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Organochlorine pesticides in placenta, blood and breast milk of mothers in Uganda: Concentrations and health risks to breast fed infants

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ABSTRACT

Exposure to organochlorine pesticides (OCPs) remains a major public health concern in low-income countries, where historical usage and poor regulation continue to result in maternal and early-life exposures. This study assessed concentration profiles of selected OCPs, namely; *p,p′*-DDT, *p,p′*-DDE, *o,p′*-DDE, *p,p′*-DDD, *o,p′*-DDD, aldrin, dieldrin, lindane, α-endosulfan, β-endosulfan, and endosulfan-sulfate in maternal blood, breast milk, and placenta samples collected from 52 healthy mothers residing in the rural Kanungu District and urban Kampala District in Uganda. Analytical quantification was performed using gas chromatography-electron capture detection (GC-ECD), and compound identity was confirmed by gas chromatography–mass spectrometry (GC-MS). Concentrations of total DDTs (∑DDTs) were 63.0, 27.1, and 35.0 ng g^{-1} lipid weight (l.w) in blood, breast milk, and placenta, respectively. *o,p′*-DDE was the predominant metabolite in blood (67% of ∑DDTs), while *p,p′*-DDE dominated in placenta and milk (34% and 70%, respectively), possibly due to degradation of technical DDT applied in past decades. Other OCPs were generally low (<Limit of detection, LOD to 88.4 ng g^{-1} l.w), except for dieldrin, which reached 130 ng g^{-1} l.w in breast milk. OCP levels were significantly higher in Kanungu than Kampala, attributable to ongoing informal pesticide use in agriculture. In general, the estimated hazard quotients were <1, which indicated that the health risks posed to infants due to ingestion of OCPs in breast milk was negligible. Our findings underscore the need for rural pesticide regulation and continuous maternal exposure monitoring.

1. Introduction

Organochlorine pesticides (OCPs), such as aldrin, chlordane, dieldrin, endrin, heptachlor, toxaphene, endosulfan, mirex, lindane, and DDTs are compounds with high molecular weight, low water solubility, and high lipid affinity. These properties enable these chemicals to penetrate biological phospholipid membranes and accumulate in fatty tissues of living organisms (Kafilzadeh, 2015). OCPs are also resistant to photolytic, chemical, and biological degradation, allowing them to persist in the environment and undergo long-range atmospheric transport (Van den Berg, 2009). Consequently, OCPs have been detected in regions far beyond their original sites of application, including oceans,

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the Arctic, and the Antarctic (Fisher et al., 2016). Importantly, OCPs are toxic and can interfere with normal biological functions in organisms that absorb them (Schug et al., 2011). In humans, their toxic effects include cancer, endocrine disruption, immune suppression, pneumonia, mental retardation, neurological disorders, low birth weights, obesity, chromosomal abnormalities, and reproductive impairment (Casas et al., 2015; Sudmalis et al., 2016; Garg et al., 2025). Due to their persistence and toxicity, many OCPs were banned or restricted under the Stockholm Convention on Persistent Organic Pollutants (POPs) (Polder et al., 2016).

The major exposure pathways for OCPs in humans include dermal absorption, inhalation, and ingestion of contaminated food, particularly animal-based products (Lee and Ji, 2022). Once absorbed, these compounds are distributed systemically via storage, excretion, and metabolic processes (Needham et al., 2005). Pregnant and breastfeeding mothers are particularly vulnerable to OCP exposure due to increased consumption of animal proteins such as fish, milk, and meat during these periods (Marks et al., 2021; Witczak et al., 2021). Indeed, several studies have identified diet as a primary contributor to OCP levels in human tissues (Cao et al., 2011; Luo et al., 2016). Once internalized, these pollutants may be transferred to the developing fetus via the placenta or to nursing infants via breast milk, thereby posing significant early-life health risks (Tutu et al., 2013; Nanes et al., 2014; Abdel Hamid et al., 2020). For example, OCPs have been associated with impaired infant anthropometric development (Diwan et al., 2013), altered childhood behaviour (Forns et al., 2016), gut microbiome disruption (Iszatt et al., 2019), and cryptorchidism in male infants (Kao et al., 2019).

In Uganda, the use of OCPs dates to the 1950s, with widespread use in pest management (e.g., in cotton farming) and in public health programmes targeting disease vectors such as tsetse flies, black flies, and mosquitoes in several districts, including Kanungu District (Amusa et al., 2021; Ssebugere et al., 2010). Lindane, endosulfan, and dieldrin were widely applied in agriculture and vector control until the 1990s, when their use was banned due to severe ecological damage, including widespread destruction of banana plantations (Kasozi et al., 2006). Although the use of OCPs within Kampala District has not been systematically investigated, the expansion of peri-urban agriculture to support the city's fast-growing population combined with atmospheric deposition may have contributed to the contamination of urban environmental systems. Several studies have confirmed the presence of OCP residues in food commodities sold within the city's markets, such as fresh carrots (Nannyonga et al., 2013), fish (Kasozi et al., 2006), honey (Mukiibi et al., 2021), fruits and vegetables (Ssemugabo et al., 2022) and cow's milk (Kampire et al., 2011).

While many studies globally have assessed OCP residues in maternal samples (e.g., Nanes et al., 2014; Lu et al., 2015; Muller et al., 2017), there remains a notable lack of such data for Uganda. In Kanungu District, only one prior study by Bimenya et al. (2007) reported levels of DDT/DDE in human plasma and urine, with no investigation of placenta or breast milk. In Kampala, an earlier study by Ejobi et al. (1996) reported OCP concentrations in breast milk, but this research predated Uganda's ratification of the Stockholm Convention, leaving contemporary trends largely uncharacterized. More recent studies (Matovu et al., 2019, 2020, 2021) have focused on other classes of pollutants such as dioxins, biphenyls, and brominated flame retardants while Odongo et al. (2024) only focused on OCPs in urine and serum of children, with no emphasis on OCPs contamination in maternal biological matrices.

The present study addresses these critical knowledge gaps by assessing current levels and distribution patterns of selected OCPs in maternal blood, placenta, and breast milk from mothers in both Kanungu and Kampala. The study also evaluates the potential health risks to nursing infants. This comparative approach aims to highlight the influence of urbanization and industrialization in Kampala, as well as the long-term impacts of historical indoor spraying and agricultural pesticide use in rural Kanungu.

2. Materials and methods

2.1. Study area

The study was conducted in Kanungu District and Kampala Capital City (Fig. 1). Kanungu, a rural district in southwestern Uganda, was selected due to its historical use of OCPs, particularly for vector control and agricultural purposes (Bimenya et al., 2007). Maternal samples from this district were collected at Kambuga Hospital. Kampala Capital City, by contrast, was purposively selected due to its rapid urbanization and population growth over the last three decades (Loha et al., 2018). According to the most recent national census, the city hosts a population of approximately 1,875,834 residents, while Kanungu District has a population of about 309,735 (Uganda Bureau of Statistics, 2024). The intensifying urban development in Kampala has driven increased peri-urban agricultural activity aimed at sustaining the growing population. These land-use changes, coupled with possible atmospheric transport of pollutants, may elevate maternal exposure to OCPs. Maternal samples from Kampala were collected at St. Francis Hospital Nsambya.

2.2. Participants and sampling procedures

Fifty-two (52) healthy pregnant women (26 from Kanungu district and 26 from Kampala capital city) participated in the study. Participants were identified during routine obstetrics checks at Kambuga Hospital (Kanungu), and St. Francis Hospital Nsambya (Kampala). Only willing mothers who had lived in Kanungu district and Kampala capital city for at least 5 years and consented to participate in the research were considered. Placenta tissues, breast milk, and blood samples were collected between July and August 2018. Placenta tissues and maternal blood samples were obtained at the time of delivery while breast milk samples were collected three weeks after the time of delivery. Each donor mother provided samples of blood (4 mL), and milk (5 mL) which was taken from breasts by manual expression with the help of a physician. Placenta tissues were collected immediately upon expulsion into sterile containers. About 3 g of cotyledons on the maternal surface of the placenta was peeled off using fingers protected by gloves. The samples were collected into clean glass bottles with aluminium seals and labelled. Sample bottles were then transferred into cooling boxes containing dry ice and transported to the laboratory where they were stored at -18 °C prior to analysis.

2.3. Ethical considerations

Permission to conduct the study was granted by the Research and Ethics Committees of Uganda National Council of Science and Technology, and St. Francis Hospital Nsambya, Uganda. Before sample collection, the donor mothers were informed of the aims of the study, and their right to withdraw from the study at any time without reprisal. Mothers who were willing to donate samples signed an informed consent form and filled out a structured questionnaire about their demographic characteristics **(Table S1)** with the help of trained personnel. All the information obtained from the donor mothers was kept confidential by the physicians and Principal Investigator.

2.4. Chemicals and standards

The reference standards for 11 OCPs (*p,p′*-DDT, *o,p′*-DDE, *p,p′*-DDE, *o,p′*-DDD, *p,p′*-DDD, dieldrin, aldrin, lindane, endosulfan-sulfate, endosulfan-α, and –β) analyzed in this study were obtained from Dr. Ehrenstorfer GmbH (Augsburg, Germany). Pesticide residue grade solvents (petroleum ether, cyclohexane, and *n*-hexane) were supplied by Merck Chemicals Ltd (UK). Florisil (PR grade 60-100 mesh) and analytical grade anhydrous sodium sulfate were obtained from Merck, Darmstadt (Germany). Working standards were prepared by diluting the individual

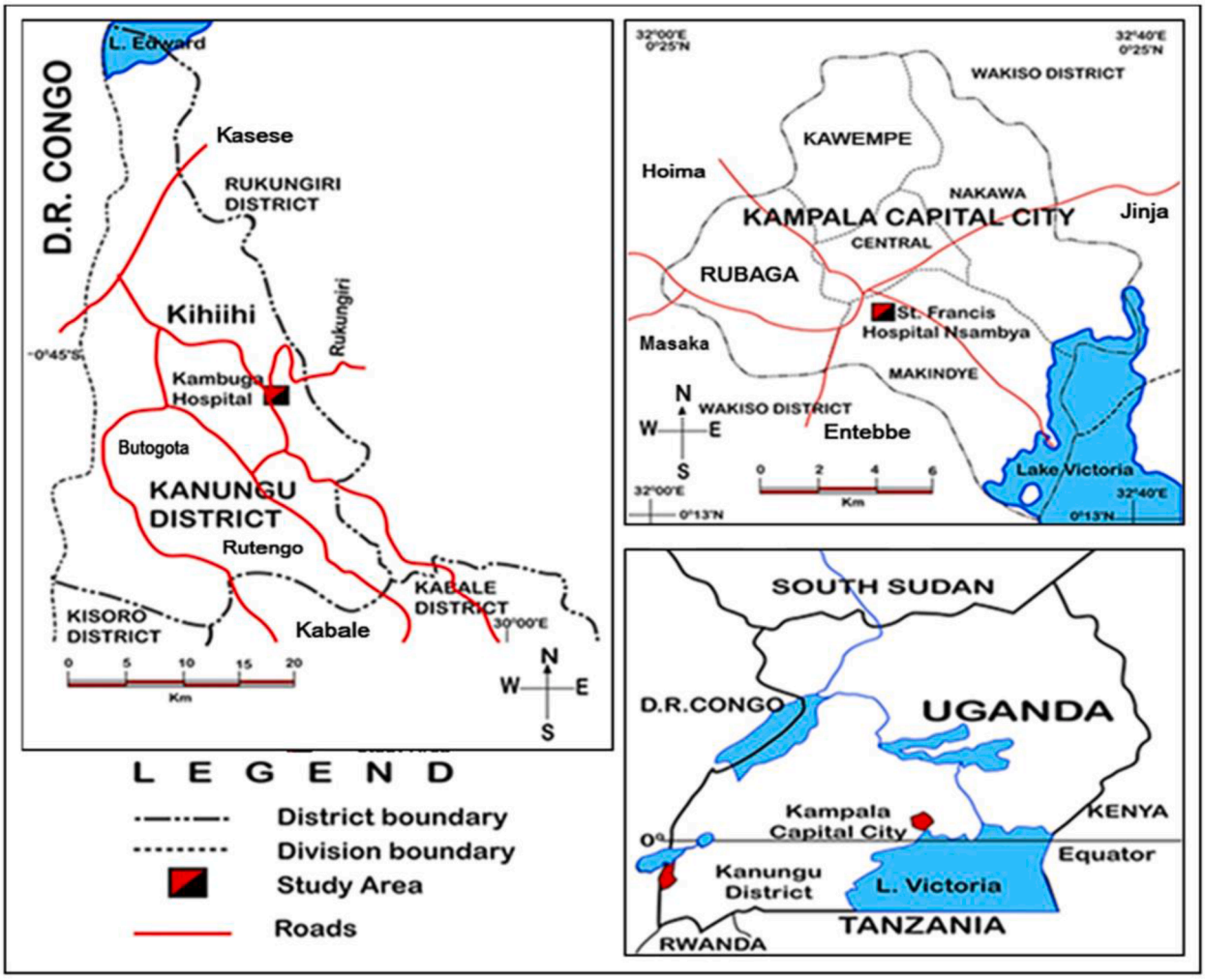


Fig. 1. Map showing the study area.

stock solutions using cyclohexane in calibrated volumetric flasks. The flasks were labelled to include the name of the standard and the preparation date.

2.5. Sample extraction and cleanup

Extraction and cleanup of samples were done following the method described by Kampire et al. (2011), but with slight modifications. Briefly, maternal samples were removed from the freezer and allowed to thaw. Placenta tissues were freeze-dried for 48 h and ground using a mortar and a pestle. One gram (1 g) of the powder was mixed with petroleum ether (5 ml) in a beaker and then transferred into a centrifuge tube. For blood and milk, samples were first stirred thoroughly, and 3 mL portions of each sample were transferred into separate centrifuge tubes. The samples were centrifuged at 300 rpm for 25 min and the supernatant was transferred into a clean flask. The extraction process was repeated three times, and the extracts combined. The combined extracts were evaporated to dryness using a rotary evaporator and the lipid content was determined gravimetrically as described by Matovu et al. (2019).

To the dried extracts of each matrix, 50 mL of petroleum-ether was added. The mixture was shaken vigorously for 2 min and then filtered through anhydrous sodium sulfate to remove any moisture. The filtrate was concentrated to 1 mL using a rotary evaporator at 40 °C and cleaned up using a glass column (4 mm id × 15 cm) packed with florisil (10 g) and anhydrous sodium sulfate (2 g). Prior to adding the extract, the column was reconditioned with about 4 mL of *n*-hexane. The concentrated extract (1 mL) was added to the column and then eluted with *n*-hexane (50 mL). The eluate was concentrated to 2 mL using a rotary evaporator and to near dryness using a stream of nitrogen gas. It was then reconstituted in *n*-hexane (1 mL) and the contents in the flask transferred into the auto-sampler glass vial for instrumental analysis.

2.6. Instrumental analysis

Quantification of analytes was performed using a Varian CP-3800 Gas Chromatograph (Palo Alto, CA, USA) equipped with an Electron Capture Detector (ECD). Chromatographic separation was achieved on a non-polar capillary column (30 m × 0.25 mm internal diameter × 0.25 μm film thickness). The column temperature was programmed as follows: 90 °C held for 1 min, then increased at a rate of 30 °C min^{-1} to 180 °C, and at a rate of 4 °C min^{-1} to 260 °C, and held for 16 min. The carrier gas was hydrogen (99.999% purity) with a flow rate of 1.2 mL min^{-1}. The injector and detector temperatures were 230 and 300 °C, respectively. The GC was operated in a split-less mode, with an injection volume of 1 μL. Data acquisition and processing were conducted using Turbochrom software (Perkin-Elmer Corporation, USA).

Compound identity was confirmed by Gas Chromatography–Mass Spectrometry (GC-MS) using an Agilent 6890N GC system coupled with a 5975 inert XL quadrupole mass spectrometer (Palo Alto, CA, USA). A fused silica capillary column (HP-5MS, 30 m length × 0.25 μm internal thickness × 0.25 mm internal diameter) was used for chromatographic

separation. The temperature of the injector and detector were 250 °C and 320 °C, respectively. The initial column temperature was 110 °C (held for 1 min) then raised at 20 °C min^{-1} to 165 °C (held for 0.5 min), and again raised at 2 °C min^{-1} to 235 °C (held for 1 min) and finally heated at a rate of 35 °C min^{-1} to 280 °C, where it was maintained for 4 min. Helium was used as a carrier gas at a flow rate of 1 mL min^{-1}. The GC-MS system was operated in a split-less mode with a purge-off of 1 min, and the injection volume was 1μL for each run. GC-MSD Chemstation Software was used for data acquisition and processing. OCP compounds in the sample extracts were identified by comparing the retention times and fragmentation patterns of the peaks in the chromatograms of the measured extracts with those in the reference standards. For each OCP, a calibration curve was constructed, and in all cases, R^2 value of the standard calibration curve for each OCP analyte was > 0.99.

2.7. Quality control and quality assurance

Procedural blanks and standards were included in the analysis. One laboratory blank was performed for each batch of 5 samples to check for any possible contamination. Individual reference standards were used to identify and quantify the levels of the analytes. The limit of Detection (LOD) for each analyte was estimated as the concentration corresponding to three times the signal-to- noise ratio. Samples were considered positive when their residue levels were > LOD, while non-detects were taken to be ½ LOD. On the other hand, limit of quantification (LOQ) values were estimated for each analyte as a concentration corresponding to ten times the signal-to-noise ratio. In addition, for each analyte, recovery studies were conducted by spiking blank samples with standard solutions of each analyte. Satisfactory recoveries were obtained by spiking blank samples at levels of 0.4 and 1.0 ng g^{-1} (placenta and blood samples), and 10 and 50 ng g^{-1} (breast milk).

2.8. Estimation of daily dietary intake and health risks posed to infants through consumption of OCP-contaminated breast milk

In the present study, the estimated daily dietary intake (EDI) (ng g^{-1} body weight day^{-1}) of infants via consumption of OCP-contaminated breast milk was calculated using Eq. (1), based on the assumption that a baby of an average weight of 5 kg consumes 700 g of breast milk per day (Du et al., 2016).

$$EDI = \frac{C_{Milk} \times 700\ g\ milk/day \times C_{Lipid}/100}{5\ Kg\ body\ weight} \quad (1)$$

Where, C_{Milk} is the concentration of the analyte in milk (ng g^{-1} l.w) and C_{Lipid} is the percent lipid content in milk. The EDI values were compared to the maximum acceptable daily intake (ADI) recommended by FAO/WHO (1985).

To further assess the risks posed to nursing infants due to consumption of breast milk contaminated with OCPs, the hazard quotient (HQ) of each pollutant was computed. HQ was determined as a ratio of the EDI to the corresponding acceptable daily intake (ADI) for humans as shown in Eq. (2).

$$HQ = \frac{EDI}{ADI} \quad (2)$$

Where the acceptable daily intake (ADI) represents an estimate of the oral daily dose at which no adverse effects because exposure to pollutants is expected. The set ADIs for *p,p′*-DDT, *p,p′*-DDE, *o,p′*-DDE, *p,p′*-DDD, α-endosulfan, endosulfan-sulfate, aldrin, dieldrin and lindane were 10, 10, 10, 10, 6.0, 6.0, 0.1, 0.1 and 5.0 ng g^{-1} body weight day^{-1}, respectively. Normally, HQ values >1 suggest potential health risk while a value <1 indicates no adverse effects due to exposure to contaminants (Hassine et al., 2015).

2.9. Statistical analysis of data

Statistical analyses were performed using Origin Pro 8.5 software and SPSS software version 23.0 for Windows (SPSS Inc., Chicago, IL, USA). Concentrations were presented on a lipid weight basis to compensate for the variations in the lipid content of the samples (Bignert et al., 1994), and to aid comparison with other studies. During statistical analysis, analytes below the LOD were estimated as LOD/2 and only OCPs with a detection frequency of >50% were included in correlation analyses (Forns et al., 2016). The Kolmogorov-Smirnov test was used to test for the normality of the data. Since the levels of OCPs were not normally distributed, statistical differences between the levels of pollutants in the different maternal samples were examined using the Mann-Whitney U test. The association between the levels of OCPs in each of the biological samples and age was determined using the Spearman's rank-order correlation. In all cases, the differences were considered significant when the exact *P*-value was <0.05.

3. Results and discussion

3.1. Maternal demographic characteristics

The demographic characteristics of the donor mothers such as parity, age, exposure to pesticides and pre-pregnancy body mass index (BMI) are summarized in **Table S1** of the Supplementary Material. The mean age of mothers from Kanungu and Kampala was 28.7 and 29.8 years, respectively. Of the 52 mothers, sixteen (16) were primiparous and the rest were multiparous. The mean weight and age of donor mothers was 75.8 ± 9.58 kilograms and 29.3 ± 8.76 years, respectively. Pre-pregnancy BMI was 34.1 ± 6.40 kg/m^2. With reference to the World Health Organization (WHO) classification, 38 % of the mothers were overweight (BMI, 25-<30 kg/m^2), while 34 % of them were obese (BMI, ≥30 kg/m^2). More mothers (84.6 %) from Kampala capital city were employed as compared to those from Kanungu (26.9 %). Generally, mothers reported to have not been exposed to any of the pesticides.

3.2. Quality control parameters

The limits of detection (LOD) were low and ranged between 0.2 - 0.7 ng g^{-1} lipid weight (l.w) in milk samples and 0.05 - 0.3 ng g^{-1} l.w in both blood and placenta samples. However, the limits of quantification (LOQ) values ranged from 0.17 to 2.33 ng g^{-1} l.w in all samples as shown in **Table S2**. Both LOD and LOQ values were lower than the regulatory limits, indicating the reliability of the method for quantification of OCPs in biological samples. In all cases, the mean percentage recoveries of the detected residues varied from 67.0 to 88.0 %. The recoveries served only to ensure that the performance of the method for each of the samples was within acceptable limits (60 – 120%) for routine analysis (Hercegová et al., 2007). Since percentage recoveries were above 60 %, residue levels were not corrected for recovery (**Table S3**).

3.3. OCPs in blood samples

3.3.1. Levels and profiles of DDTs in blood

The concentrations of DDTs and other non-DDT OCPs in maternal blood samples from Kanungu and Kampala are summarized in Table 1. Total concentration of ∑OCPs was 66.2 ng g^{-1} lipid weight (l.w) (range: 0.59–626 ng g^{-1} l.w), with significantly higher levels observed in samples from Kanungu compared to Kampala ($P = 0.048$, Mann–Whitney U test). This difference is likely attributed to the ongoing informal pesticide use in Kanungu, as has been reported in other rural agricultural zones across East Africa (Loha et al., 2018). Between the 1950s and early 2000s, OCPs such as DDT were extensively applied in Kanungu for malaria vector control and crop protection (Rwakimari, 2007). Continued circulation of residual stockpiles and weak enforcement mechanisms may contribute to sustained exposure in rural areas (Loha

Table 1
Concentrations (ng g^{-1} l.w) of organochlorine pesticides in blood samples.

Pesticide	Kanungu (N = 26)			Kampala (N = 26)			All samples (N = 52)		
							Mean lipid % (1.3 ± 1.0)		
	Mean	Range	n > LOD	Mean	Range	n > LOD	Mean	Range	n (%)*
o,p'-DDE	78.9	<0.05 – 485	16	5.55	<0.05 – 42.6	7	42.2	<0.05 – 485	23(44)
p,p'-DDE	5.81	<0.30 – 60.7	5	3.47	<0.30 – 27.6	6	4.64	<0.30 – 60.7	11(21)
o,p'-DDD	14.1	<0.09 – 206	3	0.35	<0.09 – 5.31	3	7.23	<0.09 – 206	6(12)
p,p'-DDD	11.6	<0.07 – 140	5	0.24	<0.07 – 4.62	3	5.92	<0.07 – 140	8(15)
p,p'-DDT	3.83	<0.06 – 43.5	6	2.20	<0.06 – 20.9	5	3.02	<0.06 – 43.5	11(21)
∑DDTs	114	<0.05 – 625		11.8	<0.05 – 70.3		63.0	<0.05 – 625	
Aldrin	<0.10	<0.10	0	<0.10	<0.10	0	<0.10	<0.10	0(0)
Dieldrin	0.23	<0.06 – 5.10	1	0.26	<0.06 – 4.30	2	0.24	<0.06 – 5.10	3(6)
∑DRIN	0.28	<0.06 – 5.10		0.31	<0.06 – 4.30		0.29	<0.06 – 5.10	
α-endosulfan	5.02	<0.20 – 88.4	2	0.53	<0.20 – 11.3	1	2.78	<0.20 – 88.4	3(6)
β-endosulfan	<0.05	<0.05	0	<0.05	<0.05	0	<0.05	<0.05	0(0)
∑Endosulfan	5.05	<0.05 – 88.5		0.78	<0.05 – 11.6		2.80	<0.05 – 88.5	
Lindane	<0.20	<0.20	0	<0.20	<0.20	0	<0.20	<0.20	0(0)
∑OCPs	120	0.59 – 626		13.0	<0.05 – 70.9		66.2	0.59 – 626	

* Number and percentage of samples with levels > LOD.

et al., 2018). In addition, frequent involvement in subsistence farming and closer proximity to contaminated agricultural fields likely elevated maternal exposure via dermal absorption and inhalation (Tutu et al., 2013). In contrast, mothers in Kampala are more likely to consume food from formal markets and reside farther from pesticide-affected zones, which could explain the comparatively lower OCP concentrations in their blood samples.

The concentration of ∑DDTs was 63.0 ng g^{-1} l.w (range: <0.05–626 ng g^{-1} l.w). When compared with studies from other African countries, this level was markedly lower than values reported in Limpopo, South Africa (mean: 7300 ng g^{-1} l.w; Barnhoorn et al., 2010) and Cairo, Egypt (3681 ng g^{-1} l.w; Elserougy et al., 2013). However, the concentrations reported here are within the same range as those measured in delivering women from the industrial (mean: 72; range: 0.3–448 ng g^{-1} l.w) and Atlantic (mean: 52.2; range: 0.2–125 ng g^{-1} l.w) regions of South Africa (Rollin et al., 2009).

Compared to earlier studies from Asia, Europe, and the Americas, the DDT concentrations observed in this study were considerably lower. For instance, blood levels reported in Romania ranged from 446 to 34,930 ng g^{-1} l.w (Dirtu et al., 2006); in Mexico from 1400 to 155,200 ng g^{-1} l.w (Waliszewski et al., 2012), and 5260 ng g^{-1} l.w (Waliszewski et al., 2000); in Spain, 4896 ng g^{-1} l.w (Porta et al., 2008); in Belgium, 70–3290 ng g^{-1} l.w (Charlier & Plomteux, 2002); in Sweden, 836.1 ng g^{-1} l.w (Glynn et al., 2000); and in Guangzhou, China, 283.4–6167.7 ng g^{-1} l.w (Qu et al., 2010). These findings suggest that mothers in Uganda are comparatively less exposed to DDTs than women in many industrialized

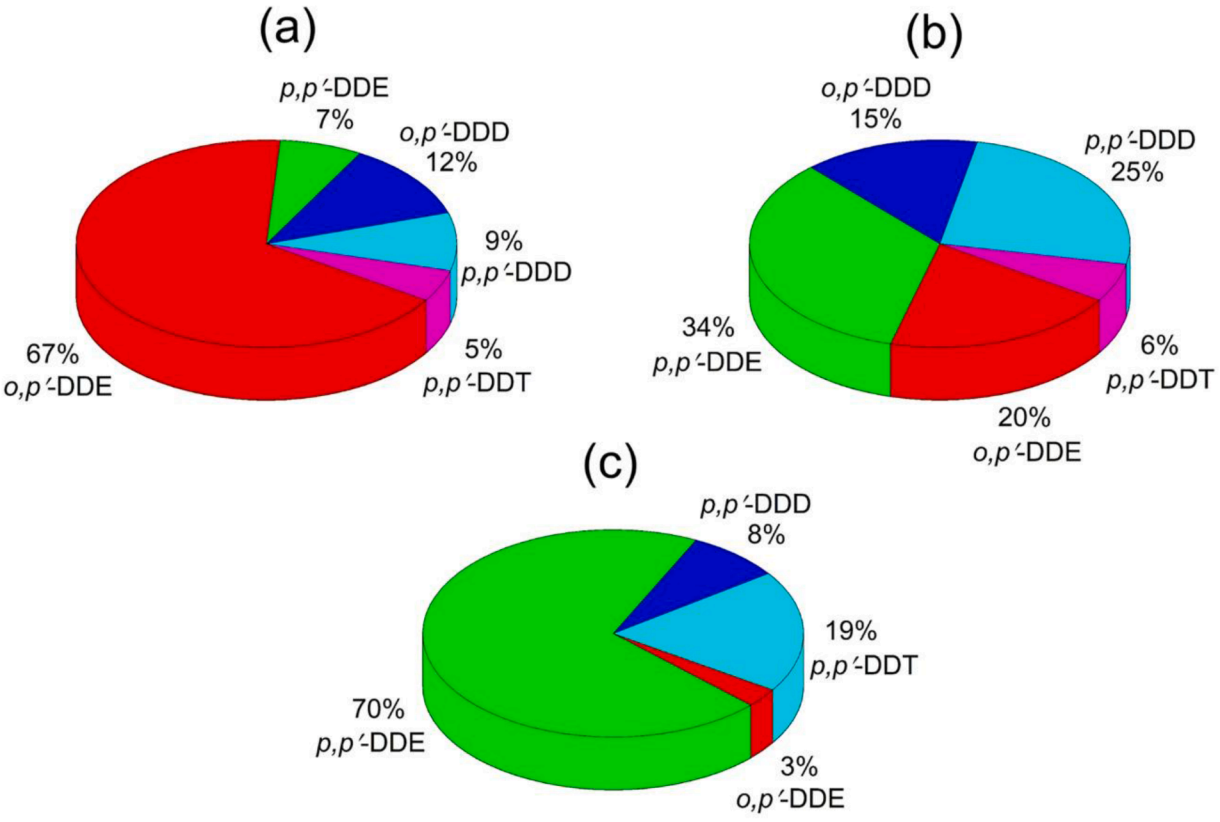


Fig. 2. Contribution of the metabolites to ∑DDTs in (a) blood, (b) placenta and (c) milk samples.

or previously high-use countries.

Considering the distribution of DDT metabolites, *o,p′-DDE* was the most abundant compound in blood, contributing 67% to the ∑DDTs, followed by *o,p′-DDD* (Fig. 2). The specific composition profile of DDT metabolites often reflects the history and source of contamination. The predominance of *o,p′-DDE* and *o,p′-DDD* in blood may be possibly attributed to long-term environmental residues of technical DDT applied in Kanungu, Kampala, or adjacent agricultural regions. Technical DDT undergoes microbial degradation to form DDE and DDD (Mansouri et al., 2017). A common diagnostic ratio (*p,p′-DDE/p,p′-DDT*) can indicate whether DDT use is recent or historical (Malisch et al., 2023b). Ratios greater than 1 suggest past input, while values below 1 indicate recent use (Jaga & Dharmani, 2003). In the present study, the observed ratio of 1.5 confirms a past application of technical DDT in or near the sampling locations.

3.3.2. Non-DDT OCP residues in blood

Although DDTs dominated the OCP profile in maternal blood, trace levels of non-DDT compounds including dieldrin and α-endosulfan were also detected (Table 1). Dieldrin was found in 6% of the samples, with a maximum concentration of 5.10 ng g^{-1} l.w, while α-endosulfan appeared in three samples, one of which exhibited a notably high concentration (88.4 ng g^{-1} l.w). In contrast, aldrin, β-endosulfan, and lindane were not detected, suggesting limited or no current exposure to these compounds in the study areas. The detection of dieldrin and α-endosulfan is consistent with their persistence in the environment and prior use in Uganda (Ssebugere et al., 2010; Kasozi et al., 2006). Dieldrin, the oxidative metabolite of aldrin, is more stable and bioaccumulative, which may explain its presence despite the absence of aldrin (Matsumura, 2012). The detection of α-endosulfan alone, without β-endosulfan or its primary metabolite endosulfan-sulfate, may indicate a recent localized input of technical endosulfan, likely from informal agricultural sources.

The limited occurrence of non-DDT OCPs in blood, especially in comparison to breast milk, is likely due to the differences in matrix composition and pharmacokinetics. Blood exhibits faster metabolic turnover than milk, and compounds with high lipophilicity preferentially partition into breast milk (Tutu et al., 2013; Matovu et al., 2019). These results highlight the importance of biological matrix selection in exposure assessment.

3.4. OCPs in placenta samples

3.4.1. Levels and profiles of DDTs in placentas

The concentrations of DDTs in placental tissues are summarized in Table 2. Although the difference was not statistically significant ($P = 0.064$, Mann–Whitney U test), ∑DDT levels in placentas from Kanungu (mean: 58.9 ng g^{-1} l.w; range: <0.05–191) were approximately five times higher than those from Kampala (mean: 11.0 ng g^{-1} l.w; range: <0.05–61.0). This trend suggests a higher maternal burden of OCPs in the rural area, likely driven by continued dietary and environmental exposure. The ∑OCPs burden in placental tissues followed a similar pattern (Kanungu: 62.7 ng g^{-1} l.w; Kampala: 12.3 ng g^{-1} l.w), reinforcing this disparity.

Among DDT metabolites, *p,p′-DDE* exhibited the highest mean concentration in Kanungu (20.3 ng g^{-1} l.w), followed by *p,p′-DDD* (13.8 ng g^{-1}), *o,p′-DDE* (13.5 ng g^{-1}), and *o,p′-DDD* (8.33 ng g^{-1}). In placenta samples from Kampala, *p,p′-DDE* (3.47 ng g^{-1}) and *p,p′-DDD* (3.58 ng g^{-1}) were dominant. The predominance of *p,p′-DDE* and *p,p′-DDD* with their respective detection frequencies of 50% and 38% suggested historical application of technical DDT, followed by in situ degradation. Notably, the ratios of *p,p′-DDE/p,p′-DDT* exceeded 1 in both locations, further supporting a legacy source rather than recent input (Jaga & Dharmani, 2003). The presence of these residues in placental tissue highlights transplacental transfer of lipophilic pollutants, consistent with patterns observed in other low- and middle-income settings (Loha et al., 2018). In Kanungu, this is likely attributed to ongoing consumption of contaminated home-produced foods such as milk, fish, and eggs (Tutu et al., 2013; Matovu et al., 2021). In Kampala, exposure may arise indirectly from market-sourced products originating from rural zones or via atmospheric transport.

The ∑DDT concentrations in placenta samples ranged from <0.005 to 191 ng g^{-1} l.w, with a mean of 35.0 ng g^{-1} l.w. These values exceeded those reported in parts of Europe, including Turku, Finland (22.13 ng g^{-1} l.w; Shen et al., 2008) and Granada, Spain (3.39 ng g^{-1} l.w; Lopez-Espinosa et al., 2007), but are lower than values reported in Taizhou (111.27 ng g^{-1} l.w) and Lina (45.51 ng g^{-1} l.w), China (Man et al., 2014), and Copenhagen, Denmark (48.78 ng g^{-1} l.w; Shen et al., 2008). These regional differences may reflect variations in historical pesticide use and exposure pathways. Individual DDT metabolites were detected in the following ranges: *p,p′-DDT* (<0.06–23.7 ng g^{-1} l.w), *o,p′-DDE* (<0.05–124 ng g^{-1} l.w), and *p,p′-DDE* (<0.30–134 ng g^{-1} l.w). These levels were lower than those observed in Italy (24–226 ng g^{-1} l.w for *p,p′-DDE*; Bergonzi et al., 2009) and Spain (0.75–76.94 ng g^{-1} l.w for *p,p′-DDT* and 5.4–535 ng g^{-1} l.w for *p,p′-DDE*; Vizcaino et al., 2014), but exceeded those reported in Kuopio, Finland (3.58–17.5 ng g^{-1} l.w for *p,p′-DDE*; Leino et al., 2013). *p,p′-DDE* and *p,p′-DDD* were the primary contributors to ∑DDTs in placenta tissues (Fig. 2), with the detection frequencies of 50% and 38%, respectively. Their predominance is consistent with the degradation of technical DDT in the environment, suggesting historic rather than

Table 2
Concentrations (ng g^{-1} l.w) of organochlorine pesticides in placenta samples.

Pesticide	Kanungu (N = 26)			Kampala (N = 26)			All samples (N = 52)		
							Mean lipid % (2.7 ± 1.0)		
	Mean	Range	n > LOD	Mean	Range	n > LOD	Mean	Range	n (%)*
o,p′-DDE	13.5	<0.05 – 124	12	0.66	<0.05 – 5.83	6	7.08	<0.05 – 124	18(35)
p,p′-DDE	20.3	<0.30 – 134	16	3.47	<0.30 – 23.2	10	11.9	<0.30 – 134	26(50)
o,p′-DDD	8.33	<0.09 – 93.1	7	2.16	<0.09 – 27.2	6	5.25	<0.09 – 93.1	13(25)
p,p′-DDD	13.8	<0.07 – 80.0	12	3.58	<0.07 – 33.7	8	8.70	<0.07 – 80.0	20(38)
p,p′-DDT	2.94	<0.06 – 23.7	6	1.12	<0.06 – 10.8	5	2.03	<0.06 – 23.7	11(21)
∑DDTs	58.9	<0.05 – 191		11.0	<0.05 – 61.0		35.0	<0.05 – 191	
Aldrin	3.13	<0.10 – 27.5	18	0.74	<0.10 – 4.01	12	1.93	<0.1 – 27.5	30(58)
Dieldrin	0.36	<0.06 – 8.30	2	0.30	<0.06 – 6.91	2	0.33	<0.06 – 8.30	4(8)
∑DRIN	3.49	<0.06 – 27.5		1.04	<0.06 – 10.9		2.26	<0.06 – 27.5	
α-endosulfan	<0.20	<0.20	0	<0.20	<0.20	0	<0.20	<0.20	0(0)
β-endosulfan	<0.05	<0.05 – 0.41	2	<0.05	<0.05 – 0.31	2	<0.05	<0.05 – 0.41	4(8)
∑Endosulfan	<0.05	<0.05 – 0.51		0.14	<0.05 – 0.41		0.14	<0.05 – 0.51	
Lindane	<0.20	<0.20 – 1.70	1	<0.20	<0.20 – 1.13	1	<0.20	<0.20 – 1.70	2(4)
∑OCPs	62.7	3.64 – 191		12.3	0.59 – 61.3		37.5	0.59 – 191	

* Number and percentage of samples with levels > LOD.

recent inputs.

3.4.2. Non-DDT OCPs in placentas

Among the non-DDT OCPs, aldrin was the most frequently detected (58%), followed by dieldrin (8%), β-endosulfan (8%), and lindane (4%). No α-endosulfan residues were detected. β-endosulfan was present at a mean concentration of <0.05 ng g^{-1} l.w. The absence of α-endosulfan, coupled with trace levels of β-endosulfan, may reflect environmental degradation of the parent isomer to its more persistent metabolite, endosulfan-sulfate (Al-Hassan et al., 2004), and/or previous localized use of technical endosulfan within or near the study sites. Aldrin and its epoxide derivative, dieldrin, were measured at concentrations up to 27.5 and 8.30 ng g^{-1} l.w, respectively. Dieldrin's presence supports its derivation from aldrin, as previously reported (Luo et al., 2016). Lindane (γ-HCH) was detected at a mean concentration of <0.20 ng g^{-1} l.w. Its detection may indicate recent environmental input, as α- and γ-HCH can undergo transformation into more persistent isomers like β-HCH (Barakat et al., 2013). Overall, exposure to non-DDT OCPs in placental tissue may be attributed to contaminated food intake, consistent with previous reports linking dietary routes, particularly of animal origin as the primary pathway for human OCP exposure (Lee et al., 2007; Mariscal-Arcas et al., 2010; Cao et al., 2011; Aerts et al., 2019).

3.5. OCPs in breast milk

3.5.1. Levels and profiles of DDTs in milk samples

The concentrations of OCPs in breast milk samples are presented in Table 3. The mean concentration of ∑DDTs was 27.1 ng g^{-1} l.w, with a range of 0.95–357 ng g^{-1} l.w. Similar to the pattern observed in the blood samples, significantly higher ∑DDT levels were detected in breast milk from Kanungu mothers compared to those from Kampala ($P = 0.038$, Mann–Whitney U test). This disparity aligns with prior observations in rural African contexts, where maternal exposure is often heightened due to continued pesticide use and greater consumption of home-produced foodstuffs (Bouwman et al., 2012; Tutu et al., 2013). In Kanungu, frequent intake of locally sourced fish and dairy may constitute a key exposure pathway (Cao et al., 2011). The predominance of *p,p′-DDE* also suggests ongoing environmental persistence of legacy DDT inputs (Mekonen et al., 2021), with possible recent use, reinforcing the importance of both dietary and environmental contact routes. In contrast, urban mothers in Kampala benefit from more diversified and commercially regulated food sources and are likely to experience lower environmental exposure. Additional factors such as increased microbial and photolytic degradation in urban microenvironments may further reduce ambient contamination levels (Loha et al., 2018).

The ∑DDT levels observed were markedly lower by two orders of magnitude than those reported by Ejobi et al. (1996), who found concentrations of 3970 ng g^{-1} l.w in breast milk samples from Kampala and Iganga Districts. This reduction may reflect improved regulatory enforcement following Uganda's adoption of the Stockholm Convention in 2001. The values reported here also fall below those documented in other regions including Shanghai, China (316 ng g^{-1} l.w; Lu et al., 2015), southwestern Ethiopia (1850 ng g^{-1} l.w; Mekonen et al., 2021), Nairobi, Kenya (473 ng g^{-1} l.w; Kinyamu et al., 1998), and Dididi, South Africa (9500 ng g^{-1} l.w; Bouwman et al., 2012). In general, the mean *p,p′-DDT, p,p′-DDE, o,p′-DDE*, and *p,p′-DDD* levels in breast milk were 5.05, 18.9, 0.82, and 2.33 ng g^{-1} l.w, respectively. Among these, *p,p′-DDE* accounted for 70% of the ∑DDTs (Fig. 2), reflecting environmental degradation of technical DDT in and around the study area.

3.5.2. Non-DDT OCP residues in breast milk

Among the non-DDT OCPs (Table 3), dieldrin was detected with a mean concentration of 14.3 ng g^{-1} l.w (range: <0.30–130), substantially higher than that of aldrin (1.18 ng g^{-1} l.w). This supports the known rapid conversion of aldrin to dieldrin in the environment, along with the greater persistence and lipophilicity of dieldrin in biological tissues (Matsumura, 2012; Souza et al., 2020). The current dieldrin levels are lower than historical values (70 ng g^{-1} l.w) reported in Kampala and Iganga in 1996 (Ejobi et al., 1996), suggesting a reduction following policy interventions under the Stockholm Convention. Additionally, the concentrations of aldrin and dieldrin found in this study were lower than those reported in Bahia, Brazil (aldrin: 142.65 ± 50.65 ng g^{-1} l.w; dieldrin: 774.62 ± 472.68 ng g^{-1} l.w) by Souza et al. (2020). The elevated dieldrin levels in that region were attributed to historical exposure.

Lindane was detected at 2.64 ng g^{-1} l.w (range: <0.20–40.0), markedly lower than previous levels in Kampala (870 ng g^{-1} l.w) and Iganga (10 ng g^{-1} l.w) (Ejobi et al., 1996). Our values were comparable to those reported from Turkey (3 ng g^{-1} l.w; Erdogrul et al., 2004), but exceeded those from Egypt (0.0018 ng g^{-1} l.w; Sharaf et al., 2008), and remained lower than the levels reported from other parts of Turkey (8 ng g^{-1} l.w; Cok et al., 2011). These variations reflected differing enforcement of pesticide bans and maternal dietary patterns.

α-Endosulfan was detected at a mean of 1.44 ng g^{-1} l.w (range: <0.20–13.0), slightly above the levels reported in Ghana (2.4; Tutu et al., 2013) and Shanghai (1.3; Lu et al., 2015). Its primary metabolite, endosulfan-sulfate, was present at a mean of 2.35 ng g^{-1} l.w, with a maximum of 17.0 ng g^{-1} l.w. These levels exceeded those from Shanghai (1.4 ng g^{-1} l.w) and Antalya, Turkey (2 ng g^{-1} l.w), but remain below the maximum values reported in Ada, Ghana (63.8 ng g^{-1} l.w; Tutu et al., 2013). The co-detection of α-endosulfan and endosulfan-sulfate, alongside the absence of β-endosulfan, may suggest recent application of

Table 3
Concentrations of organochlorine pesticides in breast milk samples (ng g^{-1} l.w).

Pesticide	Kanungu (N = 26)			Kampala (N = 26)			All samples (N = 52)		
							Mean lipid % (3.0 ± 1.6)		
	Mean	Range	n > LOD	Mean	Range	n > LOD	Mean	Range	n (%)*
o,p′-DDE	1.21	<0.50 – 17.0	8	0.44	<0.50 – 3.00	6	0.82	<0.50 – 17.0	14(27)
p,p′-DDE	26.2	<0.40 – 250	23	11.6	<0.40 – 202	17	18.9	<0.40 – 250	40(77)
p,p′-DDD	3.76	<0.70 – 50.0	9	0.89	<0.70 – 6.00	7	2.33	<0.70 – 50.0	16(31)
p,p′-DDT	8.13	<0.50 – 104	16	1.96	<0.50 – 15.0	16	5.05	<0.50 – 104	32(62)
∑DDTs	39.3	1.90 – 357		14.9	0.95 – 210		27.1	0.95 – 357	
Aldrin	1.23	<0.20 – 6.00	15	1.13	<0.20 – 10.0	12	1.18	<0.20 – 10.0	27(52)
Dieldrin	21.3	<0.30 – 130	21	7.29	<0.30 – 50.0	16	14.3	<0.30 – 130	37(71)
∑DRIN	22.6	<0.20 – 130		8.42	<0.20 – 53.0		15.5	<0.20 – 130	
α-endosulfan	2.19	<0.20 – 9.00	13	0.68	<0.20 – 13.0	8	1.44	<0.20 – 13.0	21(40)
Endosulfan-sulfate	3.52	<0.20 – 17.0	17	1.19	<0.20 – 15.0	9	2.35	<0.20 – 17.0	26(50)
∑Endosulfan	5.71	<0.20 – 25.0		1.87	<0.20 – 28.0		3.79	<0.20 – 28.0	
Lindane	3.53	<0.20 – 40.0	14	1.76	<0.20 – 8.00	10	2.64	<0.2 – 40.0	24(46)
∑OCPs	71.1	8.95 – 376		27.0	1.65 – 211		49	1.65 – 376	

* Number and percentage of samples with levels > LOD.

technical endosulfan. This is supported by the known degradation pattern and isomer ratios, as well as the long environmental half-lives of endosulfan compounds, which range from about 9 months to 6 years (German Federal Environment Agency, 2007). Biodegradation by soil fungi and bacteria typically results in endosulfan-sulfate, which is stable and lipophilic, allowing it to accumulate in maternal tissues.

3.6. Comparison in global decline of DDT levels in human milk to those in Uganda

Biomonitoring of OCP residues over time is essential to measure the success of the Stockholm Convention on Persistent Organic Pollutants (POPs), with human milk being a key biological matrix for this purpose. A recent global survey covering 44 countries, based on WHO and UNEP monitoring data from 2000 to 2019, found a general downward trend in DDT levels in human milk (measured in μg DDT complex per kg of fat) (Malisch et al., 2023b). Overall, the data showed a 49.5% drop in DDT concentrations worldwide over a ten-year period. The decline varied by region: Africa showed the most significant decrease (79.1%), followed by the Asia-Pacific (66.5%), Latin America and the Caribbean (55.0%), and Europe (between 45.5% and 48.6%). Interestingly, European countries despite having banned DDT earlier showed slower reductions, while African countries, where DDT levels were initially much higher, experienced more rapid decreases. This suggests that areas with higher starting levels may see faster declines once control measures are in place. In Africa, the percentage drops in DDT concentrations in human milk over a decade were particularly striking: Uganda (94.7%), Nigeria (88.5%), Niger (91.6%), Democratic Republic of Congo (85.1%), Egypt (84.5%), Ethiopia (81.9%), Kenya (71.0%), Mali (70.6%), and Ghana (67.1%). Among these, Uganda had the highest reduction rate. Our findings are consistent with these results, showing a 99.3% decrease in DDT levels in human milk over a 24-year period, as compared to earlier data from Ejobi et al. (1996). This decline may indicate stronger regulatory measures put in place after Uganda ratified the Stockholm Convention in 2001. Therefore, with continued efforts to eliminate sources of contamination, DDT levels are likely to keep falling and may eventually stabilize at much lower levels.

3.7. Association of levels of OCPs in biological samples and relationship with maternal age

Overall, the mean ∑OCPs (37.5 ng g^{-1} l.w) in placenta samples were lower than those in blood (66.2 ng g^{-1} l.w) and breast milk (49.0 ng g^{-1} l.w). This supports the idea that placenta facilitates nutrient and gas exchange between the mother and the fetus as well as removal of the waste from the fetal environment, and thus, may act as a diffusive barrier or a repository for chemicals that are toxic and tend to bioaccumulate (Nanes et al., 2014).

Maternal age generally did not show any significant correlations with the levels of OCPs in maternal samples, except for *p,p′*-DDE in placenta tissues (ρ = -0.4081, P =0.0385) and aldrin (ρ = 0.5747, P = 0.009) (**Table S4** of the Supplementary Material). A negative correlation between the levels of *p,p′*-DDE in placenta tissues with age could be attributed to a recent exposure of mothers to the pollutant. Furthermore, it could suggest a behavioural cohort in which younger women have a higher tendency to consume food of animal origin that could be contaminated with halogenated compounds (Matovu et al., 2019) or lack of control for potential confounders like level of education, parity and nursing history of mothers which can conceal the age correlation (Thomsen et al., 2010). The positive correlation with age of mothers for levels of aldrin in placenta tissues has been reported before (Wang et al., 2013). Older mothers (> 40 years) were present when OCPs were widely used in the studied areas and/or their neighbourhoods. Due to the persistence and bioaccumulation of pollutants in human bodies, aldrin is still being detected in maternal samples.

3.8. Health risks posed to infants through consumption of OCP-contaminated breast milk

In this study, the average EDI value for ΣDDTs (27.1 ng g^{-1} l.w) was slightly higher than the maximum residual limit of 20 ng g^{-1} l.w set by the Joint FAO/WHO Food Standards Programme Codex Alimentarius Commission, 2006, beyond which breast milk is considered to pose potential health risks to nursing infants. This higher value was largely influenced by the elevated *p,p′*-DDE levels in some of the milk samples of mothers from Kanungu District where the use of DDT was previously reported. However, the EDI values for each isomer (Table 4) were lower than the Acceptable Daily Intakes (ADIs) of 10, 10, 10, 10, 6.0, 6.0, 0.1, 0.1 and 5.0 ng g^{-1} body weight day^{-1} for *p,p′*-DDT, *p,p′*-DDE, *o,p′*-DDE, *p,p′*-DDD, α-endosulfan, endosulfan-sulfate, aldrin, dieldrin and lindane, respectively, set by the FAO/WHO Codex Alimentarius Commission (2006), which suggested that the breast milk of mothers from Kampala and Kanungu was fit for infant consumption.

In comparison with other studies in sub-Saharan Africa, the EDIs in this study were lower than those reported by Okonkwo et al. (2008) and Ejobi et al. (1996). Okonkwo et al. (2008) reported EDIs in the range 260-4,696 ng g^{-1}, n.d-10,551 ng g^{-1} and n.d-4,237 ng g^{-1} for DDE, DDD and DDT, respectively in the breastmilk of mothers from Thohoyandou City in South Africa. Similarly, Ejobi et al. (1996) reported EDI values of ΣDDT of 14.74 ng g^{-1} body weight below the maximum acceptable daily intake (ADI) of 20 ng g^{-1} body weight recommended by FAO/WHO (1985). In this study, HQ values for all OCPs in breastmilk were < 1 (Table 4) indicating that the consumption of breast milk by infants from Kampala and Kanungu was of minimal toxicological risks with respect to OCPs. Therefore, mothers should be encouraged to breastfeed their babies.

3.9. Strengths and limitations of the study

This study has generated novel data on the occurrence of OCPs in biological samples (breast milk, blood and placenta tissues) of mothers living in Kampala capital city and Kanungu District, Uganda. However, there were some limitations to the study. First, the sample sizes (N=52) for each matrix were small and, thus, might not provide sufficient statistical power to allow generalizations. Secondly, some maternal characteristics that could affect OCPs accumulation (e.g., maternal education level, parity, occupation and Body Mass Index (BMI)) were not investigated due to small sample sizes. Therefore, for a better understanding of these pollutants burden in mothers, we recommend future studies to consider larger sample sizes. Also, the interaction of OCPs with the nutrients in biological compartments, as well as investigating how much of these chemicals can be transferred to the baby during pregnancy should be assessed.

4. Conclusions

This study quantified eleven OCP residues in maternal blood, breast milk, and placenta samples collected from mothers residing in Kanungu District and Kampala Capital City. The results revealed significantly higher OCP levels in mothers from Kanungu compared to Kampala, highlighting a rural exposure burden likely linked to past and ongoing informal pesticide use. The mean ∑OCPs levels were 66.2, 49.0, and 37.5 ng g^{-1} l.w in blood, breast milk, and placenta, respectively. *o,p′-DDE* was the predominant metabolite in blood, while *p,p′-DDE* was dominant in both placenta and breast milk, consistent with known environmental degradation pathways of technical DDT. In general, OCP levels were lower than those reported for previous studies in Uganda and in several global reference regions, suggesting that regulatory actions such as Uganda's ratification of the Stockholm Convention may be contributing to reduced exposure levels. Maternal age was not significantly associated with the OCP levels in most samples, although a positive correlation was observed between aldrin and maternal age in placenta tissues,

Table 4
Estimated Daily Intakes (EDIs) and Hazard Quotients (HQs).

	p,p'-DDT	*p,p'*-DDE	*o,p'*-DDE	*p,p'*-DDD	α-endosulfan	Endosulfan-sulfate	Aldrin	Dieldrin	Lindane
ADI (ng/g/bw)	5.05	18.90	0.82	2.33	1.44	2.35	1.18	14.30	2.64
EDI (ng/g/bw)	0.020	0.080	0.003	0.010	0.006	0.010	0.005	0.060	0.011
HQ	0.002	0.008	0.0003	0.001	0.001	0.002	0.050	0.60	0.002

indicating possible bioaccumulation over time.

In 79% of the investigated breast milk samples, ∑DDT levels were below the maximum residue limit established by the FAO/WHO Codex Alimentarius Commission. Hazard quotient values for all OCPs were <1, suggesting that breast milk remains safe for infant consumption in both study areas. These findings underscore the importance of continued monitoring and targeted regulation, particularly in rural regions where informal pesticide use persists.

CRediT authorship contribution statement

Daniel Omoding: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Teddy Nantume:** Writing – review & editing, Methodology, Investigation. **John Wasswa:** Writing – review & editing, Supervision, Conceptualization. **Silver Odongo:** Writing – review & editing, Methodology, Formal analysis. **Christine Kyarimpa:** Writing – review & editing. **Ibrahim Karume:** Writing – review & editing, Methodology. **Henry Matovu:** Writing – review & editing, Methodology. **Mika Sillanpää:** Writing – review & editing. **Charles Drago Kato:** Writing – review & editing. **Josephine Nabuuma:** Writing – review & editing, Methodology. **Ashirafu Miiro:** Writing – review & editing, Formal analysis. **Patrick Ssebugere:** Writing – review & editing, Funding acquisition, Conceptualization, Investigation, Supervision.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hazadv.2025.100949.

Data availability

No data was used for the research described in the article.

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