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Research article

Occurrence, efficiency of treatment processes, source apportionment and human health risk assessment of pharmaceuticals and xenoestrogen compounds in tap water from some Ghanaian communities

Joseph K. Adjei *, Henrietta Acquah, David K. Essumang

Environmental Research Group, Department of Chemistry, University of Cape Coast, Ghana

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ABSTRACT

The occurrence of pharmaceuticals and xenoestrogen compounds (PXCs) in drinking water presents a dire human health risk challenge. The problem stems from the high anthropogenic pollution load on source water and the inefficiencies of the conventional water treatment plants in treating PXCs. This study assessed the PXCs levels and the consequential health risks of exposure to tap water from selected Ghanaian communities as well as that of raw water samples from the respective treatment plants. Thus the PXCs treatment efficiency of two drinking water treatment plants in the metropolises studied was also assessed. The study also conducted source apportionment of the PXCs in the tap water. Twenty six (26) tap and raw water samples from communities in the Cape Coast and Sekondi-Takoradi metropolises were extracted using SPE cartridges and analysed for PXCs using Ultra-fast-HPLC-UV instrument. Elevated levels of PXCs up to 24.79 and 22.02 μg/L were respectively recorded in raw and tap water samples from the metropolises. Consequently, elevated non-cancer health risk (HI > 1) to residential adults were found for tap water samples from Cape Coast metropolis and also for some samples from Sekondi-Takoradi metropolis. Again, elevated cumulative oral cancer risks $>10^{-5}$ and dermal cancer risk up to 4×10^{-5} were recorded. The source apportionment revealed three significant sources of PXCs in tap water samples studied. The results revealed the inefficiency of the treatment plants in removing PXCs from the raw water during treatments. The situation thus requires urgent attention to ameliorate it, safeguarding public health. It is recommended that the conventional water treatment process employed be augmented with advanced treatment technologies to improve their efficacy in PXCs treatment.

1. Introduction

The world's population boom over the last few decade coupled with increased industrialization and the extensive use of pharmaceuticals and related products have had a dire impact on the aquatic environment and, thus human health. Most pharmaceutical wastes from industrial, agricultural, hospital and domestic sources end up as pollutants in the aquatic environment [1]. Strikingly, pharmaceuticals are designed to have specific biological activities [2,3] and their unintended presence in aquatic environments even at

* Corresponding author.
E-mail address: joseph.adjei@ucc.edu.gh (J.K. Adjei).

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trace levels may impact the health of organisms upon exposure [4]. Unfortunately, most of the polluted waterbodies worldwide and for that matter in Ghana, serve as a source of drinking water, hence, the occurrence of pharmaceuticals in drinking water cannot be ruled out. Pharmaceuticals including steroids [5] and xenoestrogen compounds (PXCs) are classified as contaminants of emerging concern [6] and 21st-century global environmental concerns in recent years, due to their health effects on fauna and flora as well as the effect on human health [7]. Chemicals of this group are mostly endocrine-disrupting compounds (EDCs), and notably among these are bisphenol A (BPA), 4-*tert*-octylphenol (4-*t*-OP), 4-*para*-nonylphenol (4-NP) and chlorinated phenols, as well as estrone (E1), 17-α-ethinylestradiol (EE2), 17-β-estradiol (E2), 17-α-estradiol (αE2), estriol (E3), and some phthalates [1,8–10].

The 177 EDCs found by the World Health Organization (WHO) internationally, were reported to be nervous and endocrine disruptors [1,11–15]. Although multifactorial, EDCs are linked strongly to several chronic health disorders including metabolic and thyroid disorders, reproductive cancer and disorders, as well as low IQ and neurodevelopmental disease [16]. Among EDCs, the xenoestrogen compounds 4-NP, BPA and 4-*t*-OP are classified among the EU "priority hazardous" and "priority substances", respectively, in the aquatic environment [17]. The pharmaceuticals diclofenac, E2 and EE2 were listed as part of the EU substances of possible concern in the aquatic environment a decade ago [17].

Most pharmaceutical steroids are lipophilic and bioaccumulative, thus extended oral usage of pharmaceutical steroids like testosterone, EE2, E2 and related hormones have been linked with elevated risk of intrahepatic cholangiocarcinoma [18] endometrium liver, breast, lung and prostate cancers [18–22] as well as inhibit reproduction even in trace levels [23–25].

In humans, elevated levels of both synthetic (e.g. EE2) and natural estrogens caused feminization by reducing testicle size, reduced sperm quality and count, and also altering other sex characteristics [21,26–31] and issues with the central nervous systems resulting in mood disorders, depressions and poor decision-making of women in particular [32–34].

The ubiquitous xenoestrogens, 4-NP, 4-*t*-OP and BPA are quite persistent and accumulate in the aquatic environment [1,35] and exhibit elevated toxicity which manifest in, cancerous tumours, reproductive and developmental disorders as well as obesity [35–39]. Sheikh [40] concluded that 4-NP and 4-*t*-OP may disrupt the proper functioning of the thyroid hormone. Yang et al. [41] reported that 4-NP and 4-*t*-OP exposure may cause anxiety-related behaviours in rats, thus in humans, as well as cognitive functioning impairment in prenatally exposed infants [42].

Bisphenol A is also reported to induce multi-organ toxicity [43] and is implicated in genotoxic [43–45] and epigenetic mechanisms [43,46] as well as increased cardiovascular disease [47]. Primidone, an anticonvulsant drug [48] is classified by the International Agency for Research on Cancer (IARC) as a possible human carcinogen (Group 2B) [49] and has been found in groundwater, spring, and well waters [50]. Chloramphenicol is difficult to metabolize and may bio-accumulate, thus excessive ingestion is linked to bone marrow toxicity [51], anaemia, liver and kidney damage, and other serious health issues [52–54]. Prolonged diclofenac treatments have contraindications in reproductive health [55,56] mostly, resulting in reduced testicular weights and sperm functional parameters, accompanied by testicular histoarchitectures degenerations [56,57].

The main urinary and faecal metabolites of pharmaceutical estrogens are estrone (E1), E2, EE2, and estriol (E3) [58,59], indicating for faecal contaminants in surface water. All the aforementioned EDCs have been extensively researched and reported for their presence in the aquatic environment [1,60–63] and groundwater [64,65]. On the contrary, only a few literature exist for the presence of these pharmaceuticals and xenoestrogens in drinking water [66–69]. Unfortunately in most African Countries and for that matter Ghana, there is only a sparse study in the literature on the presence of these PXCs in drinking water.

Scientifically, it has been demonstrated that most conventional drinking water and waste water treatment plants are inefficient in treating PXCs [70,71] and usually the effluents of WWTP may end-up contaminating surface water which serve as source water for drinking water treatment plants. Thus, the occurrence of PXCs at significant levels in drinking water produced from conventional treatment plants [70,72]. Papagiannaki et al. [70] and Chen et al. [73] partly attributed the removal inefficiency to the high log K_{ow} (>3) of most PXCs and recommended the use of advanced treatment technologies to complement the conventional processes.

The United Nations general assembly in the year 2010 declared clean and safe drinking water and sanitation as a basic human right for life [74]. The WHO asserted that safety of drinking water is highly dependent on its source and holds both health and socioeconomic implications [74]. That is clean water sources imply less expenditure on health, as ailment incidents reduce, thereby reducing medical costs and thus improving economically productive of citizens.

Quite recently, because of the health risk involved, the European Commission's Drinking Water Directive (DWD) increased monitoring programs on the risk from exposure to these EDCs. Under this directive, three EDC were proposed as indicators of estrogenic contamination from sewage effluents as recommended by WHO: 17-beta-estradiol, bisphenol A and nonylphenol [75]. Following the recommendations in Article 13(8) of Directive (EU) 2020/2184, βE2 and 4-NP have been added to the watch list of substances and compounds of concern for water intended for human consumption [76]. Imperatively, the WHO recommended that three representative EDCs may be used as benchmarks for assessing the presence and levels of EDCs as well as their treatment efficiency as required, having maximum values of 0.1 μg/L for BPA, 0.3 μg/L for 4-NP and 1.0 ng/L for β-E2 in drinking water [75].

Unfortunately, there is no such directives or regulation in most African countries, especially Ghana for PXCs in drinking water. This may have contributed to the increased indiscriminate disposal of untreated domestic, agricultural and industrial waste into the aquatic environment, and hence in source water, resulting in their presence at elevated levels in drinking water. The occurrence of these PXCs in drinking water, especially in Ghana might have contributed to the upsurge in cancer and EDC-related health incidents in Ghana as reported by WHO and thus IARC [77]. Again despite the risk reported in literature and attempts by several international organizations to alleviate it, in sub-Saharan Africa, and for that matter Ghana, legal limits have not yet been established for EDCs in drinking water. This implies that routine monitoring program is non-existent contrary to that for the evaluation of regulated well-known physicochemical and microbial parameters. The Directive (EU) 2020/2184, also recommends a complete risk-based assessment approach in retrospect to the earlier Directive (EU) 2015/1787 for drinking water safety, possibly spanning the whole supply chain. This approach

comprises risks assessment and management of.

1. The catchment areas for raw water extracted for water purposed for human consumption in line with the WHO's guidelines and water safety plan's protocols,
2. The supply system
3. The domestic distribution systems with particular attention on primacy premises (Directive (EU) 2020/2184) [75].

It is therefore imperative to conduct a study that would help in this regard to ascertain the wholesomeness and improve the quality of drinking water in Ghana and for that matter, sub-Saharan Africa to protect human health. This study thus aims to assess the levels and the associated human health risks of the understudied PXCs in drinking water from selected Ghanaian communities as well as raw water samples from the respective treatment plants (catchment area for abstraction). This would contribute to achieving the United Nations (UN) sustainable development Goal 3 (SDG 3) section 3.9, which aims at achieving good health and well-being for all by substantially reducing the number of deaths and illnesses from hazardous chemicals and water contamination by 2030 [78]. The Efficiencies of two public drinking water treatment plants in two Ghanaian metropolises understudied were also assessed per the levels of PXCs, especially using the three WHO-recommended benchmark EDCs in raw water and treated residential tap water samples. These would also help to achieve the UN-SDG 6, aimed partly at improving water quality by minimizing the release of hazardous chemicals in untreated water and optimizing their treatment efficiency to help produce safe drinking water for all [78]. The study also conducted source apportionments to characterize the contaminants to help identify possible pollution sources to their occurrences in drinking water to help tackle the menace effectively. These may also instigate the ratification of monitoring regimes to increase surveillance on the Ghanaian waterbodies to reduce the PXCs pollutant load in source water for easy and efficient treatment into safe drinking water.

This study, being the first of its kind in literature for Ghana, will inform policy and may cause stakeholders in the water treatment and drinking water production sectors, as well as the regulatory agencies, to come up with improved policies to safeguard human health. The study may also attract the attention of international corporations and others to help in capacity-building programs such as efficient water treatment and reuse technologies to help produce clean and safe drinking water in developing countries such as Ghana [78].

2. Materials and methods

2.1. Solvents and reagents

The methanol and acetonitrile (LC grades) used were from EMD Millipore Corporation, methanoic acid and ammonium methanoate (AR) (Merck Int.). A mix pharmaceuticals standards (200 μg/mL; Lot #: A0163575, Restek Ltd.). Chloramphenicol (lot #: L16101350, USBiol-Life Sci.). Agilent HF-bond elut-C-18 SPE cartridges (6 mL, 500 mg, Agilent Technologies, USA), and MilliQ deionised (DI) water (18 MΩ) were used.

2.2. Study area description and sample collection

According to the 2021 population and housing census, the Cape Coast Metropolis, the Central region's capital has a total urban human population of 189,925 and an area coverage of 124.0 km^2 [79]. The primary source of tap/drinking water is the Brimsu Water Treatment Plant (BWTP) in the of the Cape Coast north municipality of the metropolis. The BWTP is a conventional treatment plant that takes it source from the Kakum River, and treated water production volume is about 4.0 million gallons daily. Ten (10) communities from the Cape Coast north and south municipalities were chosen for the study. They comprise Mempeasem, Abura, Ola, Pedu village, CP bus stop, 4th Ridge, Brabedze, Royal Lane Abease and Amisano.

The Sekondi-Takoradi metropolis, the capital of the Western region is one of the major industrial hubs of Ghana. It has an estimated urban population of 245,382 and an area coverage of 65 km^2 [79]. The Daboase Water Treatment Plant (DWTP) at the Mpohor Wassa district-Western region, Ghana, is the major source of treated water for the Sekondi-Takokoradi. The DWTP is also a conventional treatment plant that takes its source from the Pra River and treated water produced and distributed daily is estimated to be 5.0 million gallons (22,720 m^3) to the Sekondi-Takoradi and some parts of the Western Region. Ten communities within the Sekondi-Takoradi metropolis, viz. Kwesimintsim, Efiakuma, Nkroful, Anaji, Kansaworado, Amanful, Tankrom, Ntankoful, Fijai, andAssakai were selected for this study. The average adult population (<80 years) for the two metropolises studied were both about 55 % of the total population.

Twenty (20) tap water samples comprising ten (10) samples from ten different communities within each of the two metropolises studied were taken. Six (6) raw water samples comprising three each from BWTP and DWTP dam sites were also taken. It is worth noting that tap water sampled had the two respective treatment plant studied herein as the sole drinking water supply sources. Samples were collected in duplicate into 1.5 L high-density plastic bottles prewashed with 0.1 % nitric acid. At the laboratory, the samples integrity were preserved at a pH of 5 with dilute $H_2SO_4(aq)$ and extracted within two weeks.

2.3. Solid phase extraction (SPE)

The extraction of the analytes from the water samples was done using the USEPA method 539 and 542 [80] with slight modification.

The HF-Bond-Elut C-18 SPE-Cartridges were initially conditioned using 10.0 mL Methanol and 6.0 mL 0.05 N $HCl(aq)$ solution (pH = 2.0). About 1.0 L the samples and reagent blanks (unspiked and spiked) were loaded on the SPE-cartridges at a rate of 10.0 mL per minutes, aided by an extraction manifold (USEPA Method 542). The SPE-cartridges were then washed with 6.0-mL 0.05 N HCl (aq) and allowed to dry for 5-min under vacuum. The dried cartridge was eluted three successive times into glass vials using 3.0 mL of methanol at a time. Concentration of the extracts to dryness were achieved using a gentle streams of pure $N_2(g)$ and reconstituted with 1.0 mL ACN prior to instrumental analysis. The extracts were then transferred into 2 mL sample vials using a 13-mm 0.22-μm syringe disk-filter prior to the instrumental analyses. Replicate (n = 2) sample extractions were done.

2.4. The HPLC-UV analysis of pharmaceuticals and xenoestrogens in water samples

2.4.1. Quality control

The instrumental method used was appropriate for the European Commission's Directive 2009/90/EC3 [76], especially regarding the limits of quantifications, which allowed for the quantitation of the recommended levels within the acceptable precisions without necessitating excessive costs [76].

The external standard calibration method was employed using six (6) levels, i.e. 0.10, 0.50, 1.0, 2.0, 5.0, 10.0 mg/L in acetonitrile. A standard levels of 2.5 and 10 mg/L were used for initial and continuous calibration verification standards respectively to verify the robustness of the instrumental method. Again, in this study, system suitability test runs were conducted before and after each batch in accordance to USP criteria. Recovery analyses were performed by spiking five water samples and a 1.0 L DI water (Laboratory fortified blank, LFB) with 1.0 mg/L native standards prior to extraction. The LFB was analysed in replicates (n = 7) to ensure ongoing precisions and recovery (OPR) of the method.

Analytical data were also collected within a 2.0 % window to ensure the correct identification of anlytes for data reliability.The quality control measures taken were similar to our earlier reported study [1] and that of Fisher & Lopez [81], which were done following the EPA methods 539 and 542 with slight modification and optimization to suit the samples studied.

2.4.2. Instrumental analysis

Replicate analysis (n = 3) of standards and extracts were done using the prominence ultrafast LC 20-AD with SPD-20A detector (Shimadzu) operated in dual UV wavelength mode (222 and 256 nm) for optimum results. The flow-cell of the UV detector was also set to a temperature of 15 °C. The Luna 3 μm C-18 column with dimensions, 150 mm × 4.6 mm (i.d.) from Phenomenex was used and column's temperature was fixed at a 40 °C in an oven. The HPLC's gradient elution method were achieved using the following solvent; A: 0.14 % phosphoric acid in MilliQ DI water (18.0 MΩ cm) water (pH = 3) and B: 100 % ACN. The injection volume for the samples and standard was 5.0 μL and the solvent flow rate was kept at 0.8 mL/min [1]. The details of the solvent elution are shown in Fig. 1.

2.4.3. Data collection and statistical analysis

The analytical data collation and statistical analysis after instrumental analysis where achieved at the 95 % confidence level (CL) via the use of Shimadzu Labsolution software. Statistical multivariate data analyses were performed using IBMS-SPSS vrs 22.0 and MS-Excel toolpak. The dermal permeability coefficients (Kp) of the chemicals used for the human health risk assessments were calculated aided by EPA's "toxicity estimation software tool-T.E.S.T" vrs 5.1.1 [82] which uses the QSAR model of the chemicals. Source apportionment using the APCS-MLR receptor model [1,9,83–85] was also performed with the IBMS SPSS vrs 22.0. An earlier study

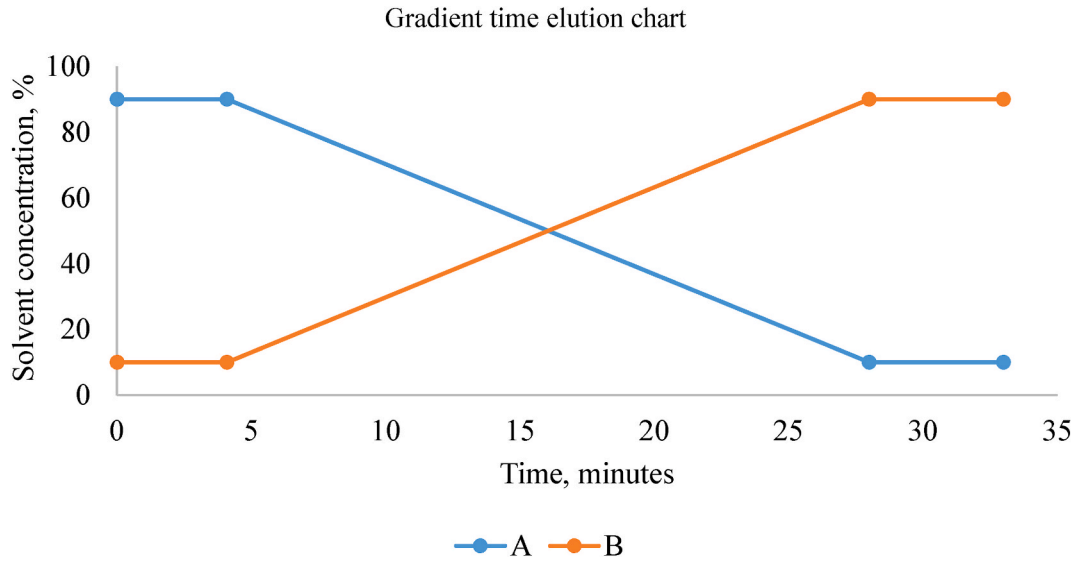

Fig. 1. A graph of the HPLC gradient time solvent elution method employed in the study.

reported by Adjei et al. [9] gives details to the mathematical description of the source apportionment using APCS-MLR receptor model. The dependent variables were the APCS values recorded.

2.5. Human health risk assessment

In 2013, EFSA's Scientific Committee noted that for EDCs biological thresholds of adverse effects are real, and preferred human health and environmental risk assessment as the best method to inform risk management decisions in guidelines that pivot judgements on the associated risk and levels of concern [86]. Thus, EDCs can be considered like most other contaminants of concern for human health and the environment, being subjected to the full rigours of risk assessment and not mere hazard analysis [75,86]. Therefore the risk assessment approach used in the current study is in accordance with the recommendations of Directive (EU) 2020/2184 made in retrospect to the earlier Directive (EU) 2015/1787 for drinking water safety.

Hence, for the current study, the following recommended equations and parameters were employed in the risk assessment for both ingestion and dermal contact routes.

For ingestion of the tap water;

$$Dose_{ingestion-H_2O}\left(\frac{mg}{kg-d}\right)=\frac{C_{H_2O}\times IR_{H_2O}\times EF\times ED\times CF}{BW\times AT} \tag{1}$$

And for dermal contact with the tap water

$$Dose_{dermal-H_2O}\left(\frac{mg}{kg-d}\right)=\frac{C_{H_2O}\times SA\times Kp\times ET_{rw}\times EF\times ED\times CF}{BW\times AT} \tag{2}$$

Where for non-cancer risk estimation, $Dose_{ingestion\ or\ dermal-H_2O}$ = Average Daily Dose (ADD) for non-carcinogens whereas for cancer risk estimation, $Dose_{ingestion\ or\ dermal\ -H_2O}$ = Lifetime Average Daily Dose (LADD) for carcinogens from the tap water ingestion or dermal contact respectively for a lifetime of 70 years. C_{H_2O} is the concentration of the contaminants (mg/L), IR_{H_2O} is the resident drinking water ingestion rate (Litres/hour), ET_{rw} is the resident water exposure time (minutes/day); EF is the exposure frequency (days/year); ED is the exposure duration (year); BW is the average bodyweight (kg); AT is the average lifetime (days); SA is the mean total adult resident (<80 years) skin surface area available for contact with water (cm^2); Kp is the chemical-specific dermal permeability coefficient (cm/hour); CF is the conversion factor.

For the non-cancer risk,

$$Hazard\ Quotients\ (HQ)=\frac{ADD\left(\frac{mg}{kg-d}\right)}{non-cancer\ ADI\left(\frac{mg}{kg-d}\right)} \tag{3}$$

The HQs for the individual compounds in a mixture were then summed for all exposure pathways assumed to be complete under the scenario to derive a hazard index (HI) for that sample. Here ADI is the acceptable daily intake of contaminants in the drinking water (mg/kg-bodyweight/day).

For the cancer risk,

$$Excess\ Cancer\ Risk=LADD\left(\frac{mg}{kg-d}\right)\times SF\left(\frac{mg}{kg-d}\right)^{-1} \tag{4}$$

Where SF is the Oral slope factor ([mg/kg -bodyweight/day]$^{-1}$). The incremental cancer risk is calculated by summing all the excess carcinogenic exposure pathways.

By employing T.E.S.T. QSAR operated by the consensus method, the Kp for the individual compounds were computed using equation (5) [87].

$$\log Kp=0.93\log K_{ow}+0.013MW-2.11 \tag{5}$$

Where K_{ow} is the predicted octanol/water solubility value and MW is the molecular weight of the individual chemicals.

The average weight of a Ghanaian adult (male and female) is about 60 kg and the average drinking water ingestion rate is about 2.00 L/day which conformed with the WHO recommended default values [88]. Thus these values were used with other default parameters from USEPA [89] (Supplementary Table S2). The HQ of compounds that recorded concentration values below the limits of quantitative (<LOQ), were calculated using half of the respective LOQ values in this study (Table 3).

The cancer risks were computed using only the four classified carcinogens, i.e. EE2, E2, primidone and 4-NP. Among the four, the oral slope factor has been established for only E2, hence the incremental risk was computed relative to the slope factor of E2. This was done because these PXCs exhibit synergistic action where the promoter and initiator effects play [8,90].

3. Results and discussion

3.1. Quality control results

The system suitability test was done using USP performance criteria, and recorded pass results for all parameters. The calibration levels of the analytes standards had linear responses with $R^2 > 0.995$ and response factors between 3.70 and 14.0 %. The quantitative limits (LOQ) computed at 95 % confidence levels (CL) ranged between, 0.005–0.086 μg/L (Table 3). Spiked recoveries ranged between 75.0 and 117 % for PXC analytes in the water samples. The QC results achieved in accordance with methods 539, 542 and 559 criteria were technically similar as that reported by Adjei et al. [1] in earlier study and depicted robustness with good estimates of precision and accuracy for analytes in the drinking water. For instance, Fig. 2 shows a well-resolved chromatogram of the PXCs and an imbedded (α), calibration levels of BPA. The QC results were comparable to results reported by Patrolecco et al. [91], Shishov et al. [92] and Cais et al. [93] in similar work. But LOQs were significantly improved (lower) than that reported for Thermo Fisher Scientific by Fisher & Lopez [81].

3.2. Levels of PXCs in raw and tap water samples and efficiency of water treatment plants

3.2.1. Levels of PXCs in the raw and tap water from cape coast metropolis and BWTP efficiency

The mean total levels of the PXCs in raw water samples from the BWTP Dam ranged from 5.60 to 24.8 μg/L (Table 1). The mean levels of the individual PXCs in the raw water samples ranged from <LOQ - 21.0 μg/L (Table 1). Bisphenol "A" was detected (0.42 μg/L) in raw water samples from sites 1 and 3 of the BWTP Dam (Table 1).

The mean total levels of PXCs in tap water samples were in the range of 4.49–22.0 μg/L for Brafoyaw – Pedu village respectively. The mean levels of the individual compounds detected in the tap water ranged from <LOQ – 14.6 μg/L. On average, among the individual PXCs, estrone was detected at elevated levels in all the samples, followed by 4-*para*-Nonylphenol when compared to the other PXCs analysed.

The recorded elevated levels of most PXCs in the raw water samples from BWTP (Table 1) suggested that the source water for the raw sample is polluted with PXCs, confirming the earlier work reported by Adjei et al. [1] on the Kakum River that serves as the source. Adjei et al. [1] recorded a mean total level of 34.8 μg/L PXCs in Kakum River, which was comparable to the slightly lower mean total level of PXCs recorded in the current study. Furthermore, the elevated levels of pharmaceutical steroids such as βE2, estrone, testosterone, and progesterone, may be attributed to the introduction of human urinary and faecal contaminants from domestic sources [58,59,68]. It is worth noting that the Kakum River serving as the source for the BWTP passes through many communities with refuse dump sites just situated en route its paths, thus the elevated levels of PXCs recorded. The mean level of estrone in Site 3 of the BWTP Dam was higher than all the levels obtained for the tap water samples from the Cape Coast Metropolis. This suggests that the raw water may have contributed significantly to the levels obtained in the tap water samples. Again, the elevated levels of estrones recorded in all the tap water samples is an indication of the inefficiency of the water treatment plants in removing the compounds. Similar trends were

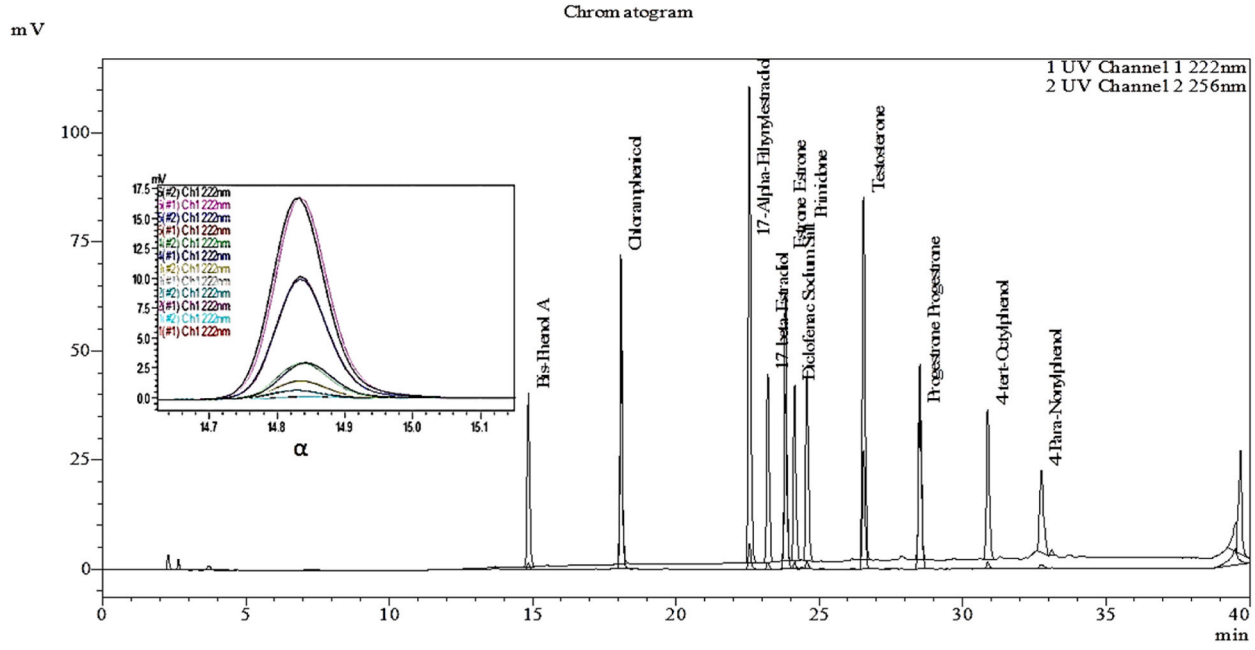

Fig. 2. A chromatogram showing a well resolved peaks for the PXCs analytes at dual wavelengths (222 and 256 nm) and (α) a calibration levels of BPA at 222 nm.

Table 1
Mean Levels (n = 3) of pharmaceutical and Xenoestrogen Compounds (PXCs, μg/L) in raw water from BWTP and tap water samples from Cape Coast Metropolis.

Compound	Raw water samples from Dam				Tap water samples								
	Site 1	Site 2	Site 3	Abura	Amisano	Brabedze	Brafoyaw	CP Bus Stop	Mempeasem	Ola	Pedu Village	4th Ridge	Royal Lane Abease
Bisphenol A	0.42	<LOQ	<LOQ	0.22	1.74	0.17	0.20	0.48	0.24	0.22	0.24	0.24	0.21
Chloramphenicol	0.22	0.50	0.35	0.13	<LOQ	<LOQ	<LOQ	0.03	<LOQ	0.10	0.20	0.08	0.07
17-Alpha-Ethynylestradiol	0.19	0.10	<LOQ	<LOQ	1.33	<LOQ	0.32	0.23	0.14	0.09	0.09	0.15	0.13
17-Beta-Estradiol	0.22	0.20	0.36	<LOQ	0.07	0.03	<LOQ	0.02	0.02	<LOQ	<LOQ	<LOQ	<LOQ
Estrone	3.04	0.45	21.01	7.89	8.76	0.31	1.28	2.02	11.09	7.99	12.32	1.48	0.27
Diclofenac	3.39	1.34	0.20	<LOQ	<LOQ	14.63	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.16	<LOQ
Primidone	0.32	0.22	0.19	<LOQ	0.32	0.12	0.07	0.13	0.09	0.10	0.10	0.28	0.09
Testosterone	1.03	0.26	0.20	0.25	0.33	0.19	0.19	0.33	0.29	0.26	0.21	0.25	0.15
Progesterone	0.86	<LOQ	1.61	<LOQ	1.11	<LOQ	0.06	0.12	0.36	0.34	0.54	0.42	0.02
4-*tert*-Octylphenol	0.58	0.30	0.41	0.23	2.32	0.11	1.12	0.59	0.79	0.25	1.19	1.84	0.74
4-*Para*-Nonylphenol	1.24	2.22	0.47	5.87	2.93	2.25	1.25	0.71	3.16	5.89	7.13	1.40	4.26
Mean total	11.51	5.60	24.79	14.59	18.90	17.81	4.49	4.66	16.18	15.24	22.02	6.29	5.94

Table 2
Mean Levels (n = 3) PXCs (μg/L) in raw water from DWTP and tap water samples from the Sekondi-Takoradi Metropolis.

Compounds	Raw water samples from Dam			Tap water samples									
	Site 1	Site 2	Site 3	Amanful	Anaji	Assakai	Effiakuma	Fijai	Kansaworado	Kwesimintsim	Nkroful	Ntankoful	Tanokrom
Bisphenol A	1.21	0.28	0.36	<LOQ	0.17	<LOQ	0.52	<LOQ	1.17	<LOQ	<LOQ	<LOQ	<LOQ
Chloramphenicol	0.24	0.12	0.12	0.04	0.04	0.08	0.21	0.01	0.05	0.02	0.01	0.09	0.03
17-Alpha-Ethynylestradiol	0.13	0.16	0.10	0.14	0.10	0.15	0.12	0.13	0.13	0.13	0.27	0.11	0.16
17-Beta-Estradiol	0.16	0.16	0.03	<LOQ	0.02	<LOQ	<LOQ	0.09	0.05	<LOQ	0.05	0.08	0.04
Estrone	3.21	3.64	2.92	1.36	0.32	0.27	0.25	1.14	0.93	<LOQ	0.29	0.12	0.28
Diclofenac Sodium Salt	0.07	0.23	0.22	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Primidone	0.18	0.26	0.43	0.19	0.09	0.07	0.03	0.15	0.29	<LOQ	0.07	0.12	<LOQ
Testosterone	0.33	0.32	0.73	0.14	0.15	0.52	0.19	0.14	0.19	0.14	0.12	0.29	0.16
Progesterone	0.45	0.66	0.61	0.15	0.10	0.07	0.03	0.04	0.02	1.15	0.17	2.94	0.93
4-*tert*-Octylphenol	0.43	0.16	0.11	0.59	0.56	0.15	0.15	0.52	0.23	0.23	0.20	0.14	0.89
4-*Para*-Nonylphenol	0.31	0.72	0.39	0.53	0.40	0.40	0.39	0.28	0.59	0.47	0.44	0.30	0.43
Mean total	6.72	6.70	6.02	3.16	1.94	1.71	1.89	2.50	3.62	2.14	1.62	4.21	2.92

observed for almost all the other compounds in all the tap water samples analysed. However, the treatment systems were comparatively quite efficient in removing pharmaceuticals like diclofenac, chloramphenicol, and to some extent primidone, than the steroidal pharmaceutical and the xenoestrogens. This happening may be attributed to the low $\log K_{ow}(< 3.0)$ of these three pharmaceuticals which makes their removal easier than the other PXC with high $\log K_{ow}(> 3.0)$ [70,73,94,95]. The frequent occurrences of the ubiquitous estrone in all the raw and tap water at elevated levels are consistent with the results reported by Alvarez et al. [96] where estrone was the most frequently detected compound in water samples. Similar trends were also reported by Papagiannaki et al. [70] for estrone among the steroidal hormones in untreated water samples.

Except for βE2 where at least 40.0 % of tap water samples exceeded the WHO maximum recommended level of 1.00 ng/L (Table 1), the other two benchmarks for EDCs in drinking water and treatment efficiency, BPA and 4-NP in all the tap water samples recorded values greater than the respective WHO recommended maximum levels of 0.10 μg/L and 0.30 μg/L [75]. These levels suggested inefficient EDCs treatment by BWTP, and consequential health risks associated with the consumption of such unwholesome drinking water. Also, the elevated levels of BPA in the tap water samples on average, may be attributed to leachates from the BPA epoxy lining of the drinking water pipe and storage systems [97,98]. However, the elevated levels of the xenoestrogens 4-NP, and 4-*t*-OP in some of the tap water samples may in addition to the inefficiencies of the treatment system, be attributed to the excessive application of demulsifiers during flocculation in conventional water treatment [99] as well leachate from PVC pipelines. For instance, Cheng et al. [100] reported higher levels of 4-NP and BPA in tap water from PVC pipes than from galvanized and stainless steel pipes. The authors asserted that the levels increased with contact time and temperature. de Aquino et al. 101] reported levels of 64.8 μg/L, 6.81 μg/L, and 4.39 μg/L for BPA, βE2, and EE2 respectively in Brazilian raw water, which were significantly higher than what were recorded in raw water for the current study. Again in Brazilian drinking water, de Aquino et al. [101] reported levels of 2.50 μg/L, 0.620 μg/L and 2.82 μg/L for BPA, EE2 and 4-NP respectively, that were higher than the levels recorded in the current study. These suggested that raw water samples studied in Brazil were relatively highly contaminated by these PXCs than that from Ghana in the current study, which retrospectively reflects the difference in levels reported in drinking water samples from the two studies.

3.2.2. Levels of PXCs in raw and tap water from the Sekondi-Takoradi municipality and DWTP efficiency

From Table 2, the mean total levels of the PXCs in raw water samples from the DWTP Dam ranged from 6.02 to 6.72 μg/L. The mean levels of the individual PXCs in the raw water samples from DWTP also ranged between 0.030 and 3.64 μg/L (Table 2). The mean BPA levels in the raw water ranged from 0.280 to 1.21 μg/L. The steroidal pharmaceutical, estrone, recorded the highest levels ranging between 2.92 and 3.64 μg/L (Table 2). Comparable trends were reported by Papagiannaki et al. [70] and Alvarez et al. [96] for estrone in most untreated water samples studied. Anthropogenic activity is known to be a major source of pharmaceuticals in the aquatic environments [102]. Pra River, the source of DWTP, is known to be highly polluted by anthropogenic activities [103,104] but comparing the levels and their consistency in the raw water from DWTP to that of BWTP, it seems the management of DWTP has taken conscious effect to reduce the PXCs burden in the raw water before treatment to improve the quality of drinking water distributed to consumers.

The mean total levels of PXCs in the tap water samples from the Sekondi-Takoradi municipality ranged from 1.62 to 4.21 μg/L (Table 2). The mean levels of the individual PXCs in tap water samples also ranged from < LOQ - 2.94 μg/L (Table 2). The pharmaceuticals generally had a significant reduction in the levels recorded for the tap water as compared to that found for raw water. However, the levels of the xenoestrogens 4-NP, and 4-*t*-OP, generally had an increase compared to that recorded in the raw water. BPA levels in the tap water samples ranged from < LOQ – 1.17 μg/L (Table 2). Moreover, among the three WHO benchmark EDC for the presence EDCs in source water and their treatment efficiency by treatment plants, βE2 recorded in 60.0 % of tap water samples significantly exceeded the maximum recommended value of 1.00 ng/L, 30.0 % of tap water samples exceeded the recommended BPA value of 0.100 μg/L and 4-NP in all the tap water samples (100 %) significantly exceeded the recommended value of 0.300 μg/L (Table 2). The results suggested that even though the DWTP management might be doing its best to reduce the PXCs burden in the drinking water distributed, it is yet to achieve the WHO's recommended safe levels for drinking water in this regard, thus the DWTP is inefficient in EDC treatment. The difficulty faced in achieving the WHO recommended limits could be attributed to the inefficiencies of the conventional drinking water treatment plants in PXC removal as reported in earlier studies [70,110]. The elevated levels of BPA in

Table 3
Methods limits of quantifications (LOQ), calculated dermal permeability coefficient, Kp (cm/hour) and acceptable daily, ADI (mg/kg/day) used for the study.

Compound	LOQ, ng/L	T.E.S.T consensus Predicted Kp, Cm/hour	ADI, mg/kg/day (reference)	slope factor,/mg/kg/day
BPA	9	1.4E-02	2.0E-07 [105]	
Chloramphenicol	6	1.0E+00	5.0E-03 [106]	
17-Alpha-Ethynylestradiol	19	1.5E-03	5.0E-06 [106,107]	
17-Beta-Estradiol	19	2.5E-03	5.0E-05 [106–108]	39 [107]
Estrone	19	2.1E-03	5.0E-05 [107,108];	
Diclofenac	86	2.1E-03	1.6E-03 [109]	
Primidone	10	3.7E-02	7.0E-04 [109]	
Testosterone	22	1.1E-02	2.0E-03 [108]	
Progesterone	65	5.0E-03	3.0E-02 [108]	
4-*tert*-Octylphenol	5	9.2E-04	1.5E-02 [107]	
4-*Para*-Nonylphenol	18	7.6E-05	5.0E-02 [107]	

some tap water samples and 4-NP in all tap water samples may also be partly attributed to leachates from the lining of PVC pipes under favourable conditions [97,100].

The results in this study are comparable to that reported in a similar study by Colin et al. [111] where BPA levels in raw water sample and tap water were up to 1.43 μg/L and 0.050 μg/L respectively although slightly higher levels were recorded in the current study. Santhi et al. [98] recorded BPA levels up to 0.220 μg/L and 0.060 μg/L in source water and drinking water respectively from Malaysia, which were also comparable to the results in this current study. Also, the level 4-NP, up to 0.590 μg/L recorded in this study was comparable to that up to 0.51 μg/L reported by Colin et al. [111]. The results reported for both the raw and tap water samples from Ghana in the current study are relatively lower than those reported by de Aquino et al. [101] in Brazilian water.

The elevated levels of βE2, BPA, 4-*t*-OP and especially 4-NP in the drinking water studied may have contributed to the surge in endocrine disruption problems in Ghana [112].

3.3. Human health risk assessment

3.3.1. Residential tap water ingestion non-cancer risk assessment

The hazard quotients (HQ) computed for compounds in the tap water samples from the Cape Coast metropolis ranged between $1.9 \times 10^{-5} - 2.8 \times 10^{2}$ (Supplementary Table S2). BPA recorded the highest elevated HQs in all the tap water samples, with values ranging between 2.7×10^{1} - 2.8×10^{2} (Supplementary Table S2). These elevated HQ values recorded far exceeded the recommended HQ value of 1.0, which is quite alarming. The compound estrone recorded the second highest HQ levels ranging between $1.7 \times 10^{-1} - 7.9$ in the tap water samples. Elevated HQ > 1 for estrone was recorded in about 60 % of the tap water samples from the Cape Coast metropolis whereas about 20 % recorded moderate risk levels (Supplementary Table S2). The rest of the compounds recorded HQ < 1 for all the samples. Thus, the non-cancer cumulative risk or Hazard index (HI) computed for a resident adult upon ingestion of tap water from the Cape Coast metropolis ranged between 2.8×10^{1}–2.8×10^{2}(Supplementary Table S2). The significantly elevated HI $\gg 1.0$ recorded for ingestion of tap water samples from all the communities studied in the Cape Coast metropolis suggested that they were unwholesome for human consumption and may have dire health implications for consumers. These risk levels may contribute to an upsurge in reproductive and development disorders as well as elevated risk of liver, kidney and cardiovascular problems in humans. This may also result in frank toxic effects on consumers. The situation as uncovered in this study requires immediate action to possibly eliminate the menace to safeguard the health of the people in such communities. Stakeholders, especially the BWTP management are thus implored to reconsider the quality of water they produced as drinking water to the masses and do the needful to ameliorate the current situation. These elevated risks may have contributed to the upsurge of non-cancer ED-related ailments among Ghanaian adults and the world.

In tap water samples from the Sekondi-Takoradi metropolis, the hazard quotients (HQ) computed for the compounds in the tap water samples ranged between $1.7 \times 10^{-5} - 1.9 \times 10^{2}$ (Supplementary Table S3). Here, BPA recorded the highest HQ values for all the tap water samples, with values ranging between 7.2×10^{-1} - 1.9×10^{2} (Table). BPA in 30 % of tap water samples recorded elevated HQ levels >1 (Supplementary Table S3). The estrone in the tap water samples recorded the next highest HQ levels with only 30 % showing a moderate risk level (Supplementary Table S3). On the other hand, the remaining compounds recorded low risk levels in all the tap water samples. These cumulated to HI levels ranging between $7.5 \times 10^{-1} - 1.9 \times 10^{2}$ at Kwesimintsim and Kansaworedo

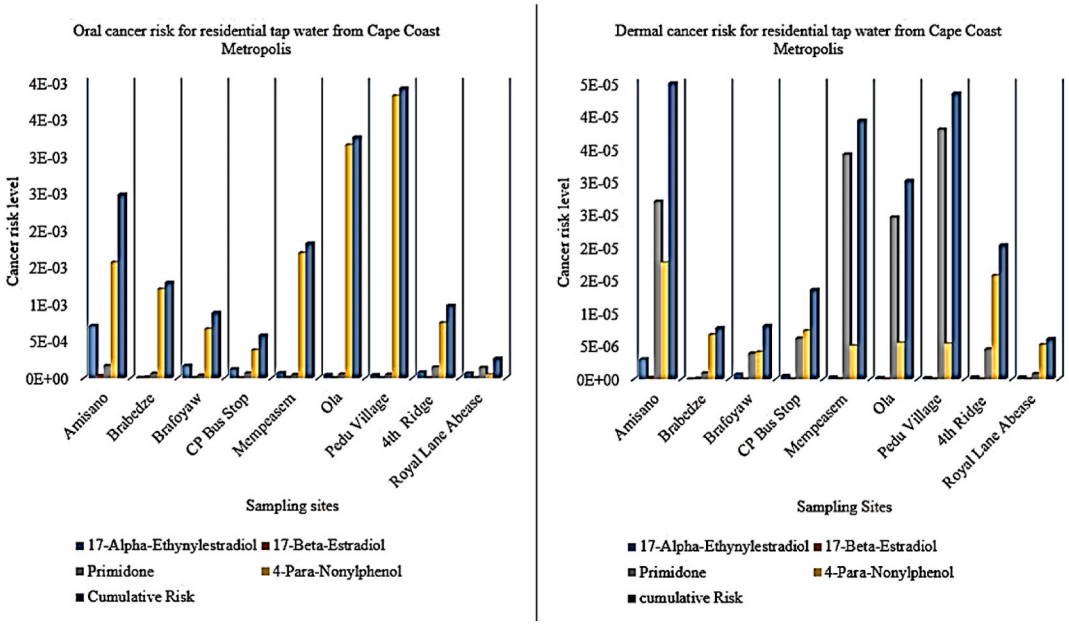

Fig. 3. Cancer risk assessment results for residential adults upon exposure to PXCs in tap water samples from Cape Coast metropolis.

respectively (Supplementary Table S3). Among the samples, tap water from Anaji, Effiakuma and Kansaworedo in an increasing order recorded significantly elevated HI ≫ 1.0 (Supplementary Table S3) whereas samples from Fijai and Amanful recorded quite elevated HI > 1. This elevated risk may have contributed to the upsurge of non-cancer health issues such as those pertaining to endocrine disruption in humans. The other 50 % of tap water samples recorded moderate risk levels with HI levels <1 (Supplementary Table S3). The risk results indicated that the tap water samples from Anaji, Effiakuma and Kansaworedo are unwholesome and may pose significant health risks to adult resident consumers. Similar trends were assumed by tap water from Fijai and Amanful though HI levels were relatively lower than the former. It is worth noting that BPA was the major contributor to the elevated risk recorded in all the samples. The risk analysis showed that though extremely elevated risks were found associated with some water samples, generally quite a large number of the samples have reduced risk indicating that the management of the DWTP may be doing their bit to supply safe drinking water to their consumers. It is thus recommended that the water supply to communities with elevated risk be monitored to ascertain and possibly eliminate the root cause of the contaminations. Stakeholders for the Sekondi-Takoradi drinking water supply are also encouraged to continue with the improvement of the water quality to help safeguard the health of consumers.

3.3.2. Residential tap water oral cancer risk assessment

The incremental cancer risk associated with the ingestion of the carcinogenic PXCs in the tap water samples from Cape Coast Metropolis by a residential adult for a 70-year average lifetime computed ranged between $3.0 \times 10^{-4} - 4.0 \times 10^{-3}$ (Fig. 3). Here all the tap water samples recorded elevated risk $>10^{-5}$ (Fig. 3), which implied ingestion of the tap water samples is associated with high cancer risk for an adult resident. The values indicated that 3 persons out of 10, 000 resident adults and also 4 persons out of 1000 resident adults respectively are likely to suffer from cancer and related issues such as brain and central nervous system tumours, breast cancer, lymphoma, cancers of the lung, liver, pancreas and prostate [16,18,21,39] in their lifetime.

For Sekondi-Takoradi metropolis tap water samples, the incremental cancer risk computed for the residential adult upon oral ingestions ranged between $8.0 \times 10^{-5} - 9.0 \times 10^{-4}$ (Fig. 4). Again, all the tap water samples from all the communities recorded elevated cancer risk levels $>10^{-5}$ (Fig. 4) though relatively low risk levels than that from Cape Coast metropolis. The levels showed that at least 8 persons out of 100,000 and at most 9 persons out of 10,000 adults respectively are likely to suffer from cancer and cancer-related issues in their lifetime.

These elevated cancer risks recorded may have contributed to the upsurge in cancer and related incidents in Ghana and the world [77]. It is thus imperative for stakeholders to take the necessary actions on this to safeguard public thereby helping to achieve section 3.9 of the UN-SDG 3 [78].

3.3.3. Residential tap water non-cancer dermal health risk assessment

From the results (Supplementary Table S2) the risk (HQ) associated with dermal exposure to the cape coast metropolis' tap water samples through shower and washing of body parts ranged between $9.7 \times 10^{-8} - 11.0$ for the compounds (Supplementary Table S2).

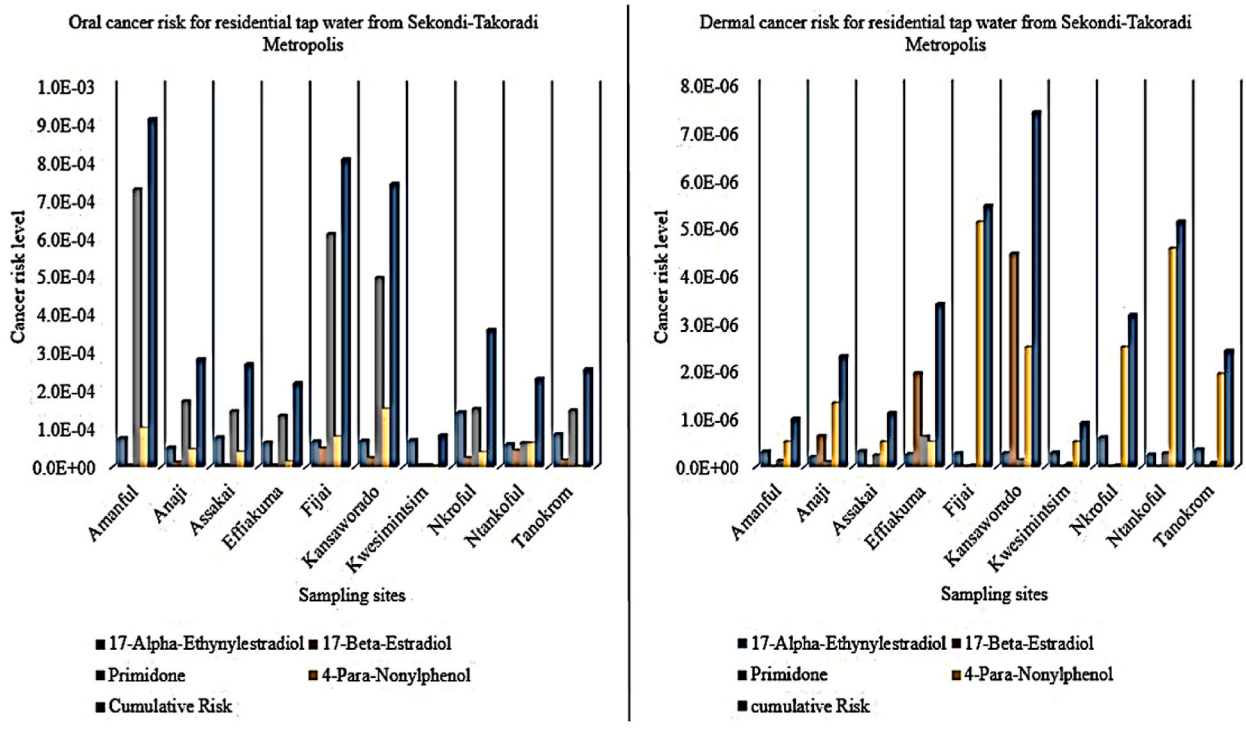

Fig. 4. Cancer risk assessment results for residential adults upon lifetime exposure to PXCs in tap water samples from Sekondi-Takoradi metropolis.

All the tap water samples analysed at the metropolis had HQ > 1. Tap water samples from Amisano recorded the highest HQ of 11.0 which indicated that the water is indeed extremely polluted and not good for showering and washing of body. The BPA was the compound with the highest HQ (>1) in all the samples. These elevated risks (HQ > 1) recorded for all the tap water samples from the Cape Coast metropolis suggested that the tap water is not appropriate for residential showering and washing of the human body. This may pose dire dermal health risks to the users. The HI associated with dermal contacts to the water samples for a residential adult thus ranged between 1.10 and 11.0 (Supplementary Table S2), implicating the tap water samples (100 %) with endocrine-disrupting related skin issues such as skin pigmentation disorders, inflammatory and allergic diseases, chloracne etc., upon exposure [113,114]. It is thus recommended once again that the management of Ghana Water Company Limited (GWCL) responsible for BWTP, help in ameliorating the issues to safeguard human health in such communities.

The compounds in tap water samples from the Sekondi-Takoradi metropolis recorded HQ levels ranging between $3.8 \times 10^{-8} - 7.6$ (Supplementary Table S3). The compound BPA recorded the highest HQ in all the samples analysed with values ranging between $2.9 \times 10^{-2} - 7.6$ (Supplementary Table S3). Samples from Anaji, Effiakuma and Kansaworado recorded associated elevated risk levels (HQ > 1) to resident adults upon dermal exposure. The elevated risk suggested such samples may pose significant skin health-related issues to users. The cumulative risk (HI) upon exposure to all the compounds in the tap water samples for an adult resident ranged between $3.0 \times 10^{-2} - 7.6$ (Supplementary Table S3). Only 30.0 % of the samples analysed had elevated HI > 1 which may significantly impact the health of users upon exposure through showering or washing of other body parts. The remaining 70 % had HI ≪1 suggesting very low dermal health risk associated with exposure to tap water from the Sekondi-Takoradi metropolis.

3.3.4. Residential tap water dermal cancer risk assessment

The dermal cancer risk calculated for lifetime average daily dose (LADD) of the carcinogenic PXCs in the tap water samples by an adult resident from the Cape Coast metropolis ranged between 6.0×10^{-6}- 5.0×10^{-5}(Fig. 3). Except for the tap water samples from Royal lane Abease and Brafoyaw, all the tap water samples from the Cape Coast Metropolis recorded elevated cancer risk ($>10^{-5}$) upon exposure (Fig. 3). These elevated risk suggested that more than 1 person in 100,000 adults are likely to suffer from skin related cancer in their lifetime.

All the tap water samples from the Sekondi-Takoradi metropolis recorded cancer risks just $\geq 10^{-6}$ (Fig. 4), which suggested low dermal cancer risk upon exposure to the classified carcinogenic PXCs in the samples by a residential adult for an average lifetime of 70 years.

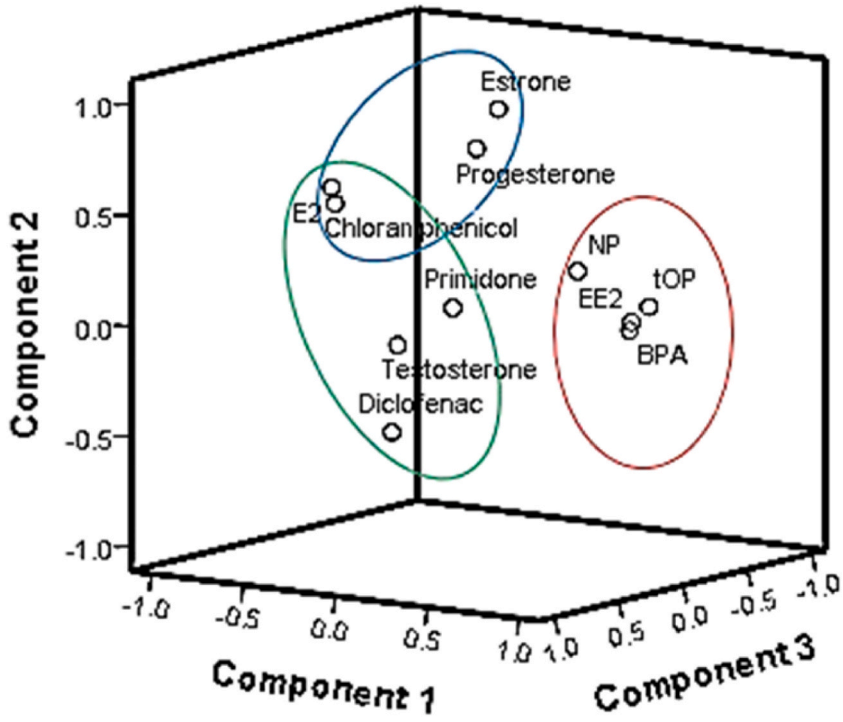

Fig. 5. APCS-MLR source apportionment results for PXCs in tap water from the Cape Coast Metropolis.
Note: Red concentric ring represents synthetic resins/plasticizers leachates source; blue concentric represents, domestic/human urinary and faecal waste sources; and green concentric ring represents pharmaceutical wastes sources. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Source apportionment

The factor analysis' PCA performed with the Varimax rotation and Kaiser Normalization prior to the APCS-MLR predicted 3 components ($p < 0.01$) for samples from Cape Coast Metropolis, designated by signature PXCs as synthetic resins/plastic leachates (FAC1), Domestic/human faecal (FAC2) and pharmaceutical wastes sources (FAC3) (Fig. 5). The three sources loadings contributed about 75.1 % to the total variance in the model after rotation, where the individual statistical significant ($p < 0.01$) contributions were 31.6 %, 26.9 %, and 16.5 % respectively for synthetic resins/plasticizers leachates (FAC1), domestic/human urinary and faecal wastes (FAC2) and pharmaceutical wastes sources (FAC3). The model summaries for the APCS-MLR (95 % CL) recorded an R-square value of 1. The model (best subset) suggested that the most important predictors of the synthetic resins/plasticizers leachates source are 4-*t*-OP ($r = 0.89$), BPA ($r = 0.93$), and EE2 ($r = 0.93$). On the other hand, the most important predictors for the domestic/human urinary and faecal waste sources were progesterone ($r = 0.83$), estrone ($r = 0.91$), E2 ($r = 0.64$) and chloramphenicol ($r = 0.50$), which resonate with literature [58,59,68]. Also, the pharmaceutical waste sources recorded primidone ($r = 0.8$), testosterone ($r = 0.73$), E2 ($r = 0.65$), progesterone, chloramphenicol and diclofenac as the best-subset important predictors.

For the Sekondi-Takoradi metropolis, the APCS-MLR predicted 3-statistically significant sources ($p < 0.01$) designated according to signature compounds as domestic pharmaceutical wastes (FAC1, 26.3 %), agricultural livestock waste sources (FAC2, 24 %), and municipal refuse damp sites (FAC3, 15.4 %). The important predictors from the best-subset model for domestic pharmaceutical wastes were Diclofenac ($r = 0.86$), testosterone ($r = 0.82$), and primidone ($r = 0.72$). That for agriculture livestock sources were BPA (0.86), chloramphenicol ($r = 0.72$), estrone ($r = 0.71$) and E2 ($r = 0.66$), whereas that of municipal refuse damp sites were 4-NP ($r = 0.78$), and EE2 ($r = 0.63$). The results suggested pharmaceuticals and agricultural livestock waste sources as the major contributor to PXCs in water from the Sekondi-Takoradi metropolis, which resonates well with the findings of Richardson & Kimura [115].

With these source apportionments results, management of GWCL, and the drinking water treatment plants understudied as well as other relevant stakeholders may capitalize to reduce the PXCs burdens in the raw water and thus the tap water samples to the safest level. This may help reduce significantly the associated human health risk upon exposure to safeguard the health of users. It is also recommended that the government of Ghana ratifies the UN-SDGs recommended monitoring regimes to increase surveillance on the Ghanaian waterbodies to reduce the PXCs pollutant load in source water for easy and efficient treatment into safe drinking water.

4. Conclusion

The study recorded elevated levels of PXCs in raw water samples and consequential elevated levels in tap water samples from the two metropolises studied. The treatment efficacy assessment using the levels of PXCs, especially that of the three recommended WHO benchmark EDCs, suggested that intrinsically, the two conventional drinking water treatment plants were inefficient in treating EDCs. Hence, the recorded elevated non-cancer and cancer risk levels for residential adults, upon oral and dermal exposure to the PXCs in tap water. Generally, tap water samples from the Cape Coast metropolis had an associated high elevated cancer and non-cancer risk, especially upon oral exposure to consumers, thus rendering them unwholesome for human consumption per WHO [74]criteria.

The source apportionment suggested the major sources of PXCs in the tap water from the Cape Coast metropolis to be synthetic resins/plastic leachates, Domestic/human faecal and pharmaceutical waste sources. Sekondi-Takoradi metropolis suggested domestic pharmaceutical wastes, agricultural livestock wastes, and municipal refuse damp sites as the significant sources of the PXCs in the tap water samples. Stakeholders and other management boards should capitalize on the suggested sources to help reduce the PXCs contaminants to the safest level to reduce the associated health risks safeguarding consumers' health.

It is recommended that GWCL optimize the treatment efficiency for PXCs by employing advanced treatment technologies such as advanced oxidation, reverse osmosis and nano-filtration [70,116] to supplement the conventional treatment processes. International organizations such as the UN, through the Development Program (UNDP), Food and Agricultural Organization (FAO), and other stakeholders should extend international cooperation and capacity-building support (in the efficient water treatment of PXC) to GWCL and other drinking water treatment facilities in developing countries to help realize the SDG-6 and thus SDG-3.

Data availability statement

No data associated with this study has been deposited into a publicly available repository but all the data are included in this article/supp. material/referenced in article.

Ethics declarations

1. Review and/or approval by an ethics committee was not needed for this study because the research involved the use of environmental/drinking water samples and chemical contaminations with no known special hazards. No animal, live vertebrates/higher invertebrate subjects or samples from human was used.
2. Informed consent was not required for this study because the study is not related to human and behavioural studies

CRediT authorship contribution statement

Joseph K. Adjei: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Henrietta Acquah:** Writing – review & editing, Writing –

original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **David K. Essumang:** Validation, Supervision, Resources, Investigation, Data curation, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e31815.

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