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HAZARDOUS CHEMICALS IN PLASTIC PRODUCTS AND FOOD CHAIN IN KENYA

POPS IN PLASTIC CONSUMER PRODUCTS AND FREE-RANGE CHICKEN EGGS FROM KENYA

CENTRE FOR ENVIRONMENT JUSTICE AND DEVELOPMENT CEJAD
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HAZARDOUS CHEMICALS IN PLASTIC PRODUCTS AND FOOD CHAIN IN KENYA

POPS IN PLASTIC CONSUMER PRODUCTS AND FREE-RANGE CHICKEN EGGS FROM KENYA

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Executive summary

Introduction

Developing countries, including countries in Africa, suffer from the health and environmental impacts of toxic chemicals and wastes more than developed countries. This is in part the result of loopholes in international legislation and abuses by large corporations and countries that export waste containing dangerous chemicals. Burning waste generates new, even more toxic chemicals, such as chlorinated and brominated dioxins and polyaromatic hydrocarbons.

Another source of human exposure to toxic chemicals is plastic consumer products. Some of chemicals in plastic products are intentionally added to confer certain properties, others end up in the products made from recycled plastics because chemicals in plastics are transferred when plastics are recycled.

Aim of the study

This study aims to determine whether persistent organic pollutants (POPs) find their way into consumer products and human food in Kenya due to waste management practices such as recycling, dumping, or burning. The research aims to contribute to the discussion on setting appropriate international standards and limits for the content of persistent organic pollutants (POPs) in consumer products and waste.

Methodology

Pooled samples of free-range chicken eggs were collected in the vicinity of potential POPs pollution hot spots:

Nairobi - Dandora, a dumpsite where plastic waste is burned;

Nairobi – Ngara market, a market which is a major e-waste dismantling site (see also photo);

Nairobi - Mirema, a “community cooker” that uses plastic waste as fuel;

Nanyuki, near a dumpsite with open burning and e-waste disposal.

Eggs from a supermarket in Nairobi were used as reference sample. The eggs were analyzed for polychlorinated and polybrominated dioxins (PBDD/Fs, PBDD/Fs), polychlorinated biphenyls (PCBs), hexachlorobenzene (HCB), pentachlorobenzene (PeCB), hexachlorobutadiene (HCBD), polychlorinated naphthalenes (PCNs), short-chain chlorinated paraffins (SCCPs), 3 isomers of hexachlorocyclohexane (HCH), 6 isomers of dichlorodiphenyltrichloroethane (DDT), 3 isomers of hexabromocyclododecane (HBCD), polybrominated diphenyl ethers (PBDEs), six novel brominated

flame retardants (nBFRs), and per- and polyfluoroalkyl substances (PFASs). All were analyzed in certified laboratories in Czechia, Netherlands, or Germany. A daily dietary intake was calculated for PCDD/Fs plus DL-PCBs, PBDD/Fs, and PF0S. The results of the calculations were compared with the tolerable daily intake (TDI) established by different regulatory authorities (EFSA and WHO).

Eighteen black plastic products (products that tend to come from recycled e-waste plastics and plastics from end-of-life vehicles (ELVs)) with elevated levels of bromine and antimony purchased from markets in Kenya were selected for laboratory analysis at the Department of Food Analysis and Nutrition, University of Chemistry and Technology based in Prague, Czechia. Groups of PBDEs, HBCD and nBFRs, and Tetrabromobishpenol A (TBBPA) were analyzed in these products. A toy car was also analyzed for brominated dioxins at the MAS laboratory in Muenster, Germany and for dioxin-activity by DR_{human}CALUX.

Results and comparison with legal threshold

In most cases, the analyzed POPs levels in the eggs from the selected hot spots in Kenya exceeded by many times the levels measured in reference samples purchased from a supermarket in Nairobi.

The levels of dl PCB congeners measured in both samples from the Ngara market were the highest ever measured in free chicken eggs globally (see comparison in graph at Figure 1). The levels of indicator PCB congeners in the two pooled egg samples from the Ngara market exceeded the EU regulatory limit of 40 ng/g fat by more than 30 and 55 times, respectively. The level of indicator PCB congeners in the eggs from the Dandora dumpsite reached half of the EU limit.

The levels of PCDD/Fs in free-range egg samples in this study were two to eight times higher than the EU regulatory limit of 2.5 pg TEQ/g in fat. The highest level was in eggs from the Dandora dumpsite, followed by eggs from the Ngara market and Mirema.

The sum of PCDD/Fs + dl PCBs was 100 and 111 times, respectively, above the EU regulatory limit of 5 pg TEQ/g fat in two pooled egg samples from the Ngara market. Based on the level of PCDD/Fs + dl PCBs in the eggs from the Ngara market, the average per capita consumption of eggs in Kenya (36 eggs per year), which is considered to be very low, would exceed the TDI for PCDD/Fs + dl PCBs by 5 to 6 times. In addition, we can also say that a person eating just one egg from the Ngara market would be exposed to a cumulative dose of dioxins and dioxin-like compounds that would span nearly 200 days to more than 250 days, based on the TDI set by EFSA.

The laboratory analysis of 18 samples of consumer products made of recycled black plastic purchased in Kenya revealed that 14 of them exceed the EU safety standard of 10 ppm. Across all 18 samples, there were six novel BFRs found at concentrations ranging from 0.2 ppm to 412 ppm. Tetrabromobisphenol A (TBBPA), the most widely used BFR, was found in 16 out of the 18 samples, at concentrations ranging from 0.3 ppm to 980 ppm.

One sample, a toy car, was analyzed for brominated dioxins and was found to contain 6,590 pg TEQ/g, which is much higher than concentrations observed, for example, in waste incineration ashes or pyrolysis residues.

Conclusions

Leakage and emissions of POP additives from waste is a source of contamination of free-range chicken eggs with BFRs and PFASs in the vicinity of dumpsites and/or community cookers using plastic waste as fuel. Burning plastic waste containing chlorinated and brominated additives generates unintentionally produced POPs (U-POPs) such as HCB, PeCB, PCDD/Fs, PBDD/Fs and dl PCBs. All forms of burning plastic waste, including their use as fuel, should be banned as this releases POPs into the environment. Wastes containing high levels of POPs can be treated by non-combustion technologies, which destroy POPs and do not generate new POPs.

In agreement with previous studies, the present study shows that children toys, hair accessories, office supplies, and kitchen utensils found on the Kenyan market are affected by unregulated recycling of e-waste plastics, which carry toxic brominated flame retardants (BFRs) into new products. To stop this practice, stricter measures to control BFRs in products and waste need to be set and enforced.

The results of this study also highlight that the new global Plastics Treaty should focus on the chemical content in plastics.

Recommendations

1. Halt the entry of plastic treated with BFRs for recycling into toys and other consumer goods

E-waste and ELVs plastic containing high levels of toxic flame retardants should be banned from entering the recycling chain.

Also, the loophole allowing exports of non-functional electronics under the guise of repair in the Basel Convention's Technical Guidelines needs to be fixed and stricter standards for the definition of hazardous wastes must be established under both the Basel and Stockholm Conventions.

African countries also need to improve their national regulations to require better control of imported waste and products, in particular, concerning POPs content.

2. Set stricter limits for POPs in waste

To eliminate human exposure to PBDEs and related harmful chemicals such as brominated dioxins (PBDD/Fs) in products and wastes, strict limit values must be established. Low POPs Content Levels (LPCLs) for waste should be established at a level of 50 ppm as proposed by the African region and accompanied with setting an unintentional trace contamination (UTC) level at 10 ppm.

3. Use separation techniques for POPs waste

In recycling workshops and plants, methods based on the total concentration of bromine should be applied to identify BFR-treated plastic and separate it out of the waste stream. For example, X-ray fluorescence (XRF) and X-ray transmission (XRT) are used at the industrial scale. In the informal plastic recycling sector in India, a simple sink-and-float method is used for BFR plastic separation.

4. Restrict BFRs as a class

The elevated levels of PBDEs and nBFRs in some consumer products reported in this study and the known and unknown adverse effects of these chemicals require a class-based approach to the restriction of BFRs. Only a class-based approach can address the regrettable substitutes and likely toxic nBFRs that are currently used without any regulation, and which will continue to circulate in the waste streams, just as their persistent counterparts.

5. Regulate and control plastic waste

The new global Plastics Treaty should focus on the chemical content of plastic materials and prohibit materials such as PVC or plastics containing brominated compounds. Facilities using plastic waste as a fuel such as community cookers need to be prohibited. These facilities openly burn plastics and have no air pollution control equipment or practices to control dioxin and other U-POPs emissions.

6. Use non-combustion technologies for POPs waste

Wastes containing high levels of POPs can be treated by non-combustion technologies, which destroy POPs and do not generate new ones. Gas phase chemical reduction (GPCR) or supercritical water oxidation (SCWO) seem to be the most promising technologies to treat POPs waste. It could benefit African countries to cooperate regionally on establishing treatment center(s) for POP waste.

Abbreviations

ABS - acrylonitrile butadiene styrene (a type of plastic used often in electronics casings)

BFRs – brominated flame retardants

Br - bromine

BTBPE - 1,2-bis(2,4,6-tribromophenoxy)ethane, one of the nBFRs

DBDPE - decabromodiphenyl ethane, one of the nBFRs

DecaBDE – commercial mixture of Decabromodiphenyl ether

EFSA – the European Food Safety Authority

ELVs – end-of-life vehicles

EU – European Union

E-waste – electronic waste

HBB – hexabromobenzene, one of the nBFRs

HBCD – hexabromocyclododecane

IARC – International Agency for Research on Cancer

IPEN – International Pollutants Elimination Network

LPCL – Low POPs Content Level

nBFRs – novel BFRs

OctaBDE - commercial mixture of Octabromodiphenyl ether (listed as hexabromodiphenyl ether and heptabromodiphenyl ether under the Stockholm Convention)

PBDD/Fs – polybrominated dibenzo-p-dioxins and furans, commonly called “brominated dioxins“

PBDEs – polybrominated diphenyl ethers

PCDD/Fs - polychlorinated dibenzo-p-dioxins and furans, usually called dioxins and/or chlorinated dioxins

PentaBDE - commercial mixture of Pentabromodiphenyl ether (listed as tetrabromodiphenyl ether and pentabromodiphenyl ether under the Stockholm Convention)

PFASs – per- and polyfluoroalkyl substances

POPs – persistent organic pollutants

TDI – tolerable daily intake

TEQ – toxic equivalent (established for calculation of dioxin toxicity levels)

UTC – unintentional trace contamination

XRF – X-ray fluorescence

1. Introduction

Developing countries, including countries in Africa, suffer from the health and environmental impacts of toxic chemicals and wastes more than developed countries. This is in part the result of loopholes in international legislation and abuses by large corporations and countries that export e-waste and end-of-life vehicles (ELVs) to Africa (Hogarh, Seike et al. 2012, Sindiku, Babayemi et al. 2015, Hogarh, Petrlik et al. 2019, Petrlik, Puckett et al. 2019, Oloruntoba, Sindiku et al. 2021). Imported materials containing dangerous chemicals such as heavy metals, toxic brominated flame retardants (BFRs), and other substances of concern become waste and are burned , often in open fires. The burning generates new, even more toxic chemicals, such as chlorinated and brominated dioxins and polyaromatic hydrocarbons.

Another source of humanexposure to toxic chemicals are plastic consumer products. There are an increasing number of studies showing that products available on the African market contain dangerous levels of toxic chemicals, including, for example, mercury (Uram, Bischofer et al. 2010), lead (Mathee 2014), short-chain chlorinated paraffins (Miller, DiGangi et al. 2017), and brominated dioxins (Sindiku, Babayemi et al. 2015, Petrlik, Brabcova et al. 2019). Some of these chemicals are intentionally added to the plastic products to confer certain properties, others end up in the products because chemicals in plastics are transferred when plastics are recycled. (Petrlik, Beeler et al. 2022). People can be exposed to these toxic substances from recycled plastics because these chemicals can migrate from plastic products during hand-to-mouth-contact (Ionas, Ulevicus et al. 2016), can be released into household dust (Harrad, Hazrati et al. 2006), or emitted during dumping (Gullett, Wyrzykowska et al. 2010, Oloruntoba, Sindiku et al. 2021), landfilling (Tongue, Reynolds et al. 2019), incinerating (Agrell, ter Schure et al. 2004, Lee, Ikonomou et al. 2007, Tu, Wu et al. 2011), burning (Gullett, Wyrzykowska et al. 2010), or recycling (Ramu, Isobe et al. 2008, Han, Wang et al. 2017).

This study aims to determine whether persistent organic pollutants (POPs) find their way into consumer products and human food in Kenya as a result of waste management practices such us recycling, dumping, or burning. The research tends to contribute to the discussion on setting appropriate international standards and limits for the content of persistent organic pollutants (POPs) in consumer products and waste.

2. Materials and Methods

Consumer products made of black plastics (plastics made from recycled e-waste) and free-range chicken eggs were collected in Kenya to test the hypothesis that POPs find their way from e-waste plastics into plastic products as a result of recycling and that they pollute food sources in areas around waste disposal sites.

2.1 Free-range chicken eggs sampling and analyses

Free-range chicken eggs were sampled in the vicinity of potential POPs pollution hot spots. The hot spots are either facilities that handle waste containing POPs, such as used electronic and electric equipment, car wrecks, or various plastic waste, or that burn wastes (mainly plastic) containing halogenated compounds (chlorine or bromine). Burning plastic waste containing chlorine and bromine unintentionally generates POPs, such as chlorinated and brominated dioxins.

We chose the following hot spots in Kenya for collecting analysisfree-range chicken eggs for analyzesanalysis:

1) Nairobi – Dandora which has a large dumpsite where there is often open burning of plastic waste;
2) Nairobi – Ngara market which is known as the e-waste dismantlingsite inside the city;
3) Nairobi – Mirema, where the so-called "community cooker" that uses plastic waste as fuel for cooking, and
4) Nanyuki dumpsite where open burning sometimes occurs and various types of wastes, including used electronic equipment, are dumped.

Several eggs were collected at each location and analyzed as a pooled sample of 5 – 8 eggs (see Table 1) in order to get more representative results (DiGangi and Petrlik 2005, Labunska, Abdallah et al. 2015, Hogarh, Petrlik et al. 2019, Arkenbout and Bouman 2021, Grechko, Amutova et al. 2021, Ismawati, Petrlik et al. 2021). We also purchased eggs from supermarket in Nairobi and sent them for analysis, for use as reference sample. The eggs were boiled before being transported to laboratories in Europe.

Sample preparation is described in previous studies (Petrlik, Hegyi et al. 2005, Petrlik, Boontongmai et al. 2022). The eggs were analyzed for the following POPs: dioxins [polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs)], polychlorinated biphenyls (PCBs),[1] brominated dioxins [polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs)], hexachlorobenzene (HCB), pentachlorobenzene (PeCB), hexachlorobutadiene (HCBD), polychlorinated naphthalenes (PCNs), short-chain chlorinated paraffins (SCCPs), 3 isomers of hexachlorocyclohexane (HCH),[2] 6

1 PCB congeners representing both groups intentionally and unintentionally produced were analyzed. The first group is represented by six or seven indicator PCB congeners, the second is expressed by 12 dioxin-like PCB congeners concentrations in samples.

2 Alfa-, beta- and gamma- isomers were analyzed. The gamma isomer is known as lindane.

***Photos 1 - 2:** Nairobit – Ngara market site with e-waste dismantling activities.*
Photos by James Wakibia.

isomers of dichlorodiphenyltrichloroethane (DDT), 3 isomers of hexabromocyclododecane (HBCD), polybrominated diphenyl ethers (PBDEs),[3] six novel brominated flame retardants (nBFRs),[4] and per- and polyfluoroalkyl substances (PFASs).[5] Chemicals, their properties, and potential health effects are described in Annex 1. All were analyzed in certified laboratories in Czechia, Netherlands, or Germany.[6] Chemical analyses for POPs in these laboratories were described in previous studies (Kalachova, Cajka et al. 2013, Petrlik, Ismawati et al. 2020, Petrlik, Bell et al. 2022). Results of the analyses are summarized in Table 1.

2.2 Sampling and analyses of plastic consumer products

Ninety-six products, including children's toys, hair accessories, kitchen utensils, and office supplies, were purchased from markets in Kenya. Since the products were made of black plastics, it was suspected they were made from recycled plastic. As X-ray fluorescence is a useful technique for determining the presence of PBDEs in plastics (Gallen, Banks et al. 2014, Petreas, Gill et al. 2016), all samples were screened using a handheld NITON XL3t 800XRF analyzer to guide the selection of samples for further laboratory analysis. The method for collecting the samples was described in the previous study (Petrlik, Beeler et al. 2022). Following the screening, 18 products with elevated levels of bromine and antimony – 7 hair accessories, 3 kitchen utensils, 4 office utensils and 4 toys – were selected for laboratory analysis at the Department of Food Analysis and Nutrition, University of Chemistry and Technology based in Prague, Czech Republic. Groups of PBDEs, HBCD and nBFRs, and Tetrabromobishpenol A (TBBPA) were analyzed in these products. The analytic methods used are explained in previous studies(Lankova, Svarcova et al. 2015, Petrlik, Beeler et al. 2022). The results of analyses for BFR in plastic products are summarized in Table 2.

In addition to the above mentioned BFRs, one sample, a toy car, was also analyzed for brominated dioxins at the MAS laboratory in Muenster, Germany and for dioxin-activity by DR_{human}CALUX using the analytical methods described in the previous study by Budin et al. (2020). The results are discussed further in the text.

2.3 Methodology for the evaluation of dietary intake of POPs from eggs

We calculated the daily dietary intake for the following groups of contaminants: 1) PCDD/Fs plus DL-PCBs; 2) PBDD/Fs, and 3) PF0S. The calculations were made by using measured levels of certain chemicals per gram of weight of the fresh egg and a calculation of a daily intake of 1/10 of an egg per day (3.6 grams of egg weight). The average body weight was taken from information

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3 16 congeners representing commercial mixtures of Penta-, Octa-, and DecaBDE were analyzed.

4 This group of chemicals was represented in our analyses by the following chemicals: 1,2-bis(2,4,6-tribromophenoxy) ethane (BTBPE), decabromodiphenyl ethane (DBDPE),hexabromobenzene (HBB), octabromo-1,3,3-trimethylpheny-1-indane (OBIND),2,3,4,5,6-pentabromoethylbenzene (PBEB), and pentabromotoluene (PBT).

5 17 PFASs and/or their groups were analyzed, including linear (L-PFOS) as well as branched (br-PFOS) perfluorooctane sulfonate isomers, perfluoro-n-octanoic acid (PFOA) and perfluorohexane sulfonic acid (PFH_xS).

6 Dioxins, brominated dioxins and dl PCBs were analyzed at the MAS laboratory based in Muenster, Germany; dioxin-activity by DR CALUX method was measured at BDS Amsterdam, Netherlands; all other POPs were analyzed at the University of Chemistry and Technology, Faculty of Food and Biochemical Technology, Department of Food Analysis and Nutrition, based in Prague, Czech Republic.

about average human body weight in different parts of the world (Walpole, Prieto-Merino et al. 2012, Wikipedia 2020c). For Africa, it is 61 kg.

The results of the calculations were compared with the tolerable daily intake (TDI) established by the European Food Safety Authority for PCDD/Fs and dl PCBs of 0.25 pg TEQ/kg of body weight (EFSA CONTAM 2018a) as well as for PFOS of - 6 ng/kg of body weight per week (EFSA CONTAM 2018b) in 2018. Also, for PCDD/Fs and dl PCBs, we compared the results with more conservative TDI of 2 pg TEQ/kg body weight, used by WHO (European Commission 2001, van den Berg, Birnbaum et al. 2006, Gies, Neumeier et al. 2007). There is no TDI for PBDD/Fs established yet. For the purpose of this study, summary of brominated, chlorinated dioxins and dioxin-like PCBs was compared to TDI for PCDD/Fs + dl PCBs.

3. Results

The most important results of the analyses of free-range chicken eggs and consumer plastic products for POPs are summarized in Tables 1 and 2 below. Their comparison with results from other countries and from previous studies is discussed in chapter.

Table 1. *Summary of results of the analyses of chicken eggs from Kenya for POPs.*

Locality	**Nairobi - Mirema (school)**	**Nairobi - Ngara market (e-waste)**	**Nairobi - Ngara market (e-waste)**	**Nairobi - Dandora (dumpsite)**	**Nanyuki - dumpsite**	**Nairobi - super-market**	**EU standard / limits**
Sample ID (eggs)	**KE_001**	**KE_002**	**KE-EG-NG_001**	**KE-EG-D002**	**KE-EG-NY_003**	**KE_SUP**	
Number of eggs in pooled sample	5	6	6	8	6	6	-
Fat content (%)	14	16	19	19	17	10	-
PCDD/Fs (pg TEQ/g fat)	12	18	12	19	5.0	0.22	II.50
dl PCBs (pg TEQ/g fat)	2.1	502	555	7.0	1.7	0.05	-
Total PCDD/F + dl PCBs (pg TEQ/g fat)	14	520	567	26	6.7	0.27	5.00
Total PCDD/Fs + dl PCBs - DR CALUX (pg BEQ/g fat)	NA	NA	77	35	4.9	NA	-
PBDD/Fs (pg TEQ/g fat)	NA	8.5	0.61	12	2.4	0.043	-
HCB	0.71	1.4	2.4	37	0.60	<0.1	-
PeCB	<0.1	<0.1	1.36	34	0.15	<0.1	-
HCBD	1.50	3.41	<0.10	1.30	<0.10	0.71	-
7 PCB	0.73	3137	2103	21	6.12	11	-
6 PCB	0.73	2235	1282	20	4.46	8.10	40.00
13 PCN	NA	NA	<0.20	<0.20	<0.20	NA	
SCCPs	102	224	65	383	<50.0	1441	-
sum HCH	0.49	1.87	1.44	0.64	0.61	< LOQ	-
sum DDT	152	134	231	90	13	0.96	-
sum HBCD	287	<4.2	<4.2	<4.2	<4.2	<4.2	
sum of PBDEs	24	75	31	639	85	< LOQ	-
sum of nBFRs	3.6	10	18	31	< LOQ	< LOQ	
sum of PFASs (ng/g of fresh weight)	1.46	NA	6.65	1.97	1.25	0.34	-
L-PFOS (ng/g of fresh weight)	0.65	NA	2.18	1.04	0.55	0.06	-
br-PFOS (ng/g of fresh weight)	0.11	NA	0.33	0.33	0.11	0.014	-
PFOA (ng/g of fresh weight)	0.06	NA	0.11	0.06	0.05	<0.01	-
PFH_xS (ng/g of fresh weight)	0.01	NA	0.04	0.03	0.04	<0.01	-

L-PFOS – linear PFOS, br-PFOS – branched PFOS.

__Table 2.__ Overview of the analytical results for the analyzed BFRs in consumer products from Kenya, in ppm (mg/kg)

No	Sample ID	Item	Group	Br (mean)	Sb (mean)	Penta BDE	Octa BDE	Deca BDE	Sum of PBDEs	Sum of HBCD	TBBPA	Sum of nBFRs	Total BFRs
				ppm	ppm	mg/kg							
1	KEN-H-4	hair clip	H	4 392	1 296	<LOQ	46	69	115	0.2	33	154	302
2	KEN-H-6	hair clip	H	4 214	1 582	<LOQ	41	64	106	1.1	50	80	236
3	KEN-H-7	head dress	H	3 754	908	<LOQ	60	85	145	<LOQ	48	82	276
4	KE-H-03	head band	H	3 703	955	0.2	79	144	223	<LOQ	75	95	393
5	KE-H-16	hair band	H	14 200	4 454	0.2	149	130	279	0.9	458	412	1,149
6	KE-H-12	hair clip	H	12 850	3 542	0.2	101	57	158	0.4	980	208	1,347
7	KE-H-02	head band	H	1 556	428	0.005	23	72	95	0.3	24	29	149
8	KE-K-10	knife handle	K	317	311	0.1	13	52	65	<LOQ	0.7	17	83
9	KE-K-25	spoon handle	K	212	74	0.03	1.8	6	8	<LOQ	0.1	0.9	9
10	KE-K-15	beer opener	K	583	193	0.1	36	80	116	0.04	63	90	269
11	KEN-O-5	pen	O	252	91	<LOQ	<LOQ	0.02	0.02	<LOQ	7	0.2	7
12	KE-O-17	pencil holder	O	1 237	289	0.006	5	78	83	0.1	16	22	122
13	KE-O-15	sponge (office)	O	234	177	<LOQ	<LOQ	0.2	0.2	<LOQ	0.04	0.3	0.6
14	KEN-O-1	pen	O	626	189	<LOQ	9	81	90	0.1	12	10	112
15	KEN-T-6	toy car	T	456	288	<LOQ	26	243	269	<LOQ	0.5	48	318
16	KE-T-16	toy car	T	357	154	0.05	12	119	132	0.05	18	30	180
17	KE-T-01	toy car	T	447	152	<LOQ	17	137	153	<LOQ	10	19	182
18	KE-T-04	toy "Minnie Mouse“	T	378	104	<LOQ	1.9	7	9	0.1	1.0	6	16

***Photos 3 – 4:** Photos of consumer products obtained from Kenyan markets which were analyzed for BFRs in this study. Photos by Kristina Zulkovska.*

4. Discussion

4.1 Comparison of POPs concentrations in eggs with other studies

In most cases (see Table 1), the analyzed POPs levels in the eggs from the selected hot spots in Kenya exceeded by many times the levels measured in reference samples purchased from a supermarket in Nairobi. One exception is one reference sample that contained the highest level of SCCPs (1,441 ng/g) in fat.. Also, the level of indicator PCB congeners in one sample from the Nanyuki dumpsite is lower than the level found in the reference sample. The pooled egg sample collected in the vicinity of the Nanyuki dumpsite had the lowest levels of most POPs analyzed in this study but the levels of PBDEs and PBDD/Fs were high, demonstrating a potential influence of e-waste at this dumpsite.

Figure 1: *The highest levels of dl-PCB in eggs and related sources measured as part of IPEN studies (striped bars) and other scientific studies (filled bars). (More information, including references to individual sites are compiled in Table S3 in supporting information to the study published in 2022). Source: (Petrlik, Bell et al. 2022).*

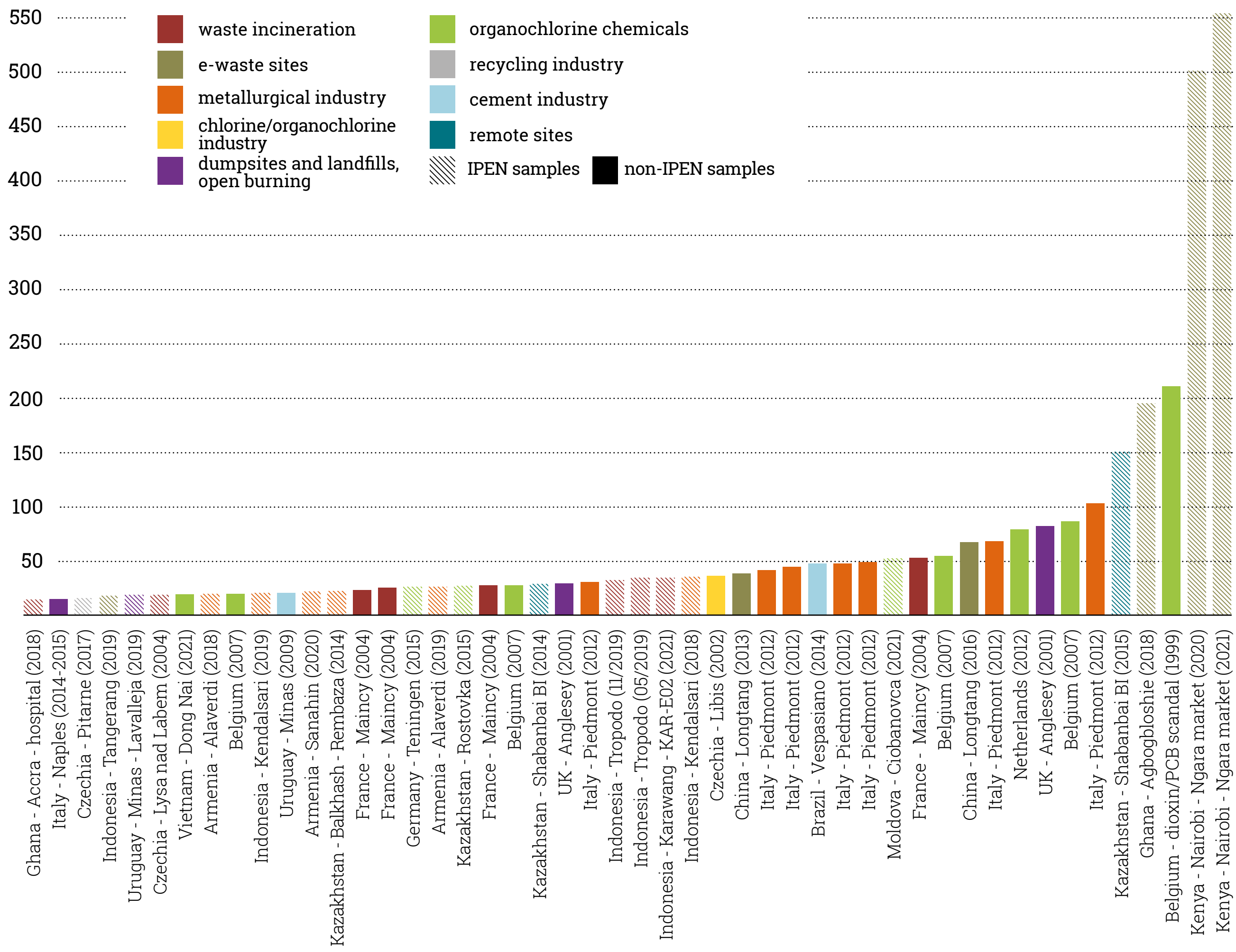

Photo 5: *Dismantling of electric and electronic waste, and potentially also end of life vehicles at Ngara market is a major source of high levels of POPs in free range chicken eggs from this site. Photo by James Wakibia.*

The levels of PCDD/Fs in free-range egg samples in this study were two to eight times higher than the EU regulatory limit of 2.5 pg TEQ/g in fat (European Commission 2016, European Commission 2022). The lowest level was in eggs from the Nanyuki dumpsite and the highest was in eggs from the Dandora dumpsite, followed by eggs from the Ngara market. The sumof PCDD/Fs + dl PCBs was 100 and 111 times respectively above the EU regulatory limit of 5 pg TEQ/g fat (European Commission 2016, European Commission 2022) in two pooled egg samples from the Ngara market. Level in the eggs from the Nanyuki dumpsite was only slightly higher than EU limit. The level PCDD/Fs + dl PCBs in the sample from the Dandora dumpsite was 26 pg TEQ/g fat, which is very close to the level of 31 pg TEQ/g fat measured in the pooled free-range egg sample from the Dandora dumpsite taken in December 2004 (Petrlik, Kamande et al. 2005). It is troubling that contamination with POPs at this locality did not decrease as the level of HCB in eggs increased from 4.4 ng/g fat in 2004 to 37 ng/g fat in 2020.

Both free-range egg samples from the Ngara market had very high levels of PCBs. The levels of dl PCB congeners measured in both samples were the highest ever measured in free chicken eggs globally, higher than in eggs contaminated with PCBs during the Belgian scandal of 1999 (van Larebeke, Hens et al. 2001) and three times higher than the level measured in eggs from an e-waste scrap yard in Agbogbloshie (Hogarh, Petrlik et al. 2019, Petrlik, Adu-Kumi et al. 2019). It is very clearly visible on the graph published in the global study from 2022 (Petrlik, Bell et al. 2022) and copied here (Figure 1). The levels of indicator PCB congeners in the two pooled egg samples from the Ngara market exceeded the EU regulatory limit of 40 ng/g fat (European Commission

Photo 6: *Plastic waste at Dandora dumpsite is a major source of BFRs and other POPs in free range chicken eggs from this site. Photo by Falkue, Creative Commons Wikipedia.*

2016, European Commission 2022) by more than 30 and 55 times, respectively. The level of indicator PCB congeners in the eggs from the Dandora dumpsite reached half of the EU limit.

„The two highest dl-PCB-contaminated pooled eggs (HC-PCB) were from Ngara e-waste dismantling market in Kenya. The TEQ contamination from dl-PCBs was 555 and 502 pg TEQ/g fat and therefore more than 100 times above the EU regulatory limit (Fig. 5). The fourth highest dl-PCB-contaminated egg was sampled by IPEN at an e-waste site in Africa (Ghana) containing 195 pg PCB TEQ/g fat (Petrlik, Adu-Kumi et al. 2019). This highlights that e-waste sites in Africa can be hotspots for high PCB contamination and exposure (see Section 3.2.8). Also from e-waste sites in China, high PCB contaminations were reported in free-range eggs (66.8 and 38.3 pg PCB-TEQ/g fat) (Zeng, Huang et al. 2018).“ (Petrlik, Bell et al. 2022).

Unintentionally produced POPs such as PCDD/Fs, PBDD/Fs, HCB and PeCB were found in high levels in free-range eggs from the Dandora dumpsite, which may be a result of open burning of waste.

The highest level of brominated dioxins was found in eggs from the Dandora dumpsite. The contamination was also high in one egg sample from the Ngara market. Levels of PBDD/Fs measured in eggs from the Ngara market and Dandora dumpsite are comparable with concentrations in eggs froms Bagong Silang, an e-waste site in the Philippines (Teebthaisong, Saetang et al. 2021).

PCNs and HBCD levels were below levels of quantification in all eggs from Kenya but the eggs from the Mirema "community cooker" vicinity had a very high level of HBCD. Contamination of eggs from Mirema was discussed in the previous study, which showed that the level of HBCD was *„the 4th highest level of this chemical ever measured in chicken eggs from African countries, more than two times higher than at the Guiyu e-waste site in China (Zeng, Luo et al. 2016)"* (Petrlik, Ochieng Ochola et al. 2020).

The dioxin level in the Mirema eggs was 12 pg TEQ g^{-1} fat, which is almost 5 times the EU limit of 2.5 pg TEQ g^{-1} fat, set as the tolerable level of dioxins (PCDD/Fs) in eggs. The contamination of eggs from Mirema was most likely caused by the dangerous practice of using plastic waste for fuel in ovens used to cook meals for school children, as emissions from the ovens ("community cookers") pollute nearby areas and contaminate the food chain

HCH levels were low in all egg samples in this study. DDT levels were increased in samples from the Ngara market and Mirema. The highest level of 231 ng/g fat found in eggs in this study is higher than the DDT levels in eggs from the vicinity of the dumpsite and previously found in the area of application of pesticides in Senegal, respectively, but were much lower than the level in most contaminated eggs with a DDT concentration of 7,041 ng/g fat from a contaminated site in Vikuge, Tanzania collected in 2005 (Petrlik, Diouf et al. 2005, Dvorska, Petrlik et al. 2009).

Table 3: *Summarized results of the calculation of dietary intake of selected POPs*

Locality	Mirema	Ngara market		Dandora	Nayuki	Nairobi - supermarket
Sample	**KE_001**	**KE_002**	**KE-EG-NG_001**	**KE-EG-D002**	**KE-EG-NY_003**	**KE_SUP**
Total content of toxic chemical(-s) in one egg (36 g)						
Total PCDD/F + dl PCBs (pg TEQ/g fw)	69	2993	3881	176	41	0.98
PBDD/Fs (pg TEQ/g fw)	N/A	49	4.20	79	15	0.15
PFOS (ng/g fw)	27	N/A	90	49	23	2.73
Intake per kg of body weight for an adult person (61 kg on average) when eating 1/10 of an egg (3.6 g)						
Total PCDD/F + dl PCBs (pg TEQ/kg bw)	0.11	4.91	6.36	0.29	0.07	0.0016
PBDD/Fs (pg TEQ/kg bw)	N/A	0.08	0.01	0.13	0.02	0.0003
PFOS (ng/kg bw)	0.04	N/A	0.15	0.08	0.04	0.0045
Exceedance of total daily tolerable intake when eating 1/10 of an egg (3.6 g) per day						
PCDD/Fs + dl PCBs (EFSA 2018) [1]	0.45	19.62	25.45	1.15	0.27	0.0064
PCDD/Fs + dl PCBs (WHO 2005) [2]	0.06	2.45	3.18	0.14	0.03	0.0008
PFOS (EFSA 2018) [3]	0,05	NA	0,17	0,09	0,04	0,01

N/A = not applicable;

[1] 0.25 pg TEQ/kg bw (EFSA CONTAM 2018a);

[2] 2 pg TEQ/kg bw (European Commission 2001, van den Berg, Birnbaum et al. 2006, Gies, Neumeier et al. 2007).;

[3] 6 ng/kg bw per week = approximately 0.86 ng/kg bw per day (EFSA CONTAM 2018b).

Notes to Table 3: *Daily intake of 1/10 of an egg (18 g) from chickens raised at selected Kenyan hot spots, or eggs bought in a Nairobi supermarket from chickens raised at a large commercial farm. 1/10 of a chicken egg is the approximate current average consumption per person per day in Kenya, based on available data (Kangethe 2022). For this calculation, zero was taken as measured in the concentration in eggs when the level of certain congeners of PCDD/Fs and dl-PCBs was measured as below LOQ; in the case of PBDD/Fs it was not calculated for samples where levels were below LOQ.*

A very high level of 639 ng/g fat of PBDEs was found in the pooled egg sample from the Dandora dumpsite. This is 22 times higher than the 29 ng/g fat found in pooled egg samples from the Dandora dumpsite in 2004 (Blake 2005). This result combined with a high level of PBDD/Fs suggests that plastics from electronics and/or car wrecks are the most likely source of this contamination at Dandora dumpsite. PBDD/Fs can be directly released from such plastics as they are unintentional contaminants of PBDE and nBFR additives in plastics (Ren, Peng et al. 2011, Ren, Zeng et al. 2017) and/or can be formed by burning waste containing BFRs (Tue, Goto et al. 2016).

The highest level of PFASs, almost 7 ng/g fresh weight, was found in eggs from the Ngara market. This level is comparable to 6.2 ng/g fresh weight found in a sample from Tangerang, Indonesia (Petrlik, Ismawati et al. 2020). The potential source of PFASs at the Ngara market needs further investigation.

4.2.1 Evaluations of dietary intake of POPs from eggs sampled at hot spots

We calculated the dietary intake for the following groups of contaminants per day: 1) PCDD/Fs plus DL-PCBs; 2) PBDD/Fs, and 3) PF0S according methodology described in chapter 2.3 above. dioxin-like PCBs was compared to TDI for PCDD/Fs + dl PCBs. In cases of Dandora and Nanyuki dumpsites, PBDD/Fs significantly contribute to daily intakes of dioxin compounds. The results are summarized in Table 3.

Based on the level of PCDD/Fs + dl PCBs in the eggs from the Ngara market, the average per capita consumption of eggs in Kenya (36 eggs per year), which is considered to be very low, would exceed the TDI for PCDD/Fs + dl PCBs by 5 6 times In addition, we can also say that by eating just one egg from the Ngara market, one person would surpass the TDI set by EFSA for dioxins and dioxin-like compounds for almost 200 to more than 250 days. The toxic burden caused by POPs in the food chain is even higher for children, because of their low body weight and vulnerability.

4.2 Comparison of plastic products analysis with results from other studies

4.2.1 Brominated flame retardants in samples from Kenya

Previous studies (Grechko, Allo'o Allo'o et al. 2022, Petrlik, Beeler et al. 2022) compared results of analyses for BFRs in plastic consumer products from Kenya with results from ten other African and Arabic countries . This comparison showed that the issue of contamination of plastic consumer products with toxic BFRs is widespread and products purchased from Kenyan markets are not very different from the rest of Africa. Samples from Kenya show the highest levels for TBBPA and belong to those with higher levels of nBFRs.

Eighteen samples of consumer products made of recycled black plastic purchased in Kenya were analyzed for BFRs. The results showed:

- Seventeen samples contained BFR DecaBDE at concentrations ranging from 0.2 ppm to 243 ppm. (10 ppm is the EU safety limit for virgin plastic; 500 ppm is the EU limit for unintentional trace contamination with PBDEs in products)
- Sixteen samples contained BFR OctaBDE at concentrations ranging from 2 ppm to 149 ppm.
- Across all 18 samples, there were six novel BFRs found at concentrations ranging from 0.2 ppm to 412 ppm.

- Tetrabromobisphenol A (TBBPA), the most widely used BFR, was found in 16 out of the 18 samples, at concentrations ranging from 0.3 ppm to 980 ppm.
- 14 of the 18 products contained PBDEs at the levels exceeding level of 50 ppm suggested as a definition for “hazardous” POPs waste by the countries of African region.

For a detailed chart of the lab analysis in Kenya see Table 2.

Table 4. *Overview of the analytical results for BFRs, per country where the samples were obtained.*

	Country	Number of samples	HBCD	ΣPBDEs	ΣnBFRs	TBBPA	ΣBFRs
Concentrations (ppm)	Burkina Faso	5	<LOQ-0.3	19-111	5.4-54	1.0-14	29-133
	Cameroon	5	<LOQ-1.5	50-210	19-225	19-113	112-495
	Egypt	7	<LOQ-12.5	17-267	5.5-103	0.4-84	58-418
	Ethiopia	4	<LOQ-2.5	35-149	25-187	1.2-243	72-646
	Gabon	8	<LOQ-4.7	0.54-209	0.03-125	0.4-89	1-424
	Jordan	4	<LOQ-1.2	30-390	20-689	7.3-186	57-1180
	Kenya	18	<LOQ-1.1	0.2-279	0.3-412	0.5-980	0.6-1347
	Morocco	7	<LOQ-3.1	37-315	6-434	10-196	98-897
	Syria	4	0.004-0.2	3.9-194	0.9-69	0.2-64	5-214
	Tanzania	11	<LOQ-1.8	50-332	21-107	30-91	138-439
	Tunisia	10	<LOQ-49	11-308	12-325	3.5-151	30-608

Source: (Petrlik, Beeler et al. 2022).

4.2.2 Brominated dioxins in toy cars

One sample, a toy ar, was analyzed for brominated dioxins and was found to contain 6,590 pg TEQ/g, which is much higher than concentrations observed, for example, in waste incineration ashes or pyrolysis residues (Lai, Lee et al. 2007, Kawamoto 2009). This confirms that these highly toxic dioxins are present and can be in very high levels in recycled plastic consumer products. Table 5 shows a comparison of PBDD/Fs levels in toys and other consumer products from other African countries and Jordan, published in the previous study (Petrlik, Beeler et al. 2022).

Photo 7: *A toy car contained high levels of brominated dioxins. Photo by Kristina Zulkovska.*

The results for the total content of PBDEs and TBBPA in those samples are also given for comparison. The level of PBDD/Fs is expressed in total amounts as well as in toxic equivalents (TEQ).

Table 5. *Overview of PBDD/F congeners test results in nine samples from seven countries.*

Sample ID	Sample description	Country	TBBPA (ug/kg)	ΣPBDEs (ppm)	17 PBDD/F congeners (pg TEQ/g)	17 PBDD/F congeners (pg/g)
CMR-0009-HA	Head dress	Cameroon	52	210	774	261,923
Ga-29-01	Lipstick	Gabon	85	194	378	88,197
Ga-08-01	Knife	Gabon	2	182	1,430	243,422
Jo-T-1N	Toy car	Jordan	99	390	3,580	741,123
Jo-T-1C	Rubik's cube	Jordan	185	254	8,180	1,120,526
MOR-HA-3A	Head dress	Morocco	29	315	885	173,957
KEN-T-6	Toy car	Kenya	0.5	270	6,590	1,590,463
TZ-K-33A	Spoon	Tanzania	33	52	210	28,751
TUN-T-18A	Toy chess set	Tunisia	36	195	513	176,370

Source: (Petrlik, Beeler et al. 2022)

The nine consumer products from African countries and Jordan showed levels ranging from 210 to 8,180 pg TEQ/g. The highest levels were found in toys from Jordan and Kenya. The level of PBDD/Fs in the toy car from Kenya, 6,590 pg TEQ/g, is much higher than the highest level of PBDD/Fs of 3,821 pg TEQ/g in black plastic consumer products from European countries, which was found in a plastic key fob purchased in Germany (Petrlík, Behnisch et al. 2018).

5. How to fix the problem?

5.1 Halt the entry of plastic treated with BFRs to be recycled into toys and other consumer goods

A major problem arose when polybrominated diphenylethers (PBDEs), BFRs listed for global elimination under the Stockholm Convention, were granted exemptions that allow plastics containing BFRs to be recycled from wastes. E-waste and ELVs plastic containing high levels of toxic flame retardants should be banned from entering the recycling chain. TMost importantly, this requires strengthening international rules. It will also require better sorting of plastics at recycling sites..

Also, the loophole allowing exports of nonfunctional electronics under the guise of repair in the Basel Convention's Technical Guidelines needs to be fixed and stricter standards for the definition of hazardous wastes must be established under both the Basel and Stockholm Conventions.

African countries also need to improve their national regulations to require better control of imported waste and products, in particular, concerning POPs content (see chapters 5.2 – 5.4 for more details on this topic).

5.2 Need for setting stricter limits

To eliminate human exposure to PBDEs and related harmful chemicals such as brominated dioxins (PBDD/Fs) in products and wastes, strict limit values must be established. Low POPs Content Levels (LPCLs) for waste that defines POPs waste according to Article 6 of the Stockholm Convention should be established at a level of 50 ppm as proposed by the African region and accompanied with setting an unintentional trace contamination (UTC) level at 10 ppm. The same UTC level is currently applied in the EU for content of PBDEs in virgin substances (European Parliament and the Council of the European Union 2019)

Out of the 18 analyzed products in this study, 14 had PBDE levels that were higher than the current EU limit and proposed value for the Stockholm Convention of 50 ppm, which means that these 14 products would be considered as POP waste if a LPCL of 50 ppm is applied. This level should be enforced in practice and introduced into the national legislation of each of the African countries. This raises the question of whether setting stricter limits than those used in EU is manageable. Practically, it is mainly a question of using separation techniques for waste containing higher levels of PBDEs and techniques available for custom control of products entering the market.

5.3 Separation techniques

Gas chromatography and mass spectrometry are usually used for laboratory quantification of brominated flame retardants in different matrices, including plastics.

In recycling workshops and plants, methods based on the total concentration of bromine are applied to identify BFR-treated plastic and separate it out of the waste stream. For example, X-ray

Photo 8: *EcoWaste Coalition, a participating organization of IPEN, successfully using a handheld XRF for analysis a large variety of products for total bromine and antimony levels, proxies of PBDE content in products. Photo: EcoWaste Coalition.*

fluorescence (XRF) and X-ray transmission (XRT) are used at the industrial scale (UNEP 2017). Typical bromine concentrations in plastics used in electric and electronic appliances are: 6-10% in high impact polystyrene (HIPS), 4-5% in polycarbonate (PC), and 6.8-9.6% in acrylonitrile butadiene styrene (ABS) (Weil and Levchik 2009). These known concentrations indicate what kind of plastics should be separated from the materials destined for recycling.

For the lab-analyzed level of PBDEs of 50 ppm and more, the total bromine (Br) content measured by XRF-device was not below 300 ppm and the antimony (Sb) level was not below 70 ppm in 83 out of the total 434 products analyzed in the study for eleven African and Arabic countries, which also included Kenya (Petrlik, Beeler et al. 2022). This method can also be used for border control of consumer products and/or waste entering into African countries, and the level of 300 ppm of total bromine content in combination with 50 ppm of antimony measured by XRF can be used as a threshold.

In the informal plastic recycling sector in India, a simple sink-and-float method is used for BFR plastic separation (UNEP 2017). Identical plastic materials are first shredded and then placed into a bath. This method is based on different densities of plastic:plastics with BFRs are significantly more dense, so it sinks, while its non-flame retardant counterparts float.

5.4 Regulation of BFRs other than PBDEs and HBCD

No limit values are currently set for novel brominated flame retardants (nBFRs) and/or tetrabromobisphenol-A (TBBPA) in consumer products or wastes. The elevated levels of PBDEs and nBFRs in some consumer products reported in this study and the known and unknown adverse effects of these chemicals require a class-based approach to the restriction of BFRs. The same approach is currently being discussed for PFASs in the EU.[7]

5.5 How to prevent contamination of the food chain with POPs

The very serious contamination of free-range chicken eggs with various POPs revealed in this study shows that e-wastes plus end-of-life vehicles (ELVs) often imported to African countries from developed countries represent a serious threat for the environment and health in Africa. The highest ever measured levels of dl PCBs in eggs were found in eggs from the Ngara market, a place where a large amount of electronic and electric equipment and/or ELVs end up in Nairobi. Technical PCB mixtures used in electric equipment or in the hydraulics of vehicles are the most likely source of this contamination. This must be stopped and better control of waste and end-of-life electronics and vehicles must be introduced and implemented internationally. This includes the introduction of stricter limits for defining POPs and hazardous wastes.

5.6 Regulation and control of plastic waste

Leakage and emissions of POP additives from waste is a source of contamination of free-range chicken eggs with BFRs and PFASs in the vicinity of dumpsites and/or community cookers using plastic waste as fuel. Burning plastic waste containing chlorinated and brominated additives generates unintentionally produced POPs (U-POPs) such as HCB, PeCB, PCDD/Fs, PBDD/Fs and dl PCBs. The new global Plastics Treaty should focus on the chemical content of plastic materials.

There is enough evidence that burning polyvinylchloride (PVC) is linked to the generation of dioxins (Stockholm Convention on POPs 2008), and this and other chlorine containing plastics can also lead to the formation of dioxins at studied hot spots in Kenya. *"Many studies show that combustion of chlorine containing waste such as PVC leads to increased formation of unintentional persistent organic pollutants as shown in Table 7*[8] *(Gullett, Lemieux et al. 1999). A regulation specifying standard fuels could be implemented"* (Stockholm Convention on POPs 2008).

International guidelines and rules are still lacking in guidance for decision-makers on steps toward substitution of such materials as PVC or plastics containing brominated compounds, although it is very well specified in Annex C, Part V of the Stockholm Convention that: *"Priority should be given to the consideration of approaches to prevent the formation and release of the chemicals listed in Part I. Useful measures could include: (d) Replacement of feed materials which are persistent organic pollutants or where there is a direct link between the materials and releases of persistent organic pollutants from the source"* (Stockholm Convention 2010).

7 https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas
8 Data from Table 7 in referenced literature were converted into Table 17 in this study.

Facilities using plastic waste as a fuel such as community cookers need to be prohibited, as does open burning of plastic waste. These facilities have no air pollution control equipment or practices for dioxin and other U-POPs emissions.

5.7 Treatment of POPs waste, including BFRs containing plastics

Wastes containing high levels of POPs can be treated by non-combustion technologies, which destroy POPs and do not generate new ones unintentionally (Bell 2020). *"Combustion and other incineration processes, such as waste to energy incinerators, pyrolysis, gasification, cement kilns, metallurgy blast furnaces, and plasma arc units, have a strong tendency to form UPOPs in emissions and in residues from their filters such as fly ash, cement kiln dust (CKD), bottom ash, and scrubber water effluent where wet scrubbers are engaged to strip flue gases. IPEN does not regard these technologies as environmentally sound due to their propensity to generate highly hazardous UPOPs*[9]," (Bell and Takada 2021).

It could benefit African countries to cooperate regionally on establishing treatment center(s) for POP waste. An advantage of some non-combustion technologies is their mobility (Bell and Takada 2021, Basel Convention 2022). Gas phase chemical reduction (GPCR) or supercritical water oxidation (SCWO) seem to be the most promising technologies to treat POP waste (Bell and Takada 2021, Basel Convention 2022).

9 See Annex C Stockholm Convention on Persistent Organic Pollutants.

6. Conclusions and recommendations

6.1 Plastic products

In agreement with previous studies, the present study shows that children toys, hair accessories, office supplies, and kitchen utensils found on the Kenyan market are affected by unregulated recycling of e-waste plastics, which carry brominated flame retardants (BFRs) into new products. To stop this practice, stricter measures to control BFRs in products and waste need to be set and enforced.

The analysis showed that products in Kenya made from recycled plastic contain highly toxic chemicals, including substances listed in the Stockholm Convention for global elimination (OctaBDE, DecaBDE, and HBCD). A very high level of brominated dioxins was identified in toys from a Kenyan market. The presence of brominated dioxins accompanying PBDEs in products underlines the urgent need to apply stricter LPCLs. Moreover, elevated levels of novel BFRs (nBFRs) and tetrabromobisphenol A (TBBPA) were detected in the analyzed products. These substances are unregulated and pose significant health risks. Only a class-based approach can address the regrettable substitutes and likely toxic nBFRs that are currently used without any regulation and which will continue to circulate in the waste streams, just as their persistent counterparts. Listing these chemicals under the Stockholm Convention as individual substances would also take much longer. Their levels in consumer products require immediate action.

Strict Low POPs Content Limits (LPCLs) should be applied in order to stop the transfer of e-waste and ELVs plastic into recycled plastics and the products made from it. Strict LPCLs can also help stop the continuing import of POPs waste into African countries. Out of the 18 analyzed products in this study, 14 had levels of PBDEs above 50 ppm, which means they would be considered as POPs waste if a LPCL of 50 ppm is applied. For the total amount of PBDEs, LPCL 50 ppm should be applied.

In addition to LPCL, Kenya and other African countries should introduce strict UTC limits for BFRs in products into their national regulations and they should enforce the limits using available separation techniques for border controls of incoming products and wastes. Only a combination of such measures will result in products and waste without toxic BFRs and related chemicals.

6.2 POPs in the food chain – demonstrated on eggs

In this study, the level of PCDD/Fs in free-range egg samples exceeded the EU regulatory limit of 2.5 pg TEQ/g fat by 2-8 times. The highest level was identified in eggs from near the Dandora dumpsite. In the case of Dandora and Nanyuki dumpsites, PBDD/Fs contribute to daily exposures to dioxin compounds significantly.

The levels of dl PCB congeners measured in both samples from Ngara market known for e-waste and ELVs dismantling were the highest ever measured in free-range chicken eggs globally. By eating just one egg from the Ngara market, one person would exceed the tolerable daily intake (TDI) set by EFSA for dioxins and dioxin-like compounds for nearly 200 to more than 250 days. The toxic burden caused by POPs in the food chain is even higher for children because of their low weight and overall vulnerability of their developing bodies .

The highest level of PFASs of almost 7 ng/g of fresh weight was identified in eggs from the Ngara market. This level is comparable to 6.2 ng/g of fresh weight in an eggs sample from Tangerang, Indonesia.

A very high level of 639 ng/g fat of PBDEs was identified in the pooled egg sample from the Dandora dumpsite. The contamination of eggs from the Dandora dumpsite was high for other POPs as well. The content of PCDD/Fs + dl PCBs in the sample from the vicinity of the dumpsite was 26 pg TEQ/g fat, which is very close to the level of 31 pg TEQ/g fat identified in the pooled free-range chicken egg sample from the Dandora dumpsite taken in December 2004. It is troubling that contamination with POPs in this site did not decrease as level of HCB in eggs increased by more than 8 times. The level of PBDD/Fs were the highest among hot spots sampled for this study.

In addition, the levels of dioxins in eggs from the vicinity of the community cooker in Mirema exceeded the EU regulatory limit of 2.5 pg TEQ/g fat by almost 5times. A high level of HBCD was identified in the same sample of eggs. These levels may have resulted from using plastic waste as fuel to cook meals for school children.

The results of this study highlight that the new global Plastics Treaty should focus on the chemicals in plastics. All forms of burning plastic waste, including their use as fuel, should be banned as this releases POPs into the environment. Wastes containing high levels of POPs can be treated by non-combustion technologies, which destroy POPs and do not unintentionally generate new POPs.

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8. Annex 1: Persistent Organic Pollutants (POPs)

Persistent organic pollutants (POPs) represent a large group of chemicals, which persist for a long time in the environment and bioaccumulate. They have potential for long-range environmental transport, and they also have adverse effects on human health and the environment (Stockholm Convention 2010).

8.1 Intentionally produced POPs

The intentionally produced POPs considered in our study were mainly technical chemicals and their mixtures used intentionally in electric and electronic equipment or the automotive industry as well as those used as additives to plastics.

8.1.1 Non-dioxin-like polychlorinated biphenyls (PCBs)

Polychlorinated biphenyls (PCBs) were produced until the 1980s in large volumes and they were used by industries as heat exchange fluids, in electric transformers and capacitors, and as additives for paint, carbonless copy paper, and plastics (Stockholm Convention 2019). Approximately 1.3 to 2 million tonnes of PCB were industrially produced in various countries from 1929 until the 1980s (Breivik, Sweetman et al. 2002, Weber, Herold et al. 2018a). Twelve PCB congeners are considered dioxin-like PCBs because of their effects and properties similar to PCDD/Fs (van den Berg, Birnbaum et al. 2006, European Commission 2012). These congeners are listed as unintentionally produced POPs in Annex C to the Stockholm Convention (Stockholm Convention 2010). Technical mixtures of PCBs are characterized by six,[10] sometimes seven[11] indicator PCB congeners. In the EU, maximum levels in food are set for six indicator PCB congeners (European Commission 2012, European Commission 2016).

8.1.2 Polychlorinated naphthalenes (PCNs)

Polychlorinated naphthalenes (PCNs) were produced for uses similar to PCBs, so they are their predecessors in a way. PCNs make effective insulating coatings for electrical wires. Others have been used as wood preservatives, rubber and plastic additives, for capacitor dielectrics, and in lubricants. At present, intentional production of PCNs is assumed to have ended (Stockholm Convention 2017). But they are also unintentionally generated during high-temperature processes in the presence of chlorine, similarly to PCDD/Fs and dl PCBs.

The following PCN congeners were measured in the samples for this study: PCN 4, PCN 9, PCN 18, PCN 20, PCN 41, PCN 42, PCN 52, PCN 56, PCN 66, PCN 70, PCN 73, PCN 74, and PCN 75.

8.1.3 Short-chain chlorinated paraffins (SCCPs)

Short-chain chlorinated paraffins (SCCPs) are a group of POPs added to the Stockholm Convention

10 PCB 28, PCB 52, PCB 101, PCB 138, PCB 153, and PCB 180.
11 PCB 28, PCB 52, PCB 101, PCB 118, PCB 138, PCB 153, and PCB 180.

for global elimination in 2017. Chlorinated paraffins (CPs) are complex mixtures of certain organic compounds containing chloride: polychlorinated n-alkanes. SCCPs can be used as a plasticizer in rubber, paints, adhesives, and flame retardants for plastics as well as an extreme-pressure lubricant in metal-working fluids (Stockholm Convention 2017). At low levels, SCCPs are toxic to aquatic organisms, disrupt the endocrine function, and are suspected to cause cancer in humans (POP RC 2015). SCCPs are additives in plastics that might also be expected in waste imported to and/or produced in Kenya. They were often used in manufacturing wires and cables (POP RC 2009).

8.1.4 Brominated flame retardants (BFRs)

8.1.4.1 Polybrominated diphenyl ethers (PBDEs)

Polybrominated diphenyl ethers (PBDEs) are a group of brominated flame retardants that include substances listed in the Stockholm Convention for global elimination, such as PentaBDE (2009), OctaBDE (2009), and DecaBDE (2017). PBDEs are additives mixed into plastic polymers that are not chemically bound to the material and therefore, leach into the environment. PBDEs have adverse effects on reproductive health as well as developmental and neurotoxic effects (POP RC 2006, POP RC 2007, POP RC 2014). DecaBDE and/or its degradation products may also act as endocrine disruptors (POP RC 2014).

PentaBDE has been used in polyurethane foam for car and furniture upholstery, and Octa- and DecaBDE have mainly been used in plastic casings for electronics. OctaBDE made up 10%-18% of the weight (Stockholm Convention 2016) of CRT television and computer casings and other office electronics made of acrylonitrile butadiene styrene (ABS) plastic. DecaBDE makes up 7%-20% of the weight (POP RC 2014) of many different plastic materials, including high-impact polystyrene (HIPS), polyvinylchloride (PVC), and polypropylene (PP) used in electronic appliances. As this study examines samples from sites affected by the presence of electronic waste and/or by its incineration, all of the above-mentioned PBDEs were part of the main focus of our investigation.

8.1.4.2 Hexabromocyclododecane (HBCD)

Hexabromocyclododecane (HBCD) is a brominated flame retardant primarily used in polystyrene building insulation. HBCD is an additive mixed into plastic polymers that is not chemically bound to the material and that therefore may leach into the environment. HBCD is highly toxic to aquatic organisms and has negative effects on reproduction, development, and behavior in mammals, including transgenerational effects (POP RC 2010). HBCD is also found in packaging materials, video cassette recorder housings, and electric equipment.

HBCD was listed in Annex A of the Stockholm Convention for global elimination with a five-year specific exemption for use in building insulation that expired for most Parties in 2019 (Stockholm Convention 2013).

8.1.4.3 Tetrabromobisphenol A (TBBPA)

Tetrabromobisphenol A (TBBPA) is the largest-volume flame retardant used worldwide (Kodavanti and Loganathan 2019), covering around 60% of the total global BFR market (Law, Allchin et al. 2006), While most of the TBBPA is chemically bonded to the polymer matrix of printed circuit boards, it is also used as a flame retardant additive in the manufacturing of ABS resins and HIPs as an alternative to PBDEs and HBCD, and for banned OctaBDE mixtures in ABS plastic in particular (POP RC 2008, Abou-Elwafa Abdallah 2016). The main applications for plastic containing TBBPA include TV set back-casings and business equipment enclosures (ECHA 2008).

TBBPA is a cytotoxicant, immunotoxicant, and thyroid hormone agonist with the potential to disrupt estrogen signaling (Kitamura, Jinno et al. 2002, Birnbaum and Staskal 2004). It is also classified as very toxic to aquatic organisms and is on the OSPAR Commission's List of Chemicals for Priority Action because of its persistence and toxicity (OSPAR Commission 2011).

While earlier risk assessment studies concluded that there is no risk to human health associated with exposure to TBBPA (EFSA CONTAM 2011), recent studies have identified this chemical as "probably carcinogenic to humans" (Grosse, Loomis et al. 2016, IARC 2020).

TBBPA has been detected in almost all environmental media all over the world, rendering it a ubiquitous contaminant (Abou-Elwafa Abdallah 2016). It was found to bioaccumulate, e.g. in peregrine falcon eggs (Schwarz, Rackstraw et al. 2016). TBBPA was also identified in a soil sample from the Agbogbloshie e-waste scrapyard at a level of 149 ng g-1 dw, which was higher than the levels of nBFRs, but lower than the level of PBDEs analyzed in the same sample. It was not found to accumulate in the eggs from that site (Petrlik, Adu-Kumi et al. 2019).

Human exposure studies revealed dust ingestion and diet as the major pathways of TBBPA exposure in the general population.

There are no current restrictions on the production of TBBPA in the EU or worldwide.

8.1.4.4 Novel brominated flame retardants (nBFRs)

In addition to PBDEs, HBCD, and TBBPA, a group of six novel BFRs was chosen for analysis in the environmental samples from the localities studied in Kenya.

Novel BFRs (nBFRs) are a group of chemicals that in many cases replaced the restricted BFRs. Different sources list different chemicals among this group, but only a few of them are measured in the environment. Recent studies also show that nBFRs are becoming widespread in the environment, including in food (Shi, Zhang et al. 2016). A review of the levels of BFRs in soil concluded that: *"Although further research is required to gain baseline data on NBFRs in soil, the current state of scientific literature suggests that NBFRs pose a similar risk to land contamination as PBDEs"* (McGrath, Ball et al. 2017).

The scientific panel of the EFSA evaluated 17 "emerging"[12] and 10 "novel"[13] BFRs in 2012 and suggested that: *"There is convincing evidence that tris(2,3-dibromopropyl) phosphate (TDBPP) and*

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12 The group of emerging BFRs included: BEH-TEBP – Bis(2-ethylhexyl) tetrabromophthalate, BTBPE – 1,2-Bis(2,4,6-tribromophenoxy)ethane, DBDPE – Decabromodiphenyl ethane, DBE-DBCH – 4-(1,2-Dibromoethyl)-1,2-dibromocyclohexane, DBHCTD – 5,6-Dibromo-1,10,11,12,13,13-hexachloro-11-tricyclo[8.2.1.02,9]tridecene, EH-TBB – 2-Ethylhexyl 2,3,4,5-tetrabromobenzoate, HBB – 1,2,3,4,5,6-Hexabromobenzene, HCTBPH – 1,2,3,4,7,7-Hexachloro-5-(2,3,4,5-tetra-bromophenyl)- bicyclo[2.2.1]hept-2-ene, OBTMPI – Octabromotrimethylphenyl indane (OBIND in this study), PBB-Acr – Pentabromobenzyl acrylate, PBEB – Pentabromoethylbenzene, PBT – Pentabromotoluene, TBNPA – Tribromoneopentyl alcohol, TDBP-TAZTO – 1,3,5-Tris(2,3-dibromopropyl)-1,3,5-triazine-2,4,6-trione, TBCO – 1,2,5,6-Tetrabromocyclooctane, TBX – 1,2,4,5-Tetrabromo-3,6-dimethylbenzene, and TDBPP – Tris(2,3-dibromopropyl) phosphate.

13 The group of novel BFRs included: BDBP-TAZTO – 1,3-Bis(2,3-dibromopropyl)-5-allyl-1,3,5-triazine-2,4,6(1H,3H,5H)-trione, DBNPG – Dibromoneopentyl glycol, DBP-TAZTO – 1-(2,3-Dibromopropyl)-3,5-diallyl-1,3,5-triazine-2,4,6(1H,3H,5H)-trione, DBS – Dibromostyrene, EBTEBPI – N,N'-Ethylenebis(tetrabromophthalimide), HBCYD – Hexabromocyclododecane (HBCD or HBCDD are additional abbreviations used for this chemical, already listed in Annex A to the Stockholm Convention), HEEHP-TEBP – 2-(2-Hydroxyethoxy)ethyl 2-hydroxypropyl 3,4,5,6-tetrabromophthalate, 4'-PeBPO-BDE208 – Tetradecabromo-1,4-diphenoxybenzene, TTBNPP – Tris(tribromoneopentyl) phosphate, and TTBP-TAZ – Tris(2,4,6-tribromophenoxy)-s-triazine.

dibromoneopentyl glycol (DBNPG) are genotoxic and carcinogenic, warranting further surveillance of their occurrence in the environment and in food. Based on the limited experimental data on environmental behaviour, 1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE) and hexabromobenzene (HBB) were identified as compounds that could raise a concern for bioaccumulation" (EFSA CONTAM 2012). EFSA's panel also stated that for most of the BFRs that were evaluated, there was not sufficient data about their presence in the environment for meaningful conclusions to be drawn.

Decabromodiphenyl ethane (DBDPE) was introduced in the early 1990s as an alternative to DecaBDE in plastic and textile applications (Ricklund, Kierkegaard et al. 2010). It was used mainly in wire coatings and polystyrene, in both cases as a replacement for DecaBDE. This widespread contaminant is a highly hydrophobic compound (with a log Kow of 11.1); (Covaci, Harrad et al. 2011). DBDPE has been identified in sewage sludge (De la Torre, Concejero et al. 2012), indoor dust (Julander, Westberg et al. 2005, Ali, Harrad et al. 2011), outdoor dust (Muenhor, Harrad et al. 2010, Anh, Tomioka et al. 2018), chicken eggs (Tlustos, Fernandes et al. 2010), and food in general (Tlustos, Fernandes et al. 2010, Shi, Zhang et al. 2016).

BTBPE was first produced in the 1970s and is used as a replacement for OctaBDEs (Hoh, Zhu et al. 2005). It was identified in various abiotic media (dust, the atmosphere, sediment, water) and biotic media (zooplankton, mussels, fish, aquatic birds' eggs, honey, chicken eggs, or food in general) (Hoh, Zhu et al. 2005, Julander, Westberg et al. 2005, Ali, Harrad et al. 2011, Wu, Guan et al. 2011, Mohr, García-Bermejo et al. 2014, Poma, Volta et al. 2014, Petrlik 2016, Petrlik, Kalmykov et al. 2017, Anh, Tomioka et al. 2018).

This compound has the ability to bioaccumulate and to biomagnify in aquatic food webs (Law, Halldorson et al. 2006, Wu, Guan et al. 2011). Similarly to DecaBDE, a commercial mixture of BTBPE was found to contain brominated dioxins (PBDD/Fs) and/or to support their formation during the treatment of ABS plastic (Tlustos, Fernandes et al. 2010, Ren, Zeng et al. 2017, Zhan, Zhang et al. 2019). BTBPE has been identified in increased concentrations during passive air sampling conducted in Indonesia in 2005–2006 (Lee, Sverko et al. 2016).

HBB has commonly been used for the manufacturing of paper, wood, textiles, plastics, and electronic goods (Yamaguchi, Kawano et al. 1988, Watanabe and Sakai 2003) and it is *"likely widely distributed, as verified both by chemical analysis and estimated properties"* (Arp, Møskeland et al. 2011).

The laboratory of the Department of Food Chemistry and Analysis of the University of Chemistry and Technology, Prague, routinely measures six nBFRs in environmental samples, including the egg samples for this study: 1,2-bis(2,4,6-tribromophenoxy) ethane (BTBPE), decabromodiphenyl ethane (DBDPE), hexabromobenzene (HBB), octabromo-1,3,3-trimethylpheny-1-indane (OBIND), 2,3,4,5,6-pentabromoethylbenzene (PBEB), and pentabromotoluene (PBT).

Out of this group, BTBPE, DBDPE, and HBB are monitored more often in environmental samples (Munschy, Héas-Moisan et al. 2011, Mohr, García-Bermejo et al. 2014, Poma, Volta et al. 2014, Vorkamp, Bossi et al. 2015).

8.1.5 Per- and polyfluoroalkyl substances (PFASs)

Per- and polyfluoroalkyl substances (PFASs) are a large class (OECD 2018) of more than 4,500 very persistent fluorinated chemicals (including PFOS) that have been widely used in packaging, textiles and plastics. Scientists are concerned with their widespread presence in the environment, and in the Madrid Statement said that they: *"call on the international community to cooperate in limiting the production and use of PFASs and in developing safer nonfluorinated alternatives"* (Blum, Balan et al. 2015). Later, in the Zurich Statement, they called upon regulators to address PFASs as chemically-related groups rather than as individual substances (Ritscher, Wang et al. 2018).

In animal studies, some long-chain PFASs have been found to cause liver toxicity, disruption of lipid metabolism and of the immune and endocrine systems, adverse neurobehavioral effects, neonatal toxicity and death, and tumors in multiple organ systems (Lau, Anitole et al. 2007, Post, Cohn et al. 2012). More health effects are summarized in the Madrid and Zurich statements as well as in the toxicological profiles of PFASs (Blum, Balan et al. 2015, ATSDR 2018, Ritscher, Wang et al. 2018, Fenton 2019).

The EFSA has sharply lowered the permitted intake of PFOS from 150 ng/kg body weight/day to 13 ng/kg body weight/week (EFSA CONTAM 2018b). An investigation of PFASs substances in Indonesia found that they are unregulated and contaminate both coastal sediments and breast milk (BaliFokus/Nexus3 Foundation 2019).

8.1.5.1 PFOS

Perfluorooctanesulfonic acid (PFOS) and its salts were listed in the Stockholm Convention in 2009 along with perfluorooctane sulfonyl fluoride (PFOSF). The Stockholm Convention expert committee concluded that, "*PFOS is extremely persistent. It does not hydrolyse, photolyze or biodegrade in any environmental condition tested*" (POP RC 2006a). In animal studies, PFOS has been shown to cause cancer, neonatal mortality, delays in physical development, and endocrine disruption (Thomford 2002a, Thomford 2002b, Luebker, York et al. 2005, Jacquet, Maire et al. 2012, Du, Hu et al. 2013). PFOS-related substances have been used in the packaging and paper industries in both food packaging and commercial applications to impart grease, oil and water resistance to paper, paperboard and packaging substrates (KemI 2004).

8.1.5.2 PFOA

Perfluorooctanic acid (PFOA) is another common member of the PFASs family of substances. Governments added PFOA, its salts and PFOA-related substances to the Stockholm Convention for global elimination in 2019. PFOA and related substances have a large variety of uses, e.g. in the manufacturing of many fluoropolymers, for the semiconductor industry, and in firefighting foams, ski waxes, paper packaging for microwave popcorn, and baking paper (POP RC 2016).

Higher maternal levels of PFOS and PFOA are associated with delayed pregnancy, and reduced human semen quality and penis size (Fei, McLaughlin et al. 2009), (Joensen, Bossi et al. 2009, Di Nisio, Sabovic et al. 2018). In humans, PFOA is associated with high cholesterol, ulcerative colitis, thyroid disease, testicular cancer, kidney cancer, pregnancy-induced hypertension, and immune system effects. It is also transferred to the fetus through the placenta and to infants via breast milk (POP RC 2016).

8.1.5.3 PFHxS

Perfluorohexane sulfonate (PFHxS), with its salts and PFHxS-related substances, is another group of PFASs listed in the Stockholm Convention (Stockholm Convention 2022). PFHxS was commonly used as a surfactant (foam formation for reduction of fuel fires) and a surface protector (in metal plating processes, consumer products such as carpets, textiles, and in the leather industry). It is one of the most persistent compounds in the environment, with an estimated serum elimination half-life of PFHxS in humans on an average of 8.5 years (range 2.2–27 years), even higher than for other PFASs (POP RC 2019).

The most common exposure pathways for humans are mainly intake of food and drinking water, but exposure can also come from indoor dust inhalation and from consumer products containing PFHxS or its precursors (POP RC 2019). PFHxS can trigger hypersensitivity and suppression of the immune system (asthma, allergic reactions), changes of lipids and protein metabolism pathways, changes in liver and thyroid functions, and impact the reproductive system (Ali, Roberts et al. 2019, POP RC 2019).

8.1.5.4 Other PFASs

There is a range of other PFASs that could be present in wastes imported or locally produced in Kenya. Samples from Kenya were analyzed in the laboratory of the University of Chemistry and Technology in Prague for 17 PFASs, both individual substances and/or their groups.[14]

8.2 Unintentionally produced POPs

There is a large group of POPs, which were not produced intentionally and added to any products, but occurred as unintentional by-products at one of the phases of the production of chemicals or disposal of waste containing halogenated compounds. These POPs are listed in Annex C to the Stockholm Convention (Stockholm Convention 2010). We have also added polybrominated dioxins (PBDD/Fs), which are not listed in Annex C, to our study.

8.2.1 Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs)

Dioxins belong to a group of 75 polychlorinated dibenzo-p-dioxin (PCDD) congeners and 135 polychlorinated dibenzofuran (PCDF) congeners, of which 17 are of toxicological concern. Levels of PCDD/Fs and dl-PCBs are expressed in total WHO-TEQ, calculated according to toxic equivalency factors (TEFs) set by a WHO expert panel in 2005 (van den Berg, Birnbaum et al. 2006). These WHO TEFs were used to evaluate dioxin-like toxicity in the pooled samples of chicken eggs, soil, sediment, and dust samples in this study.

Chlorinated dioxins (PCDD/Fs) are known to be extremely toxic. Numerous epidemiological studies revealed a variety of human health effects linked to chlorinated dioxin exposure, including cardiovascular disease, diabetes, cancer, porphyria, endometriosis, early menopause, alteration of testosterone and thyroid hormones, and an altered immune system response, among others (White and Birnbaum 2009, Schecter 2012). Laboratory animals given dioxins suffered a variety of effects, including an increase in birth defects and stillbirths. Fish exposed to these substances died shortly after exposure. Food (particularly of animal origin) is the major source of exposure for humans (BRS 2017).

Chlorinated dioxins became known to the public in the 1970s as a result of contamination with Agent Orange, a defoliant pesticide mixture sprayed by the U.S. during the Vietnam War. The production of 2,4,5 T pesticide as a basic ingredient for Agent Orange left one of the most seriously contaminated sites in Europe (Zemek and Kocan 1991, Kubal, Fairweather et al. 2004,

14 List of 17 PFASs included in the analysis: PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUdA, PFDoA, PFTrDA, PFTeDA, PFBS, PFHxS, br-PFOS, L-PFOS, PFDS, PFOSA

Weber, Gaus et al. 2008) and sickened workers with many symptoms of exposure to the most toxic of dioxin congeners, 2,3,7,8-TCDD (Pelclová, Urban et al. 2006, Bencko and Foong 2013).

8.2.2 Dioxin-like polychlorinated biphenyls (dl PCBs)

Polychlorinated biphenyls (PCBs) are a group of 209 congeners that can be divided into two groups according to their toxicological properties: 12 congeners exhibit toxicological properties similar to dioxins and are often referred to as "dioxin-like PCBs" (dl-PCBs). They are suggested to be a part of the total TEQ levels (van den Berg, Birnbaum et al. 2006), and this study includes their levels in total PCDD/Fs + dl PCBs TEQ concentrations in all samples except HNK-SOIL-01.

The other PCB congeners do not exhibit dioxin-like toxicity but have a different toxicological profile and are referred to as "non-dioxin-like PCBs" (ndl-PCBs) (European Commission 2011).

8.2.3 Polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs)

There are also other unintentionally produced POPs that are not yet listed in the Stockholm Convention. With the broad use of brominated flame retardants, the question has arisen about the presence of polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs)[15] in the food chain, as they are found in different environmental media (Kannan, Liao et al. 2012). The WHO expert panel concluded that polybrominated dibenzo-p-dioxins (PBDDs), dibenzofurans (PBDFs), and some dioxin-like polybrominated biphenyls (dl-PBBs) may contribute significantly to daily human background exposure to the total dioxin toxic equivalencies (TEQs) (van den Berg, Denison et al. 2013).

PBDD/Fs are the most relevant group of unintentionally produced POPs in the sites that were sampled with e-waste and/or plastic waste, which may contain brominated flame retardants, like those in Agbogbloshie, Ghana, and Samut Sakhon, Thailand, respectively (Teebthaisong, Petrlík et al. 2018, Hogarh, Petrlik et al. 2019).

Since 1986, PBDD/Fs have been known to be potential by-products of commercial PBDE mixtures (Buser 1986). They were also found to be by-products of some novel BFRs such as DBDPE (Brenner and Knies 1990) or BTBPE (Ren, Zeng et al. 2017, Zhan, Zhang et al. 2019). This is similar to the chlorinated dioxins that have been observed as impurities in PCBs and other chlorinated chemicals. PBDFs have also been found to be formed by sunlight exposure during normal use, as well as during the disposal/recycling processes of flame-retarded consumer products (Kajiwara, Noma et al. 2008). Some studies found PBDD/Fs in copper metal recycling (Mei, Guorui et al. 2015), in the air around a waste incinerator plant (Gao, Zhang et al. 2014), around an open burning site (Gullett, Wyrzykowska et al. 2010), and, recently, in children's toys (Budin, Petrlik et al. 2020). PBDD/Fs are similar to PCDD/Fs; however, they have been studied less extensively than their chlorinated analogues.

PBDD/Fs have been found to exhibit similar toxicity and health effects to their chlorinated analogues (PCDD/Fs) (Mason, Denomme et al. 1987, Behnisch, Hosoe et al. 2003, Birnbaum, Staskal et al. 2003, Kannan, Liao et al. 2012, Piskorska-Pliszczyńska and Maszewski 2014). They can, for example, affect brain development, damage the immune system and fetus, or induce carcinogenesis (Kannan, Liao et al. 2012). *"Both groups of compounds show similar effects, such as induction of aryl hydrocarbon hydroxylase (AHH)/EROD activity, and toxicity, such as induction of wasting syndrome, thymic atrophy, and liver toxicity"* (Behnisch, Hosoe et al. 2003).

15 The synonym "brominated dioxins" is used for this group of chemicals as well, while "dioxins" applies for PCDD/Fs. We use both these shorter synonyms in this report.

In general, brominated dioxins are less regulated than chlorinated dioxins. For example, PBDD/Fs are not currently listed under the Stockholm Convention (Stockholm Convention 2010), although there is clear evidence that they display very similar properties to PCDD/Fs, which have been listed in Annex C of the Convention since its origin in 2001. In 2010, the Stockholm Convention POPs Review Committee recommended further assessment of PBDD/Fs, including *"releases from smelters and other thermal recovery technologies, including secondary metal industries, cement kilns and feedstock recycling technologies"* (POP RC 2010).

8.2.4 Hexachlorobenzene (HCB), pentachlorobenzene (PeCB), hexachlorobutadiene (HCBD)

Pentachlorobenzene (PeCB) and hexachlorobenzene (HCB) are primarily produced unintentionally during combustion as well as during thermal and industrial processes. They also occur as a by-products during the production of chlorinated hydrocarbons such as perchloroethylene, trichloroethylene, carbon tetrachloride, or pesticides. In the past, they were produced intentionally as pesticides or technical substances. Perchloroethylene was and still is used in dry cleaning or for cleaning in machinery, and trichloroethylene and carbon tetrachloride have been used extensively as degreasing agents and as solvents for other chlorine-containing compounds. PeCB was used as a component in PCB products, in dyestuff carriers, as a fungicide, as a flame retardant, and as a chemical intermediate for the production of the pesticide quintozene (POP RC 2008).

In high doses, HCB is lethal to some animals and, at lower levels, adversely affects their reproductive success. Researchers also found that HCB, similarly to other organochlorinated compounds, has a transplacental transfer (Sala, Ribas-Fitó et al. 2001). HCB has been found in food of all types (BRS 2017).

Although globally the consumption of HCB-contaminated food is the primary source of HCB exposure, other potential exposure pathways include the inhalation of HCB-contaminated air, skin contact, in utero exposure, and breast milk (Reed, Büchner et al. 2007). The study also found that in addition to cancer, the human health effects associated with HCB exposure encompass systemic impairment (thyroid, liver, bone, skin) and damage to the kidneys and blood cells, as well as the immune and endocrine systems. It also causes a teratogenic effect and impairs the nervous system.

PeCB is very toxic to aquatic organisms and may cause long-term adverse effects in the aquatic environment (POP RC 2007).

Hexachlorobutadiene (HCBD) occurs as a by-product during the production of the same chlorinated hydrocarbons as PeCB and HCB, as a part of the so-called "hexa-residues". It is also formed unintentionally during the incineration processes of such substances as acetylene and chlorine residues. HCBD is very toxic to aquatic organisms and has been shown to cause kidney damage and cancer in animal studies as well as chromosomal aberrations in occupationally exposed humans (Pohl, McClure et al. 2001, POP RC 2012, Balmer, Hung et al. 2019). Systemic toxicity following exposure via oral, inhalation, and dermal routes may include fatty liver degeneration, epithelial necrotising nephritis, potentially causing chronic inflammation, central nervous system depression, and cyanosis (BRS 2017, Balmer, Hung et al. 2019).

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