is important, as human health is at risk. Many previous studies imply that variations in malaria distribution are partly caused by anthropogenic climate change. For instance, the impact of malaria, a leading cause of morbidity and death in south-eastern Asia, is projected to worsen as a result of climate change [57]. Southern African contexts have already seen examples of changes in malaria patterns, and as such, if current protocols were followed, this would mean an increased spread in the distribution of DDT in southern African waterways [58].

4.4. Evidence of human health risks due to DDT residues in African waterways

In seven of the 24 reviewed studies [25–28,34,42,43], DDT residues exceeding 1 μg/L were detected in various water sources, including surface water and tap water designated for consumption [26,27,34,42]. The highest total DDT concentration of 81.2 μg/L was detected in the Msunduzi River in South Africa [25]. South Africa's notably high DDT levels, in comparison to other African countries, may be attributed to its continued use for malaria control in specific regions of the country (Bornman et al., 2020), coupled with its persistence and bio accumulative nature. The prolonged utilization of DDT of over 80 years in South Africa has resulted in its accumulation in the environment and wildlife, including aquatic birds and anuran species (Bouwman et al., 2019).

DDT levels found in African water sources were higher than those found in the South Asian, South Chinese, and South American reviews (Table 7) with the latter two conforming to WHO guidelines. The highest DDT concentration found in the South Asian review, was 23.6 μg/L detected in Lake Chilika in India, a source of fish for nearby communities [50]. The other water source (Tapi River in India) in the South Asian review that had DDT concentrations greater than the WHO guideline, was not a source of water that directly exposed humans.

In the South American review, the highest level of DDT found was 0.1 μg/L in Santa Marta Bay [22]. All observed water sources were coastal and seawater, unsuitable for human consumption. In the South Chinese review, the highest DDT concentration detected was 0.2 μg/L in the Shenzhen River. Hence, the DDT levels from all the sites were lower than the WHO guideline. Although there were no reports of water from the study sites in the South Chinese review being used for drinking, the fish from some of the water sources were consumed by nearby communities [20]. All the DDT residue concentrations detected in studies from other geographic regions in non-potable water were therefore lower than the WHO guideline.

High levels of DDT in Africa compared to other continents can be attributed to its use for malaria control through Indoor Residual Spraying (IRS), contributing significantly to its presence in the environment (Mabaso et al., 2004). Furthermore, the persistence of DDT in the environment and its long history of usage in Africa, spanning over 80 years, may account for its heightened prevalence (Bouwman et al., 2019).

Seven studies included in this review conducted human health risk assessments. The DDT concentrations detected in all the studies [15,24,26,29,31,37,44] were below the WHO guidelines except for the study conducted by Yahaya et al. [26] in South Africa (DDT concentration = 1.43 μg/L).

Three studies by Affum et al. [15]; Adeyinka et al. [29] and Berni et al. [44] found the cancer risk for infants and children consuming sampled water to be higher than the US-EPA (2005) acceptable level (1×10^{-6}). Conversely, the cancer risk for adults in these studies remained below the acceptable level [15,29,44]. Notably, the cancer risk associated with water from the Sundays and Swartkops estuaries, a water source for bathing and drinking, as reported by Olisah et al. [24], was found to be below the permissible guideline of 1×10^{-6} for drinking and bathing water. One in a million, or 1×10^{-6}, represents the acceptable lifetime cancer (health) risk. A risk level between 1×10^{-6} and 1×10^{-4} is regarded as concerning, while one above 10^{-4} is regarded as an unacceptable risk (US-EPA, 2005).

The HQ for non-carcinogenic risks associated with DDT concentrations in water in studies by Olisah et al. [24]; Yahaya et al. [26]; Berni et al. [44]; Ogbeide et al. [31] and Abera et al. [37] was below one. In contrast, the study by Adeyinka et al [29], conducted in the Asa Dam River in Nigeria, which supplies drinking water to nearby communities, found significantly high HQs values for children but not for adults, with the highest value recorded at 4.38. The study conducted by Adeyinka et al [29] suggests that children are at a high risk of acquiring non-cancer effects from consuming DDT contaminated water from the ASA Dam River. This African review, therefore, presents more evidence of risks to human health due to DDT residues in waterways, when compared to reviews in other regions. This implies that African populations are more exposed to DDT through water pollution, through drinking water and other water/-environmental sources.

Children exhibit a higher risk compared to adults when exposed to DDT in drinking water due to their higher water intake relative to their body weight and higher vulnerability to adverse health effects [59]. The presence of DDT and its metabolites in drinking water can therefore pose a range of health risks to children, including acute diseases, developmental effects, endocrine disruption, and cancer (Barnhoorn et al., 2009).

4.5. Limitations and future research dimensions

This review found studies conducted in 11 African countries, with no studies identified in the other 41 African countries. Consequently, the review lacks representation across the African continent. While there was representation from Eastern, Western, Northern, and Southern African regions, the distribution of studies across these regions varied significantly, with 42% of the studies emanating from South Africa (21%), and the Western African countries, Nigeria and Ghana (21%).

Only two of the 24 studies [24,45], conducted sampling across all the different seasons of the year. Hence, most of the studies did not measure DDT levels over different seasons. Furthermore, most studies did not collect water samples from multiple water sources in the study areas, with only five studies [15,36–39] monitoring from a range of different water sources.

Table 7
Comparison of DDT levels in water systems of different continents.

References	Continents	Countries	Max DDT levels (μg/L)
[22]	South America	Colombia	0.1
[50]	South Asia	India	23.6
[20]	Asia	South China	0.2

WHO Standard limit of DDT in water: 1 μg/L).

Moreover, in 13 studies (54%), the number of samples collected was not specified, hence it cannot be confirmed whether the number of samples was sufficient to give reliable results. As previously mentioned, only seven studies conducted risk assessments, while most of the studies that had DDT concentrations higher than the WHO guideline of 1 μg/L did not conduct risk assessments.

Furthermore, we only reviewed articles written in English, thereby excluding studies published in other languages. Additionally, the review process involved a single reviewer, which may have introduced some errors in data extraction and potentially led to selective reporting of results from the included studies.

The limitations highlight a need for future research to investigate the presence of DDT in diverse African settings. Additionally, studies investigating the long-term health effects of DDT in these settings would be an important future avenue of inquiry.

5. Conclusion

This review of 24 African studies conducted in 11 countries over the recent 13 years found compelling evidence of the significant environmental implications and adverse human health risks posed by DDT residues in various African waterways despite the limited research on the continent. DDT residues were found in multiple water sources, with most of the detections occurring at variable concentrations throughout the year, with the highest levels detected during the wet season. These residues were detected in water samples collected from areas where DDT is employed for malaria vector control or where it was historically used, such as in agricultural settings. Evidence indicating risks to human health was found, as more than a third of the concentrations of DDT residues detected exceeded the WHO drinking water guidelines and/or cancer permissible limits. This was particularly evident in many of the sampled drinking water sources.

The findings of this review underline the importance of seeking solutions to reduce or remove exposure to DDT in these settings. Foremost among these solutions is the pressing need for alternative approaches to malaria vector control. This includes the evaluation of the impact of mutations identified in Anopheles funestus mosquitoes, resulting in resistance against DDT thereby reducing its effectiveness. Secondly, this review emphasizes the critical importance of developing and implementing appropriate policies and interventions, including those preventing or reducing emissions of DDT residues into the environment. This includes ensuring that African countries fulfil the requirements of the Stockholm Convention to cease the utilization of persistent organic pollutants.

Thirdly, the improvement in access to health care to communities in these settings is crucial considering the health risks posed by DDT exposure which adds to multiple other health risks. Fourthly, there is a need to ensure appropriate education and awareness among these communities of the health risks posed by DDT exposure and the importance of reducing exposure. Lastly, this review also highlights the need to increase research on the continent considering the limited data available, especially larger studies conducting seasonal monitoring of DDT residues in multiple water sources, including drinking water, and assessing health risks.

Funding and conflict of interest

This work was supported by the National Research Foundation (NRF) [grant number: 133652]. The authors do not have any conflicts of interest.

Data availability statement

Question	Response
Data Availability Sharing research data helps other researchers evaluate your findings, build on your work and to increase trust in your article. We encourage all our authors to make as much of their data publicly available as reasonably possible. Please note that your response to the following questions regarding the public data availability and the reasons for potentially not making data available will be available alongside your article upon publication. Has data associated with your study been deposited into a publicly available repository?	No
Please select why. Please note that this statement will be available alongside your article upon publication. as follow-up to "Data Availability	All data has been included in article/supp. material/referenced in article

CRediT authorship contribution statement

Lethabo Makgoba: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Amber Abrams:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martin Röösli:** Writing – review & editing. **Guéladio Cissé:** Writing – review & editing. **Mohamed Aqiel Dalvie:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Gill Morgan from the Faculty of Health Science library at the University of Cape Town, is acknowledged for assistance with the literature search.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e28054.

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