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Review

Bisphenol A in Selected South African Water Sources: A Critical Review

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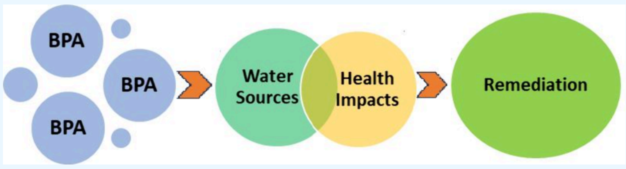

ABSTRACT: Bisphenol A (BPA) is a pollutant that has gained the attention of scientists globally because of its ubiquity in environmental matrices as well as its toxicity in the environment. It is listed as a priority pollutant in South Africa, capable of health risk impacts, which, according to the European Union, should not exceed 2.5 μg/L in water. In South Africa, historical data on its environmental occurrence is sparingly available, although research on BPA and other endocrine disruptors is currently gaining momentum. Surface, ground, and wastewater constitute the major proportion of the water sources that are prone to contamination by emerging pollutants such as BPA. In order to gain a holistic perspective of this chemical, a detailed review was carried out using over five hundred peer-reviewed articles that investigated the occurrence of BPA in South African aquatic systems. This study shows that Gauteng and Western Cape are the Provinces with the highest reported number of BPA occurrences in water. The data also shows that surface water constitutes 41% of all BPA articles while matrices like ponds and lagoons have no recorded studies. Its presence was attributed to anthropogenic activities such as the generation of domestic, agricultural, and industrial waste. Local application of removal techniques such as adsorption and photocatalysis on laboratory and field samples has shown good prospects (especially photocatalysis) in mitigating current challenges related to the occurrence of BPA. However, there is room for more innovative initiatives. Although there is a ban on the use of BPA for making baby bottles, additional regulations can be put in place regarding the use of BPA in making plastics or other packaging materials from which BPA can leach.

1. INTRODUCTION

Endocrine disrupting chemicals (EDCs) refer to a broad spectrum of organic compounds that have been implicated as a cause for concern when present in the environment, specifically in water because they are regarded as emerging pollutants. Studies on their occurrence, concentration, and mobility, especially in the South African aquatic system, are very scant.[1] This, therefore, underscores the need for painstaking investigations by relevant stakeholders such as government departments, municipalities, and nongovernmental organisations to put strategies in place to address the challenges posed by the occurrence of bisphenol a (BPA) and other EDCs in water.

EDCs are artificial or naturally occurring chemical agents that can mimic hormones and disrupt the normal functioning of the endocrine system.[2] EDCs are present in various environmental matrices such as groundwater, river water, surface water, and wastewater.[3−5] There are also growing indications that some of these contaminants can negatively impact both the environment and human health.[6] Besides the aforementioned water systems, they are also present in household chemicals, air, and food and can find their way into humans through inhalation, ingestion, and dermal absorption.[7] Some of these compounds can be toxic even at low levels (e.g., chlorophenols) and can persist in the environment for a long period of time.[8] Globally, the occurrence of these harmful and unwanted chemicals in water has been discussed extensively in scientific publications. However, the lack of sustainable solutions to water challenges, as well as the emergence of new and ambiguous pollutants make the subject relevant among water experts.

Like other countries, South Africa is faced with a steady rise in the number of toxicants in water resources which requires effective monitoring.[9] To synergize the scientific effort of individual research groups in the country, the Water Research Commission of South Africa (WRC) initiated the EDC research program which was geared toward competency building for EDC research.[10] Subsequently, researchers are rising to the challenge of unraveling the complexity of organic pollutants; one of which is bisphenol A (BPA), a highly ubiquitous chemical because of its use as an additive for polyvinyl chloride (PVC) found in plastics.[11] Plastics are one

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of the most common waste products in the environment, bringing to mind the enormity of exposure and potential harm this chemical can cause to humans as well as wild or aquatic life.

It has been reported that the South African coastal regions alone accommodate over 3,000 particles of plastic per square km and not less than 1 million tons of plastics are discarded yearly in the country.[12] Unfortunately, a lot of plastics are not subject to biodegradation but will gradually disintegrate into microplastics[13] over time, connoting the environmental persistence of pollutants that can be released from plastics.

Classified as an industrial estrogen,[14] BPA is an organic chemical with the molecular formula $(CH_3)_2C(C_6H_4OH)_2$ which gained market value in 1957.[15] Physically, it is solid at room temperature, sparingly soluble in water but readily dissolves in organic solvents such as ethanol and toluene.[15] Figure 1 shows the structure of BPA while Table 1 shows the physical and chemical characteristics of BPA. It is used to plate the inner surfaces of tins used for tinned food and drinks to mitigate rusting.[16] In the synthesis of PVC plastics, BPA is employed as an antioxidant and as a stabilizer, as well as an ingredient for the manufacture of thermal papers and dental sealants.[17] BPA is also utilized as a binding/hardening agent in the production of binding and filling materials, as well as paints.[18] The availability of BPA in environmental media strictly depends on industrial application because BPA is man-made and does not exist naturally.[19] Some other industrial applications include hospital and laboratory equipment, water pipes, portable computers, mobile phones, baby bottles, and food packaging materials.[20] In South Africa, the day-to-day usage of synthetic compounds containing BPA, especially at elevated quantities, has resulted in their discharge (from waste) into environmental water bodies.[21]

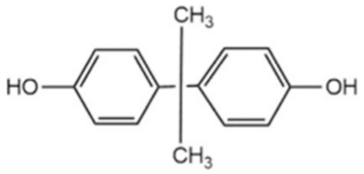

Figure 1. Structure of BPA[29]

Table 1. Physical and Chemical Characteristics of BPA[a]

Properties	Values
Molecular weight	228.29 g/mol
IUPAC name	4,4− (propane −2,2-diyl) diphenol
Formula	$C_{15}H_{16}O_2$
Chemical abstract service number CAS no	080−05−7
Melting point	153 °C
Boiling point	360 °C at 101.3 kPa (220 °C at 4 mmHg)
Relative density	1.2 g/cm^3 at 25 °C
Vapor pressure	5.3×10^{-09} kPa (at 25 °C)
Water solubility	300 mg/L (at 25 °C)
pK_a	101
Water solubility	120 mg/L (at 25 °C)
Relative density	1.2 g/cm3 (at 25 °C)
Specific gravity	1.195−1.2 g/cm^3 (at 25 °C)
Half-life	Water= 37.5
	Sediment = 337.5
	Soil = 37.5
Log Know	172.8 L/kg (wet weight)

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Globally, BPA has been known to be used in the making of plastics since the 1950s;[22] however, its use has been discontinued due to health concerns.[23] For example, Ellis et al.[24] cited Canada as the first country to ban its use in the year 2010 while Malaysia also banned its use in 2012.[25]

Owing to its toxicity, researchers have also synthesized alternative replacement compounds identical in physical and chemical characteristics to BPA but with perceived lower toxicity.[26] These compounds are analogues of BPA such as bisphenol F (BPF), bisphenol S (BPS), bisphenol A diglycidyl ether (BADGE), bisphenol E (BPE), bisphenol B (BPB), and bisphenol AF (BPAF).[27]

According to Swartz et al. BPA is a priority EDC in South African wastewater both from domestic and industrial sources.[21] Corrales et al. reviewed over 500 articles to decipher the global spread of BPA in environmental matrices.[28] However, no publications were identified from any African country with the exception of Tunisia.

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1.1. Major Routes to Human and Environmental Exposure.

BPA originates mainly from anthropogenic factors,[30] such as industrialized processes that release chemicals into the environment. Although the use of BPA in baby bottles was banned in South Africa in the year 2011,[31] it is unlikely that every material containing BPA that was imported or manufactured preregulation has been eradicated from the country. South Africa is also the first country in Africa to join the list of countries where baby bottles containing BPA have been banned (this excludes other food packaging products),[32] a move previously adopted by the European Union, Canada, France, and some states in the United States of America such as New York and California.[31]

After the ban on BPA, a study by Aneck-Hahn et al.,[33] showed the presence of BPA in commercial bottled water. Jager et al.[34] also found BPA in cling film, which is food packaging materials sold commercially. BPA can leach from the linings of canned food into the contents, leaving the consumers susceptible.[23] Potable water can also be difficult to access in some rural communities. Thus, the water is stored in plastic containers which could increase the chances of BPA contamination.[26] All these indicate various means whereby humans can be exposed to BPA via ingestion.

World Integrated Trade Solution[35] recorded high values of BPA import into South Africa. Additionally, according to Ubomba-Jaswa et al.,[36] South Africa is the highest producer of plastic on the African continent, with 8,987 kilotonnes. This connotes that the actual potential availability for BPA in the South African environment is higher than what is already documented. Gauteng, KwaZulu-Natal, and Western Cape are the leading provinces in South Africa with regard to the production of plastics. Thus, much industrial waste is anticipated in these locations and possibly higher environmental availability of BPA.[37]

There are currently no regulations controlling plastic products containing BPA (besides feeding bottles), and it is challenging to recognize other accompanying toxic chemicals.[32] Consequently, a study by Du Preez et al.,[32] investigated the everyday handling and disposal of plastic among young people in South Africa. This study highlighted microwaving, freezing, dishwashing, refrigeration, and prolonged exposure to sunlight as consumer practices that can facilitate the leaching of BPA. It can also be inferred from this study that these individuals have no understanding of the health challenges that can emanate from the wrong handling of plastic. They broadly disregarded the plastic code, which educates them on how to handle such material. This constitutes part of the ways BPA is generated from household uses, and a change in plastic handling can generally reduce human ingestion and the percentage availability of BPA in the environment.

Individuals employed in industries involved in the manufacturing or handling of materials containing BPA face a higher risk of exposure. This includes workers in plastic manufacturing plants, recycling facilities, and retail positions that involve frequent handling of receipts. Occupational exposure generally occurs through the inhalation of dust particles containing BPA and direct skin contact.[38,39]

During the production and disposal of products containing BPA, the compound is released into the environment, leading to contamination of air, water, and soil. Individuals residing in close proximity to industrial areas or landfills may experience higher exposure levels through environmental pathways, such as drinking contaminated water or inhalation.[40]

The presence of BPA in South African geology was also researched, but no information was reported to this effect. However, in literature, BPA was reported to have penetrated the soil through insecticide and herbicide application during agricultural activities.[41]

The objective of this review is to present an overview of BPA in major South African water resources, the optimiztic remediation options that have been explored, and perceived knowledge gaps. To the best of the authors' knowledge, no article in South Africa has been published that consolidates the occurrences of only BPA in the various water matrices considered in this study. However, some authors such as Mhuka et al.[42] and Gani et al.[43] have published on a broad range of emerging contaminants in South African water systems.

This study also hopes to remind local researchers of the general health impacts of BPA so that there can be a refocus on the pollutant and a concerted drive to manage its contamination in water.

1.2. The Toxicology of Bisphenol A.

The presence of Bisphenol A (BPA) has raised concerns regarding its potential toxicological impacts, specifically as an endocrine disruptor. The toxicology of BPA indicates that it can cause adverse health effects in many areas of the human physiological systems. Continued research and strict regulatory measures are necessary to mitigate the public health and ecological impacts of BPA. The endocrine system is driven by hormones and comprises the adrenal, parathyroid, pituitary, and thyroid glands, as well as the ovaries, pancreas, and testes[44] which carry out their function in a complex yet systematic way. BPA is not beneficial to the human body in any way and is perceived to be detrimental.[45] Yuki et al.[46] discovered the ability of BPA to alter neural arrangements in pluripotent stem cells from humans which ultimately interfere with cerebral development. In another study, Ma et al.[17] conclude that BPA can antagonize human reproductive functions by interrupting the activity of sex hormones which could lead to infertility. Further detrimental health effects of BPA include prostate and breast cancer, compromised immunity, cerebral damage, oligospermia, precocious puberty, insulin resistance, cardiovascular disease, diabetes, obesity, liver dysfunction, neuro-behavioral alterations, and immune disorders on exposure to the fetus.[7,33,47]

Because of the potential damage EDCs, in general, can do to human physiology, researchers have gone a step further in quantifying their potential health risk which takes into consideration the concentrations of the pollutant of interest in the environment of a given sample population as well as the different exposure routes such as ingestion, inhalation, and dermal adsorption.[48] For example, Van Zijl et al.[49] scrutinized the carcinogenicity and health risk of BPA among other EDCs in distribution point water and bottled water from Pretoria and Cape Town. The study reports that the maximum hazard quotient for both water sources is below 1 and thus contains safe levels of BPA, with the concentration found in most of the distribution point samples at 0.01 to 28.83 ng/L. The authors also noted the migration of EDCs from distribution pipes (from source) into water as one of the avenues of human exposure.

1.3. Bisphenol A in the Global Environment.

The widespread presence of BPA in consumer products and industrial applications globally has resulted in its extensive dispersal in the environment, raising significant concerns due to its endocrine-disrupting effects. BPA is consistently detected in various environmental matrices such as water bodies, soil, air, and biota. Water systems are particularly vulnerable, as they are directly exposed to effluents and urban wastewater, which often contain BPA residues. Studies have reported BPA concentrations ranging from trace levels to several parts per million in rivers, sediments, and municipal wastewater across different continents, highlighting its wide distribution.[28] For example, in Italy BPA was found in 13 bottled water brands and 10 tap water samples at a mean concentration of 458.57 ng/L,[27] China at 253 ng/L in surface water,[50] Brazil at 3.7 to 194 ng/L in raw water[51] and the United States at 0.8 to 10 μg/L in wastewater effluents.[52]

1.4. Global Regulations on Bisphenol A (BPA) Exposure.

Many countries have implemented regulations or outright bans on BPA, especially in consumer products related to food. Developed nations have mostly restricted or banned the use of BPA in children's products and materials that come in contact with food. This is in response to growing concerns from the public and scientific communities about the safety of BPA, especially for infants and young children.

1.4.1. Regulations in North America.

Initially, the United States Food and Drug Administration (FDA) considered BPA to be safe. However, in light of new scientific evidence, their position has changed. Currently, the FDA has forbidden the use of BPA in baby bottles, sippy cups, and infant formula packaging. While the use of BPA in other consumer products remains legal, many manufacturers have voluntarily phased it out from food containers and water bottles due to consumer demand (FDA, 2023).[53] Canada was one of the first countries to classify BPA as a toxic substance. Since 2008, its use has been prohibited in baby bottles and infant feeding products. This proactive stance has influenced further assessments of the impact of BPA and has resulted in regulatory adjustments in other consumer goods.[54,55]

1.4.2. European Union (EU).

The European Union has implemented comprehensive regulations on BPA. Since 2011, the use of BPA in baby bottles has been banned, and further restrictions have been imposed on its usage in materials intended for contact with food. In 2018, the European Chemicals Agency (ECHA) significantly reduced the allowable limit for BPA in thermal papers in all member states to minimize dermal exposure (ECHA, 2018).[56]

1.4.3. Asia-Pacific Regulations. China has adopted a similar approach to that of the EU and North America, banning the use of BPA in baby bottles since 2011. Additionally, they established guidelines and standards for the use of BPA in other materials that come in contact with food. This reflects the growing concerns about food safety among the Chinese population.[57] Japan's approach to regulating BPA differs slightly from that of other regions. Rather than enacting outright bans, Japan has focused on voluntary reduction. Since the early 2000s, the Japanese industry has worked with the government to move away from using BPA in food containers and packaging materials. This cooperative effort has led to a significant decrease in BPA exposure among the Japanese population (AIST, 2007).[58] In Australia, major manufacturers and retailers voluntarily phased out the use of BPA in baby bottles since 2010, opting for this approach instead of relying on legislation. The Australian government supports this action, as research conducted by Food Standards Australia New Zealand (FSANZ) has found that BPA does not pose notable health risks at current exposure levels in other products (FSANZ, 2010).[59] Countries in South America, such as Brazil, have implemented bans on BPA in baby bottles as well (ANVISA, 2011).[60]

BPA regulations in African countries differ greatly, with many lacking specific legislation addressing this chemical. As these nations continue to develop industrially and strengthen trade relations, stricter regulations on substances like BPA are likely to be implemented, aligning with regions that uphold high chemical safety standards. This progressive development is crucial for protecting public health and ensuring the availability of safer consumer products across the continent. In South Africa, the manufacturing, importation, exportation, and sale of polycarbonate infant feeding bottles containing BPA are prohibited.[31] Additionally, there is a growing awareness of the potential health risks associated with BPA in the country.[61]

With respect to drinking water, policies are also being put in place. For example, regulatory agencies such as the Environment Protection and Heritage Council, National Health and Medical Research Council, and Natural Resource Management Ministerial Council, all within Australia collaboratively set a guideline value of 200 μg/L for BPA in drinking water.[62] The Minnesota Department of Health and the European Union also set permissible drinking water limits for BPA in water at 20 μg/L[63] and 2.5 μg/L respectively.[64]

2. RESEARCH PROCESS

Robust scientific databases such as google scholar, PubMed, and Scopus were searched extensively using keyword combinations such as "BPA" or "Bisphenol a" "emerging contaminants" "micropollutants" + "South Africa", "South African water" + "surface water", "groundwater", "borehole", "wastewater", "freshwater", "rainwater", "bottled water" and hundreds of articles were perused. This study considered research articles that quantified BPA in water matrices from the earliest available publications (the year 2008) up until the year 2023. PhD thesis and MSc dissertations with the required information were also included. Furthermore, this review regarded any available data for leachate and sludge because of their strong affiliation with water in the ecosystem. The matrices evaluated in this study include wastewater, surface water (river/dam/sea), drinking water (bottled and tap water), and groundwater (borehole/spring).

2.1. Levels of Bisphenol A in South Africa.

Corrales et al. reported that the global monitoring of BPA in water started at the end of the 1990s.[28] The academic body in South Africa only recently began to study BPA actively in water systems from the year 2008. Besides water sources, no article was published on the availability of BPA in food substances within South Africa prior to the year 2022.[65] Clearly, this indicates a deficit of data, however, research in the country and the number of scientific articles on BPA in water sources began to appear since 2008 as depicted in Figure 2.

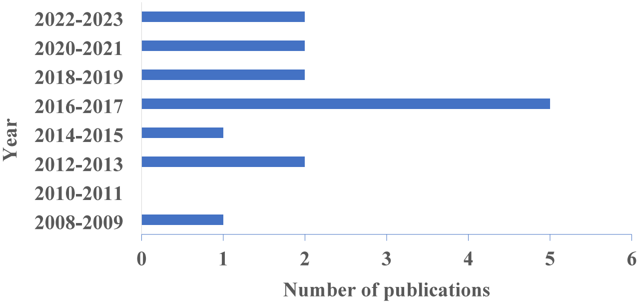

Figure 2. Number of South African publications on the determination of BPA in Surface water, wastewater, Sea water, drinking water, and groundwater.[66,67,30,68,69,6,49,70,71,33,72,73,4,74,75]

2.2. Wastewater.

Wastewater treatment plants (WWTP) are the last line of defense against ambiguous pollutants especially in urban areas. However, some authors have reported that they do not completely remove EDCs.[4,76] About 970 treatment plants have been established in South Africa geared toward treating 7,589,000 kiloliters of wastewater everyday.[77]

A study by Adeleye,[14] set out to identify and quantify BPA alongside other EDCs in 4 WWTP in Western Cape, South Africa namely; Bellville WWTP, Scottsdene WWTP, Zandvliet WWTP, and Beaufort West wastewater reclamation plant, recorded concentrations in the range of 12−210 μg/L in the influents and 1.3−10.3 μg/L in the effluents. These reports show a good measure of removal of BPA by the treatment plants. However, the amounts of residual BPA in the effluents can eventually contaminate destination water bodies. Moreover, a concentration of 10.3 μg/L is high enough to introduce undesirable effects on aquatic organisms and human health. In a more recent study, Struzina investigated the presence of BPA in drinking water treatment plant (DWTP) in Pretoria and in Vhembe.[26] The study confirmed no detectable amounts of BPA (and analogues), irrespective of the limit of detection of 1 ng/L. According to Olujimi et al.[78] and Olujimi et al.[30] EDCs in WWTP influents can be derived from domestic, industrial, and agricultural waste. The same authors also published the concentrations of BPA in wastewater influents and effluents in Cape Town. In their study, the concentration of BPA ranged from 291.339 to 384.8 μg/L in wastewater influent and from nondetectable (ND) to 3.94 μg/L in the effluent. These concentrations are completely unsafe when compared to the European Union's standard of 2.5 μg/L.[64] Farounbi and Ngqwala reported BPA concentrations of influent and effluent from four (4) wastewater treatment plants in Eastern Cape,

Table 2. Summary of the Environmental Occurrence of BPA in South Africa

S/N	Sample	BPA level	Province	Extraction method	Assay method	Reference
1	Wastewater	3.94 μg/L	Western Cape	Liquid−Liquid Extraction	UPLC/MS	Olujimi et al.[30]
2	Wastewater	0.0916 ng/L	Gauteng	Solid Phase Extraction	GC × GC TOFMS	Olorundare et al.[68]
3	Wastewater	Detected	Gauteng	Liquid−Liquid extraction	GC-MS	Mahomed et al.[66]
4	Wastewater	20 ng/L	Mpumalanga	Auto trace Solid phase extraction	GCxGC-HRTOFMS	Wanda et al.[70]
5	Wastewater	4891.65 ng/L	Western Cape	Solid phase extraction	UPLC-MS/MS	Archer et al.[75]
6	Wastewater	301 ng/L	Gauteng	Solid Phase extraction	UPLC/TQD-MS	Archer et al.[69]
7	Wastewater	53.60 ng/L	Northwest	Auto trace Solid phase extraction	GCxGC-TOFMS	Wanda et al.[72]
8	Wastewater	1.684 μg/L	Eastern Cape	Solid Phase extraction	UPLC-MS	Farounbi and Ngqwala,[4]
9	River	5.11 ng/L	Northwest	Auto trace Solid phase extraction	GCxGC-HRTOFMS	Wanda et al.[70]
10	River	0.4770 μg/L	Eastern Cape	Solid Phase extraction	UPLC-MS	Farounbi and Ngqwala,[4]
11	River	239 ng/L	Gauteng	Solid Phase extraction	UPLC/TQD-MS	Archer et al.[69]
12	River	1396.65 ng/L	Western Cape	Solid phase extraction	UPLC-MS/MS	Archer et al.[75]
13	Seawater	≡ 0.12 ng/L	Western Cape	Solid Phase Extraction	UPLS-TQ-MS	Petrik et al.[6]
14	Stream	800 μg/L	Free State	Solid phase extraction	HPLC	Adoons[73]
15	Surface water	Detected	Gauteng	Sorptive extraction with sequential salting out	TD-GC × GC-TOFMS	Wooding et al.[71]
16	Dam	6.8 ng/L	Gauteng	Auto trace Solid phase extraction	GCxGC-HRTOFMS	Wanda et al.[70]
17	Drinking water	3.79 ng/L	Gauteng	Solid Phase Extraction	UPLC-MS/MS	Van Zijl et al.[49]
18	Drinking water	7.43 ng/L	Western Cape	Solid Phase Extraction	UPLC-MS/MS	Van Zijl et al.[49]
19	Drinking water	0.06798 ng/L	Western Cape	Solid Phase Extraction	GC-MS	de Jager et al.[67]
20	Drinking water	0.04728 ng/L	Gauteng	Solid Phase Extraction	GC-MS	de Jager et al.[67]
21	Bottled water	10.06 ng/L	Gauteng	Solid Phase extraction	GC-MS	Aneck-Hahn et al.[33]
22	Groundwater	0.29 ng/L	Gauteng	Solid phase extraction	-	Ligavha-Mbelengwa et al.[74]
23	Spring	181 ng/L	Mpumalanga	Auto trace Solid phase extraction	GCxGC-HRTOFMS	Wanda et al.[70]

namely, Makhanda wastewater (formerly known as Grahamstown), Qonce wastewater (formerly known as King Williams), Alice wastewater and Uitenhage wastewater.[4] Although all the samples had BPA present, effluents from Uitenhage had the highest concentration of 1.684 μg/L which is still within the safety limit based on the European Union recommendation (2.5 μg/L). Some WWTPs and water reclamation plants (WRP) within the country have, however, shown superior BPA removal as high as 99.7% (WWTP C), 98.5% (WRP A), and 93.4% (WWTP B) which could be due to the design technology of the plants.[21]

While Adeleye, Farounbi and Ngqwala, and Olujimi et al. all set out to determine the concentration of BPA in wastewater, only Adeleye also studied the efficiency of the wastewater treatment plants as well as the release rate of the contaminant. Additionally, many articles generally attribute the source of BPA to industrial and domestic waste, without specific details of points of origin. Olujimi and Adeleye clearly point out that the use of toilet paper is a significant way to generate BPA in wastewater. This information simplifies the ambiguity of BPA in water and makes this article relatable even to nonscientists. The quantification of BPA in wastewater by the studies is significant, but none of the authors went further to quantify how much each of the major sources contributed to the total BPA in wastewater.

Duenas-Moreno et al.[79] cited that the use of sludge and wastewater in agricultural activities such as irrigation can lead to groundwater pollution. This aligns with the opinion of Gumbo et al.[80] who observed that vegetable irrigation with wastewater came with potential health hazards when a microbial study was conducted in Malamulele, Limpopo Province. Mora et al.'s study further confirmed this when they listed journals that identified organic contaminants in groundwater where irrigation with wastewater had taken place.[81]

Without any form of doubt, the presence of BPA in wastewater, especially in the effluents, is a worrisome situation that needs to be examined. Addressing the levels of BPA in the effluent will directly reduce its availability in other environmental media since effluents are one of the major gateways into the environment.

2.3. Drinking Water.

Drinking water comes in various forms, one of which is bottled water which can contain trace levels of unwanted chemicals that might not be detectable except with highly sophisticated instrumentation. Aneck-Hahn et al. investigated the presence of BPA in commercially available polyethylene terephthalate (PET) bottled water stored at two temperatures, 20 and 40 °C.[33] The result showed that BPA was detected in every sample at concentrations ranging from 0.9 ng/L to 10.06 ng/L. Its presence was attributed to leaching from water pipes, which were used to transport the source water thus exonerating the PET bottles. This claim was supported by an article by SANBWA (South African National Bottled Water Association) wherein it was stated that BPA is not part of the chemical composition of PET bottles and thus cannot discharge into the water content.[82] In other words, BPA in bottled water can be traced backward from the final commercial packaging bottle to the source or the transporting vessel. This is contrary to the discovery of Ginter-Kramarczyk et al.,[83] where BPA was observed to leach into bottled water, especially with the increase in temperature. Furthermore, according to SANBWA, 70% of all bottled water in South Africa is sourced from natural mineral and Spring water.[84] This makes it quite difficult to implicate natural mineral and Spring water as the source of BPA in any bottled water because BPA is not naturally occurring, and the available investigations in ground and spring water (Table 2) show trace amount of BPA.

In a more recent study, Struzina investigated the presence of BPA from drinking water treatment plants (DWTP) in Pretoria and in Vhembe.[26] The study confirmed no detectable amounts of BPA (and analogues), irrespective of the limit of detection (1 ng/L). Momba et al.[85] showed that drinking water treatment plants get their source water from boreholes and springs. Arguably, the water sources from Aneck-Hahn et al. and Struzina are from the same type of source, but the processes (i.e., transport vessel) they are subjected to can redefine their chemistry. The small number of studies on BPA in drinking water in South Africa is a limiting step to fully understanding the absence or presence, as well as the potential causes of BPA in drinking water.

From a regulatory perspective, the steady increase in the adoption of bottled water by consumers, as well as the rise in the use of plastic packaging materials, warrants the monitoring of EDCs in commercial bottle water.[33] The bottled water market in South Africa is also expected to grow at an annual rate of 2.87% between 2023 and 2027.[86] These statistics require continuous monitoring of BPA not just in the finished product but in the water source(s) which can be a contributing factor. Rainwater was also researched in this study, but no data was found.

2.4. Surface Water.

Several communities especially in rural or semiurban areas utilize environmentally available water. These communities also often use surface water such as river or dam for indiscriminate waste disposal and subsequently reuse such water for domestic purposes.[9] Of all the rivers and dams available in South Africa, only few references have been cited for BPA analysis.

Petrik et al. analyzed seawater (Atlantic Ocean) from Green Point, Cape Town, and found BPA at nanogram per liter levels.[6] In Gauteng Province, surface water, which receives effluents from a WWTW was also analyzed with samples taken upstream (100 m) and downstream (3.5 km) from discharge. Interestingly, BPA downstream had a mean concentration of 396.4 ng/L, higher than upstream (which is closer to the effluent source) with a concentration of 239.0 ng/L. This unexpected trend was attributed to the reintroduction of materials containing BPA into the river by human activity such as indiscriminate waste disposal.[4,69] Wanda et al. also investigated a range of emerging pollutants, including BPA in surface water. Samples from Mkomazane and Lipoponyane Rivers in Mpumalanga, Krokodil, and Magalies Rivers, as well as Hartbeerspoort dam in Northwest and Roodeplaat in Gauteng, were all analyzed for an approximate duration of 2 years.[70] The highest result ranged from ND to 81.24 ± 3.2 ng/L which should not be detrimental to human health based on European guidelines. The observed occurrence of BPA in the majority of the water sources in this study was attributed to the influence of municipal wastewater which is often the culprit because BPA's environmental availability has not been related to any natural factor. In Eastern Cape Province, 4 major rivers, namely Bloukrans, Tyhume, Buffalo, and Swartikops, were sampled upstream, midstream, and downstream and analyzed for BPA.[4] The liquid chromatography coupled with mass spectrometry (LCMS) results showed the presence of BPA in all samples, with the highest concentration of 0.4770 μg/L at Bloukrans River downstream and the lowest of 0.0067 μg/L at Swartikops River upstream. In both sample areas, BPA concentration was higher midstream than downstream. This phenomenon is not surprising as the authors' perspective aligned with that of Archer et al.[69] that waste materials containing BPA have been reintroduced somewhere in between. In a more recent study by Ojemaye et al., seawater collected near the coastal zone of Camps Bay in Cape Town was also analyzed using LCMS, but BPA was below the limit of quantification (0.05 ng/L).[87] Overall, more BPA studies have been done on surface water than other sources as seen in Figure 3.

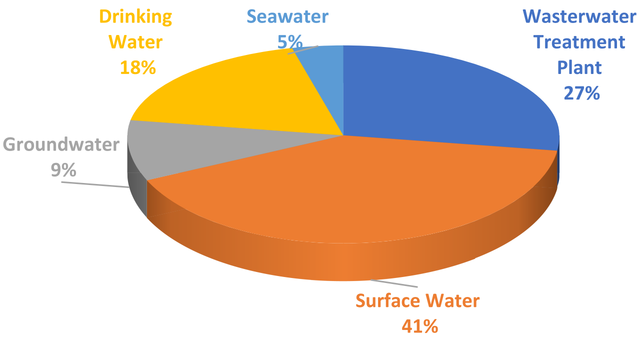

Figure 3. Percentage distribution of BPA studies per matrix in South Africa from 22 journals.

All the studies enumerated above agree on determining the concentration of BPA in surface water. However, the different authors had secondary motivations for their studies. For example Petrik et al. and Ojemaye et al. considered the bioaccumulation of BPA by marine Species, Archer et al. interrogated the fate of ECs (including BPA) in surface water, and Wanda et al., the general insufficiency of data (i.e., distribution and removal options) of some emerging contaminants in water which cripples the ability to draw necessary conclusions. The management and preservation of the aquatic environment was of great concern to Farounbi, Ngqwala, and Petrik et al. because surface water received toxic chemicals and other incompletely removed pollutants from WWTP effluent. A number of perspectives have already been appraised, but there remain areas of controversy that require urgent attention. For example, the rapidly growing population and industrialization, especially in the cities, will naturally put pressure on surface water. On the contrary, the level of training and education afforded to the WWTP workers in rural and suburban areas can also influence the quality of effluent going to the surface water. These and many more valid concerns of the authors can inform a quality and regulatory framework for the effluent-surface water value chain from which recommendations can be made. One such recommendation can be the certification of a river for fishing, based on the monitoring of BPA and other emerging chemicals on surface water in order to protect aquatic ecosystems and human health.

The Indian Ocean and the Southern Ocean are other water bodies around South Africa that could be carrying EDCs. Furthermore, most of the surface water analyzed has been connected to the effluents of WWTP. The sampling and analysis of surface water unconnected to WWTPs is therefore recommended to discover any unsuspected source of BPA.

2.5. Groundwater.

Although the occurrence of BPA in the environment is believed to be less of a problem in low socioeconomic status communities (because of its direct relationship with urbanization and industrialization),[88] however, this may not be totally true. Edokpayi et al. have shown that most households in rural settlements in the country depend on groundwater.[89] Regrettably, the surveillance of emerging contaminants in the country's groundwater is poor.[43] Spring water (which is a form of groundwater) from a secondary school in Mpumalanga was analyzed, and the concentration

Table 3. Summary of BPA Remediation Methods Explored in South Africa

	Material/Adsorbent	Technique	Preparation Method	BPA Concentration	Removal Efficiency/Adsorption Capacity	Mechanism of Removal	Reusability Cycles	Reference
1	Ag@TiO_2−PANI	Photocatalysis	Oxidative polymerization	5 mg/L	99.7% (Visible light) 99.5% (UV radiation)	Degradation by positive holes h+ and superoxide $\bullet O^{2-}$	4	Sambaza et al.[102]
2	MOS_2/Ag@WO_3/EG	Photoelectrodegradation	1. Hydrothermal/solvo thermal method 2. Light-assisted photoreduction deposition	10 mg/L	99.2%	Degradation by $\bullet O^{2-}$, •OH, and h+ radicals High charge separation and redox capability	4	Mafa et al.[104]
3	Polyaniline (PANI)-wrapped TiO_2 nanorods	Photocatalysis	Hydrothermal synthesis and oxidative polymerization	5 mg/L	99.7%	Adsorptive photocatalytic degradation	5	Sambaza et al.[103]
4.	TiO_2/Ag_2O @EG electrode	Photoelectrochemical procedure	Hydrothermal process	-	87%	Generation of hydroxyl radical	-	Ama et al.[105]
5.	CFA/GO/PANI + Cr(VI)	Photocatalysis	Hydrothermal synthesis	10 mg/L	86%	Adsorption of BPA and degradation by •OH, $\bullet O^{2-}$, h+ radicals. photoelectrochemical activity of Cr (VI)	-	Umejuru et al.[106]
6	Manganese and iron-phthalocyanine (MnPc, FePc)	Catalyzed oxidation		75 μM	67.6 ± 8.4% (MnPc,) 53.9 ± 4.1% (FePc)	-		Kruid et al.[107]
7	N-CNT/PES blend membrane	Membrane Filtration	Floating catalyst chemical vapor deposition method and phase-inversion method	181.26 ± 3.9 ng/L	98.59%	BPA rejection and pure water flux	-	Wanda et al.[108]
8	Silicon dioxide (silica) (SiO_2) and germanium dioxide (GeO_2) embedded poly(ether sulfone) (PES) blend membranes	Membrane filtration	Phase-inversion method	5.19 ± 0.8 to 53.60 ± 4.25 ng/L	97.0% (SiO_2) 96% (GeO_2)	BPA rejection and pure water flux	-	Wanda et al.[72]
9	Nano zerovalent iron particles (PEG-nZVI) stabilized with polyethylene glycol	Dielectric barrier discharge and Fenton process	Borohydride reduction method	10 mg/L	100%	Activity of •OH radical from photo-Fenton process	-	Tijani et al.[101]
10	N-CNTs-β-Cyclodextrin and Fe/N-CNTs-β-Cyclodextrin Nanocomposites	Adsorption	Microwave polyol method	-	80.65 mg/g	Hydrophobic interaction and the hydrogen-bonding interaction simultaneously	-	Mphahlele et al.[114]
11	Nanosilica	Adsorption	-	50 mg/L	4.267 mg/g		-	Orimolade et al.[115]
12	Polypropylene (PPY)/polyaniline (PANI) composite	Adsorption	Polymerization of aniline and pyrrole	50 mg/L	≡80%	Electrostatic interactions, p−p nonelectrostatic, hydrophobic nonelectrostatic interactions	-	Hlekelele et al.[116]
13	Laccase bonded polyethylenimine/poly(ether sulfone) (Lac-HPEI/PES) membrane	Membrane filtration	Electrospun of HPEI/PES Immobilization by glutaraldehyde cross-linker	100 μg/L	89.6%	BPA rejection and pure water flux		Koloti et al.[109]

was estimated at 181 ± 3.2 ng/L. Borehole water from Blesbokspruit environs (Gauteng) was also examined for emerging organic chemicals, and BPA was determined in 3 of the 4 sampling sites. The lowest concentration recorded was 0.29 ng/mL, (the highest concentration for borehole water was not disclosed).[74] Although no mention was made of a close-by WWTP, which could easily be attributed to as the source in groundwater, these insights show that BPA can be in unsuspecting water sources. The presence of BPA in the 2 available studies on groundwater could be an indication of a bigger and unexpected presence of BPA which requires further analysis of groundwater sites in all provinces in order to close the knowledge gap. Just like the case of spring and borehole water mentioned above, identifying the source of BPA is also an important aspect of managing the occurrence of BPA in groundwater. Additionally, the assessment of the health impact where BPA has been identified will be instrumental in ensuring that the water is fit for domestic use as is the case for most groundwater.

Dueñas-Moreno et al.[79] earlier proposed that landfill leachate, as well as anthropogenic activities that facilitate the eventual movement of pollutants from the environment to groundwater aquifers, are part of the factors that introduce BPA and phthalates into groundwater. Olujimi et al. discovered very high levels of BPA in landfill leachate in Cape Town.[30] The concentration of BPA in the leachate was estimated at 9.59 ± 1.48 mg/L which poses a serious threat to groundwater networks within close proximity. BPA was also discovered in sludge at 0.84 ± 0.11 μg/g and 0.148 μg/L but these levels are within permissible range.[30,90] Contaminated surface water, soil, sediments, influents, and effluents from wastewater can also introduce pollutants.[79] The aforementioned factors may be the reasons for the occurrence of BPA in the areas featured in this review, and besides bottled water, consumption of groundwater is one of the ways BPA can be introduced to humans. A summary of all reported environmental occurrences of BPA in water within South Africa is provided in Table 2.

3. REMEDIATION OF BISPHENOL A

Considering the health risks associated with human (and animal) life, researchers in South Africa have been proactive in designing remediation methods, though mostly on laboratory scale. These approaches are intended to manage present or future environmental challenges where BPA will affect the purity of water, especially in communities that rely on untreated sources for domestic purposes. Furthermore, the inability of wastewater treatment plants to completely eliminate emerging contaminants from the influents also necessitates additional purification methods in this field. Globally, many other researchers have recently explored a variety of methods including novel palm kernel shell magnetically induced biochar adsorbent,[91] hybrid clay/TiO_2 composite adsorbent,[92] carbon and zeolitic tuff adsorbent,[93] spoilt milk derived adsorbent,[94] chemically activated sunflower stem biochar adsorbent,[95] TiO_2/clinoptilolite hybrid photocatalyst,[96] thin-film composite membrane,[97] microfiltration membrane,[98] biodegradation using microorganism consortia[99] and even hybrid methods such as ceramic membrane filtration coupled with peroxymonosulfate activation and adsorption[100] among others. The studies mentioned above, alongside numerous others not referenced and the ones that are currently ongoing, underline the relevance of BPA as a relevant environmental contaminant and the need to develop a globally applicable solution, especially since environmental matrices can be different. In South Africa, both advanced oxidation processes, i.e., photocatalysis, and adsorption, have been explored and are discussed subsequently, with Table 3 providing a summary.

3.1. Remediation Methods Used in South Africa.

3.1.1. Advanced Oxidation Processes. The Fenton process is one of the ways of achieving advanced oxidation. Tijani et al. investigated the degradation of BPA by photofenton processing using a combination of polyethylene glycol stabilized nano zerovalent iron particles (PEG-nZVI) and a dielectric barrier discharge (DBD).[101] 0.06 g of nZVI in the DBD set up completely degraded (100% removal) 10 mg/L BPA in simulated wastewater within 30 min, however, intermediate products such as 4-nitrophenol ($C_6H_5NO_3$), 4-nitrosophenolate ($C_6H_4NO_2$), 4-(prop-1-en-2-yl) cyclohexa-3,5-diene-1,2-dione, ($C_9H_8O_2$), 4-(2-hydroxylpropan-2-yl) cyclohexane-3,5-diene-1,2-dione ($C_9H_{10}O_3$), and 1,2-dimethyl-4-(2-nitropropan-2-yl)benzene ($C_9H_{10}NO_4$) were generated. Usually, the oxidation process strives to achieve complete mineralization because some intermediate products might be more biotoxic than the parent compound. However, 0.06 g of the material is a good investment for an almost absolute degradation of a 10 mg/L BPA solution.

Sambaza et al. researched the degradation of 5 mg/L BPA using PANI (polyaniline) supported Ag@TiO_2 nanocomposite via visible and UV light.[102] TiO_2 is a well-researched semiconductor used for photocatalytic degradation of organic pollutants, while PANI was used as a conducting polymer to ensure charge separation, which is one of the major challenges with the use of TiO_2 in photocatalysis. The authors remarked that this design had not been reported in literature, and the results showed a removal of over 99% with visible and UV light, respectively. Sambaza et al. continued research on BPA degradation, but this time using PANI-wrapped TiO_2 nanorods exposed to UV light with a view to wastewater application.[103] The impacts of humic acid and nitrates, which are probable coexisting ions were also described. This method achieved 99.7% degradation, and the mechanism of the reaction was attributed to the activities of holes (h^+), hydroxyl radical (OH·), and superoxide ($\cdot O^{2-}$). While the presence of nitrates enhanced the degradation of BPA via the generation of hydroxyl radicals (OH·), humic acid negatively impacted degradation by obstructing the active sites on the PANI-TiO_2 nanorods catalyst. The authors further explained that PANI contributed as an adsorption site as well as enhanced the charge separation, which compensated for the weakness of TiO_2. This study indeed highlighted competing ions as a relevant challenge scientists must overcome, especially during real-life applications.

In another study, Mafa et al. used molybdenum disulfide/silver@tungsten trioxide and exfoliated graphite to design a photoanode (MOS_2/Ag@WO_3/EG) capable of photodegrading BPA under visible light.[104] The authors cited enhanced charge carrier separation as one of the benefits of this approach and the result showed that under visible light, BPA removal of 99.2% was achieved. In addition, real samples such as deionized, tap, and streamwater were also used in this study, and removal of 100%, 65.4%, and 29.0% after 90 min of irradiation time was achieved, respectively. One of the explanations given for BPA degradation decline, especially in stream samples, is its lower transmittance of light, which obstructs the excitation of photoexcited charge carriers.

Ama et al. explored a combination of photocatalysis and electrochemical oxidation using exfoliated graphite (EG), titanium dioxide (TiO_2) and silver oxide (Ag_2O) photoanode ($TiO_2/Ag_2O@EG$) under sunlight.[105] According to this study, exfoliated graphite enhanced the degradation (87%), compared to using TiO_2/Ag_2O alone (66%), however, it was noted that the degradation took a significant time of 240 min. The use of sunlight in this study underscores the possibility of a visible light-only activated oxidation process, though further research is required to ensure that the intensity of sunlight, mass of catalyst, and reaction time are attractive.

In a more recent study, Umejuru et al. designed a material capable of adsorbing Cr (VI) from water (by adsorption), and the spent adsorbent was reused as a photocatalyst to degrade BPA.[106] After the successful removal (96%) of Cr (VI) from water by coal fly ash functionalized and modified with graphene oxide and polyaniline (CFA/GO/PANI) at pH 2, the CFA/GO/PANI+Cr (VI) spent adsorbent was used to achieve 86% degradation of 10 mg/L BPA from solution within 0−105 min under visible light. This method demonstrates the reusability of adsorbents and researchers going forward should consider designing adsorbents not just for one pollutant or remediation technique but for adaptable purposes.

Water from Gray Dam, Makhanda was also spiked with 75 μM BPA and examined for degradation capacity of manganese and iron-phthalocyanine (MnPc, FePc) catalyst at pH 6.61 and without any light source.[107] MnPc achieved a mean removal of 67.6 ± 8.4% while FePc achieved an average of 53.9 ± 4.1%. However, when the buffered solution was used at pH 7, BPA removal was 62.9 ± 6.0% for MnPc and 88.2 ± 1.6% for FePc, respectively. The authors referred to the elevated levels of dissolved organic compounds in the dam water which infers that other materials could have been degraded alongside BPA during the catalytic oxidation with FePc.

3.1.2. Membrane Technology. In order to remove BPA from field samples, Wanda et al. applied a membrane technology where a nitrogen-doped carbon nanotube/poly(ether sulfone) membrane (N-CNT/PES) was experimented on spring water and wastewater from Mpumalanga and Northwest Provinces.[108] Besides BPA, a number of emerging contaminants were removed by this setup which works by assessing pure water flux and emerging contaminant rejections using the cross-flow filtration system.[108] The N-CNT/PES membrane basically collects the pollutants and prevents them from passing through. Effluent from a WWTP (Eerstehoek) as well as spring water, which contained 21.34 ± 0.5 ng/L and 181.26 ± 3.9 ng/L of BPA, underwent 98.30% and 98.59% removal, respectively, from the samples. This method offers the advantage of removing multiple emerging pollutants simultaneously, although the researchers concluded that further research is needed to address the concerns of membrane concentrate stream which builds up when the system is applied.

Wanda et al. also used silicon dioxide (silica) (SiO_2) and germanium dioxide (GeO_2) nanoparticles engrafted into poly(ether sulfone) (PES) membranes in a subsequent study.[72] Water samples from Northwest Province with a BPA concentration range of 5.19 ± 0.8 to 53.60 ± 4.25 ng/L were used. The highest removal for GeO_2 was 96.0% while 97% was recorded for SiO_2. The removal was effective, but the use of N-CNT/PES proved to be superior for BPA remediation. Enzymes such as laccase have also been examined for BPA remediation. In a novel study by Koloti et al., laccase was immobilized on a dendritic nanofibrous membrane and used for BPA removal in a dead-end filtration system.[109] The results showed 89.6% removal, and the material was recycled 4 times with at least 73% efficiency. A major strength of this approach was the negligible leaching of the laccase enzyme into the solution because of a covalent bond between the enzyme and membrane.

3.1.3. Adsorption. The material(s) used as adsorbents, the method of synthesis, and the experimental factors play a major role in the success of adsorption experiments. Materials such as mesoporous silica nanoparticles from sugar cane waste ash, organoclay, banana and coconut bunch, as well as peanut shell biochar, have been used as adsorbents for BPA in other countries.[110−113]

In South Africa, Mphahlele et al.[114] compared the BPA sorption capacity of nitrogen-doped carbon nanotubes copolymerized with cyclodextrins (N-CNTs-β-CD) and metal-dispersed nitrogen-doped carbon nanotubes-β-cyclodextrin (Fe/N-CNTs-β-CD) under different experimental conditions. Fe/N-CNTs-β-CD exhibited higher adsorption capacity (79.85 mg/g) than N-CNTs- β-CD (38.9 $mg\cdot g^{-1}$) although the percentage removal was not expressly stated. It was also observed that pH and temperature had a negligible effect on the BPA sorption rate. Also, the Langmuir Isotherm was more suitable, and the reaction conformed to a pseudo-second-order model. As stated by the authors, additional research will be required on the reusability, financial implications, and durability of the adsorbent. This concern not only applies to this study but to all adsorption studies.

Consequently, the adsorption capacity of Fe/N-CNTs-β-CD is much higher than that of nanosilica derived from rice husk as researched by Orimolade et al.[115] The adsorption capacity of the adsorbent in their study was 4.267 mg/g at the optimum experimental condition of pH 8, 0.2 g adsorbent dosage and 45 min contact time, with the data fitting to the Langmuir isotherm model. This study used agricultural waste which is a class of material that has gained popularity among scientists because it is affordable, excludes toxic chemicals, saves time, and ensures complete removal when compared to conventional remediation methods.[115]

Hlekelele et al.[116] investigated the removal of BPA using a polymer composite polypropylene and polyaniline (PPY/PANI) that can be used as an adsorbent as well as a catalyst to activate Fenton reaction in the advanced oxidation reaction. The material proved more effective in adsorption than for advanced oxidation, achieving ≡80% and ≡70% respectively, using a 50 mg/L BPA solution. Sadly, the polymeric composite was not effective for BPA adsorption when sewage water was used, except when an increased adsorbent mass was considered, thus questioning its applicability for real-life scenarios.

In summary of this section, the presence of BPA in one of the least expected water resources (i.e., in groundwater) within the country has proven the undesirable level of its availability or perhaps a hint of a larger picture. The remediation methods cited in this paper represent an attempt to be proactive in managing the situation using global technologies, however, applied in the local context with a distinctive methodology. All the remediation studies were carried out in South Africa, and the results reflect the level of commitment that has been invested in solving the in-country environmental problem (although the problem is also globally relevant). Subsequently, the level of funding dedicated to research in South Africa, especially at the University level can also be linked to the success of the results achieved thus far. Additionally, the contribution to the body of knowledge by novel studies like Sambaza et al.,[102] Umejuru et al.,[106] and Koloti et al.,[109] to mention a few, have practicalized new ideas that are transferrable and repeatable globally for the development of further solutions within and without the scope of BPA.

4. DATA GAPS AND RESEARCH DIRECTIONS FOR BISPHENOL A IN SOUTH AFRICA

4.1. Expansion of Sampling Matrices. There is a significant data gap regarding BPA and its analogues in South Africa due to the limited scope of the sample matrices investigated. Current studies have primarily focused on wastewater, groundwater, rivers, and drinking water. However, several other environmental matrices remain underexplored, including storage tanks, lagoons, ponds, seawater, freshwater, leachate, sludge, sediments, and borehole water near waste dump sites. Including these matrices in the analysis is crucial for comprehensively understanding BPA distribution and its environmental fate. BPA has been studied in various sample matrices, as discussed in this review. However, the sample size of the matrices studied so far is a minority to the true picture of wastewater, groundwater, rivers, streams, dams, and tap (drinking) water in the country (which are yet to be investigated).

4.2. Health Impact Studies. In comparison to developed countries, there is a notable deficiency in extensive health impact studies on BPA in South Africa. This is because only one article was found (in the course of this review) where the carcinogenicity and hazard quotient of BPA were calculated, and no article was found where the hazard quotient was ≥ 1.[49] This indicates an insufficiency of research in this niche and studies should be carried out to determine health risk impacts in at least the water sources used for domestic purposes. Furthermore, in areas where the concentration of BPA is high, i.e., Cape Town, it is necessary to carry out the necessary health studies/investigations on residents, and these studies could serve as a foundation for evidence-based policymaking and public health advisories.

4.3. Study of BPA Analogues. BPA analogues, including BPF, BPS, BADGE, BPE, BPB, and BPAF, present additional challenges. Recent studies suggest that these compounds have leaching and toxicity profiles similar to BPA. However, there is limited research quantifying their presence in South African water systems. It is crucial to address this gap, especially considering that these compounds are often used as substitutes for BPA and may pose similar or even greater health risks. Comprehensive studies to identify and quantify these analogues are necessary to ensure that substitutions do not inadvertently increase health risks.[117]

4.4. Remediation Strategies. The remediation of BPA has been attempted using the methods enumerated above, but advanced oxidation processes showed the highest BPA removal potential. There is, therefore, a need to upscale this method to field trials followed by feasibility studies for large-scale use. For example, the inability of wastewater treatment plants to completely remove BPA can be managed by an additional oxidation process setup. Also, drinking water treatment plants that serve communities and bottled water manufacturing companies are areas where this method is suitable. This introduces the advantage of not only removing/reducing BPA but other undiscussed toxic pollutants that could have been released into surface water.

4.5. Regional Investigations and Risk Assessments. There is a lack of data on the occurrence of BPA in certain provinces, such as Limpopo. It is imperative to conduct focused investigations in these areas, with a specific focus on wastewater treatment plants and connected surface waters. Furthermore, considering South Africa's significant role in the production of packaging materials, it is crucial to enhance both qualitative and quantitative risk assessments of food packaging. This greater understanding will help assess the wider exposure risks associated with BPA in food containers and packaging materials, guiding regulatory actions and ensuring consumer safety.[118]

It is essential to address these critical data gaps through targeted research, expanded monitoring efforts, and feasibility studies for remediation technologies. These initiatives will not only provide a clearer understanding of the environmental and health impacts of BPA in South Africa but will also contribute to the development of more effective regulatory and public health strategies. Such efforts are essential for protecting ecosystems and public health from the risks posed by BPA and its analogues.

5. CONCLUSION

As industrialization and human population size increase, more waste will be generated industrially and domestically, thus the availability of BPA in water sources could increase. Furthermore, the bottled water industry is expected to grow locally between 2023 and 2027; such growth will require commensurate BPA monitoring.

This review has shown that there is currently insufficient information on the environmental occurrence of BPA in South African water systems. Only the year 2016−2017 recorded 5 published articles, while the following years have not surpassed that number. Perhaps researchers are oblivious to its potential environmental availability, or its health impacts are underestimated. Further insights from this study reveal that higher levels of BPA were determined more in environmental waters from Gauteng and Western Cape Province, while none was recorded in Provinces like Limpopo. The ban on baby bottles containing BPA in South Africa is commendable, but more legislative and regulatory initiatives, as well as scientific investigations, will be required to manage its presence and concentration in the environment, considering the high imports of BPA for other manufacturing purposes.

Clearly, effluents from waste treatment plants are discharged into rivers and streams. Thus, influents, effluents, surface water, and groundwater require not just microbial but chemical (i.e., EDC) monitoring. Wastewater and surface have the highest investigations in South Africa, but there is a need to be particular about groundwater or other forms of untreated water that people depend on for daily use. At the point of this review, only pockets of studies are available on the different water matrices, which underscores the need for a BPA surveillance network in the country. Advocacy and orientation of people across all socio-economic status environments are also important to inform people of the proper way to handle waste and dissuade indiscriminate disposal into streams by human activity, as identified by some authors.

Considering its potential health effects, trace concentrations in water should provoke scientific curiosity thus motivating researchers to investigate as well as estimate the health impacts wherever they are identified. In this study, BPA was established to be present in a number of water systems, even though some were at trace levels.

Remediation techniques such as adsorption, advanced oxidation processes, and membrane technology have been researched by scientists in South Africa. The results show good prospects with notable areas of further research. Thus, the funding and field installations of these optimistic designs capable of reducing BPA to unharmful levels are recommended.

Introducing and promoting local regulatory measures (such as 'maximum allowable concentration') would also be instrumental in protecting life once it is established that BPA-rich water is in contact with human or animal life directly and indirectly.

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Oladipo T. Ologundudu conceptualized and wrote the manuscript. Titus A.M. Msagati, Oluseun E. Popoola, and Joshua N. Edokpayi reviewed and edited the manuscript.

Notes

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■ REFERENCES

(1) Agunbiade, F. O.; Moodley, B. Occurrence and Distribution Pattern of Acidic Pharmaceuticals in Surface Water, Wastewater, and Sediment of the Msunduzi River, Kwazulu-Natal, South Africa. *Environ. Toxicol. Chem.* **2015**, *35* (1), 36−46.

(2) Wells, V. *Endocrine Disruptors in Drinking Water and Associated Health Effects. A knowledge synthesis*; University of Guelph, 2013. https://ncceh.ca/sites/default/files/Guelph-Wells-2013.pdf (accessed 2023-09-23).

(3) Edjere, O.; Asibor, I. O.; Bassey, U. Distribution of Phthalate Esters in Underground Water from Power Transmission Sites in Warri Metropolis, Delta State, Nigeria. *J. Appl. Sci. Environ. Manage* **2016**, *20* (3), 599−605.

(4) Farounbi, A. I.; Ngqwala, N. P. Occurrence of Selected Endocrine Disrupting Compounds in the Eastern Cape Province of South Africa. *Environ. Sci. Pollut Res. Int.* **2020**, *27* (14), 17268−17279.

(5) Orata, F. Chemicals of Emerging Concern in Surface and Wastewater: A Perspective of Their Fate Within the Lake Victoria Catchment Area of Kenya. 2020; pp 1−16. DOI: DOI: 10.4018/978-1-7998-1871-7.ch001.

(6) Petrik, L.; Green, L.; Abegunde, A. P.; Zackon, M.; Sanusi, C. Y.; Barnes, J. Desalination and Seawater Quality at Green Point, Cape Town: A Study on the Effects of Marine Sewage Outfalls. *S. Afr. J. Sci.* **2017**, *113* (11/12), 10.

(7) De Bruin, L. What's that in Your Drinking Water? Water and Health. *Water Wheel* **2017**, *16* (6), 26−28, DOI: 10.10520/EJC-c16345a12.

(8) Chimuka, L.; Nefale, F.; Masevhe, A. Determination of Phenols in Water Samples Using A Supported Liquid Membrane Extraction Probe and Liquid Chromatography With Photodiode Array Detection. *S. Afr. J. Chem.* **2007**, *60*, 102−108.

(9) Kruger, A.; Pieters, R.; Horn, S.; van Zijl, C.; Aneck-Hahn, N. The Role of Effect-Based Methods to Address Water Quality Monitoring in South Africa: A Developing Country's Struggle. *Environ. Sci. Pollut. Res.* **2022**, *29*, 84049−84055.

(10) Burger, A. E. C. WRC Programme on Endocrine Disrupting Compounds (EDC's)Volume 1 Strategic Research Plan for Endocrine Disrupters in South African Water Systems; WRC Report No. kv 143/05; Water research commission, 2005. https://www.wrc.org.za/wp-content/uploads/mdocs/KV-143-05.pdf (accessed 2023-09-27).

(11) Wang, H.; Jiang, L.; Gu, S.; Wang, X. Migration of Bisphenol A From Polyvinyl Chloride Plastics To Solvents Of Different Polarities And Packaged Food In China. *Packag. Technol. Sci.* **2021**, *34* (2), 127−137.

(12) Awuchi, C. G.; Amagwula, I. O. Environmental Pollutants and Contaminants of Emerging Concern: An African Perspective. *J. Life sci.* **2021**, *2* (3), 39−50.

(13) Ubomba-Jaswa, E.; Kalebaila, N. Framing the Plastic Pollution Problem Within the Water Quality−Health Nexus: Current Understandings and Policy Recommendations. *S. Afr. J. Sci.* **2020**, *116* (5/6), 22−24.

(14) Adeleye, A. P. Perfluorinated Compounds, Bisphenol A And Acetaminophen in Selected Wastewater Treatment Plants in and Around Cape Town, South Africa. MTech Thesis, Cape Peninsula University of Technology, 2016. https://etd.cput.ac.za/bitstream/20.500.11838/2331/1/213281503-Adeleye-AP-Mtech-Chemistry-Appsc-2016.pdf (accessed 2023-09-23).

(15) Yang, O.; Kim, H. L.; Weon, J.-I.; Seo, Y. R. Endocrine-disrupting Chemicals: Review of Toxicological Mechanisms Using Molecular Pathway Analysis. *J. Cancer Prev* **2015**, *20* (1), 12−24.

(16) Erkekoglu, P.; Kocer-Gumusel, B. Environmental Effects of Endocrine-Disrupting Chemicals: A Special Focus on Phthalates and Bisphenol A. In Larramendy, M. L., Soloneski, S., Eds.; *Environmental Health Risk - Hazardous Factors to Living Species*. InTech, 2016. DOI: 10.5772/62455.

(17) Ma, Y.; Liu, M.; Wu, J.; Yuan, L.; Wang, Y.; Du, X.; Wang, R.; Marwa, P. W.; Petlulu, P.; Chen, X.; Zhang, H. The Adverse Health Effects of Bisphenol A and Related Toxicity Mechanisms. *Environ. Res.* **2019**, *176*, No. 108575.

(18) Careghini, A.; Mastorgio, A. F.; Saponaro, S.; Sezenna, E. Bisphenol A, Nonylphenols, Benzophenones, and Benzotriazoles in Soils, Groundwater, Surface Water, Sediments, and Food: A Review. *Environ. Sci. Pollut. Res.* **2015**, *22* (8), 5711−5741.

(19) Canadian Society for Intestinal Research. The Facts behind the Buzz over BPA. https://badgut.org/information-centre/a-z-digestive-topics/the-facts-behind-the-buzz-over-bpa/ (accessed 2024-06-18).

(20) Vogel, S. A. The Politics of Plastics: The Making and Unmaking of Bisphenol a "Safety". *Am. J. Public Health.* **2009**, *99* (Suppl 3), S559−S566.

(21) Swartz, C. D.; Genthe, B.; Chamier, J.; Petrik, I. F.; Tijani, J. O.; Adeleye, A.; Coomans, C. J.; Ohlin, A.; Falk, D.; Menge, J. G. Emerging Contaminants in Wastewater Treated for Direct Potable Re-use: The Human Health Risk Priorities in South Africa. Volume

III: Occurrence, Fate, Removal and Health Risk Assessment of Chemicals of Emerging Concern in Reclaimed Water for Potable Reuse; WRC Report no. tt 742/3/17; Water Research Commission, 2018. https://www.wrc.org.za/wp-content/uploads/mdocs/TT%20742%20Vol%203%20web.pdf.

(22) The BPA Controversy: Can A Plastic Really Make You Sick? https://sitn.hms.harvard.edu/flash/2008/issue47/ (accessed 2024-02-16).

(23) Gore, A. C.; Crews, D.; Doan, L. L.; Merrill, M. L.; Patisaul, H.; Ami Zota, A. Introduction to Endocrine Disrupting Chemicals (EDC): A Guide for Public Interest Organizations and Policymakers. 2014. Endocrine Society, *76*, https://www.endocrine.org/-/media/endosociety/files/advocacy-and-outreach/important-documents/introduction-to-endocrine-disrupting-chemicals.pdf.

(24) Ellis, J.; Papaluca, A.; Hamtiaux, M.; Hales, B. F.; Robaire. A Case Study of Canadian Regulation of BPA: Insight Into the Science. *Duke Environ. Law Policy Forum* **2022**, *32*, 295−327. https://scholarship.law.duke.edu/delpf/vol32/iss2/3.

(25) BPA Milk Bottles Banned in Malaysia from March 2012. https://a-p-p-a.org/pdf/bulletin.pdf (accessed 2024-02-16).

(26) Struzina, L. The Presence of Plasticizers, Bisphenols, and Flame Retardants in Potable Water and Their Removal Through Conventional Drinking Water Treatment. MSc. Thesis, McGill University, 2022. https://escholarship.mcgill.ca/concern/theses/c821gq95k (accessed 2023-09-23).

(27) Russo, G.; Laneri, S.; Di Lorenzo, R.; Neri, I.; Dini, I.; Ciampaglia, R.; Grumetto, L. Monitoring of Pollutants Content in Bottled and Tap Drinking Water in Italy. *Mol.* **2022**, *27* (13), 3990.

(28) Corrales, J.; Kristofco, L. A.; Steele, W. B.; Yates, B. S.; Breed, C. S.; Williams, E. S.; Brooks, B. W. Global Assessment of Bisphenol A in the Environment: Review and Analysis of its Occurrence and Bioaccumulation. *DOSE-RESPONSE* **2015**, DOI: 10.1177/1559325815598308.

(29) Ohore, O. E.; Zhang, S. Endocrine Disrupting Effects of Bisphenol A Exposure and Recent Advances on its Removal by Water Treatment Systems. A Review. *scientific-african.* **2019**, *5*, No. e00135.

(30) Olujimi, O. O.; Fatoki, O. S.; Daso, A. P.; Akinsoji, O. S.; Oputu, O. U.; Oluwafemi, O. S.; Songca, S. P. Levels of Nonylphenol and Bisphenol A in Wastewater Treatment Plant Effluent, Sewage Sludge and Leachate from Cape Town, South Africa. In *Handbook of Wastewater Treatment: Biological Methods, Technology, and Environmental Impact*; Valdez, C. J., Maradona, E. M., Ed.; 2013. .

(31) Department of Health. Foodstuffs, Cosmetics and Disinfectants Act: Regulations: Prohibition of Manufacturing, Importation, Exportation and Sale of Polycarbonate Infant Feeding Bottles Containing Bisphenol A (No. R. 879 of 2011). Department of Health 2011. https://faolex.fao.org/docs/pdf/saf108195.pdf accessed 20/06/2024.

(32) Du Preez, M.; Van der Merwe, D.; Wyma, L.; Ellis, S. M. Assessing Knowledge and Use Practices of Plastic Food Packaging among Young Adults in South Africa: Concerns about Chemicals and Health. *Int. J. Environ. Res. Public Health* **2021**, *18*, 10576.

(33) Aneck-Hahn, N. H.; Van Zijl, M. C.; Swart, P.; Truebody, B.; Genthe, B.; Charmier, J.; Jager, C. Estrogenic Activity, Selected Plasticizers and Potential Health Risks Associated with Bottled Water in South Africa. *J. Water Health* **2018**, *16* (2), 253−262.

(34) de Jager, C.; Aneck-Hahn, N.; Van Zijl, M.; Hayward, S.; Swart, P.; Genthe, B. Endocrine Disrupting Chemicals in Commercially Available Cling Film Brands in South Africa, Human and Ecological Risk Assessment. *An Int. J.* **2019**, *25* (6), DOI: 10.1080/10807039.2018.1471659.

(35) World Integrated Trade Solution (WITS). (2018). https://wits.worldbank.org/trade/comtrade/en/country/ZAF/year/2018/tradeflow/Imports/partner/ALL/product/290723. Accessed 29-06-2024.

(36) Ubomba-Jaswa, E.; Kalebaila, N. Framing the Plastic Pollution Problem Within the Water Quality−Health Nexus: Current Understandings and Policy Recommendations. *S. Afr. J. Sci.* **2020**, *116* (5/6), 3.

(37) Trade and Industrial Policy Strategies. Manufacturing Subsectors Other chemicals, Rubber, and Plastics. March 2021. https://www.tips.org.za/images/Manufacturing_subsectors_other_chemicals_rubber_and_plastics.pdf accessed 20/06/2024.

(38) Heinälä, M.; Ylinen, K.; Tuomi, T.; Santonen, T.; Porras, S. P. Assessment of Occupational Exposure to Bisphenol A in Five Different Production Companies in Finland. *Ann. Work Expo. Health.* **2017**, *61* (1), 44−55.

(39) Ribeiro, E.; Ladeira, C.; Viegas, S. Occupational Exposure to Bisphenol A (BPA): A Reality That Still Needs to be Unveiled. *Toxics* **2017**, *5* (3), 22.

(40) Meeker, J. D. Exposure to Environmental Endocrine Disruptors and Child Development. *Arch. Pediatr. Adolesc. Med..* **2012**, *166* (10), 952−958.

(41) Zaborowska, M.; Wyszkowska, J.; Borowik, A.; Kucharski, J. Bisphenols—A Threat to the Natural Environment. *Materials* **2023**, *16* (19), 6500.

(42) Mhuka, I.; Dube, S.; Nindi, M. M. Occurrence of Pharmaceutical and Personal Care Products (PPCPs) in Wastewater and Receiving Waters in South Africa using LC-Orbitrap MS. *Emerg. Contam.* **2020**, *6*, 250−258.

(43) Gani, K. M.; Hlongwa, N.; Abunama, T.; Kumari, S.; Bux, F. Emerging Contaminants in South African Water Environment- A Critical Review of their Occurrence, Sources and Ecotoxicological Risks. *Chemosphere* **2021**, *269*, No. 128737.

(44) Hiller-Sturmhöfel, S.; Bartke, A. The Endocrine System: An Overview. *Alcohol Health Res. World.* **1998**, *22* (3), 153−164. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6761896/pdf/arh-22-3-153.pdf.

(45) Cimmino, I.; Fiory, F.; Perruolo, G.; Miele, C.; Beguinot, F.; Formisano, P.; Oriente, F. Potential Mechanisms of Bisphenol A (BPA) Contributing to Human Disease. *Int. J. Mol. Sci.* **2020**, *21* (16), 5761.

(46) Fujiwara, Y.; Miyazaki, W.; Koibuchi, N.; Katoh, T. (2018). The Effects of Low-Dose Bisphenol A and Bisphenol F on Neural Differentiation of a Fetal Brain-Derived Neural Progenitor Cell Line. *Front. Endocrinol.* **2018**, *9*, DOI: 10.3389/fendo.2018.00024.

(47) Chouhan, S.; Yadav, S. K.; Prakash, J.; Sing, S. P. Effect of Bisphenol A on Human Health and its Degradation by Microorganisms: A review. *Ann. Microbiol.* **2014**, *64*, 13−21.

(48) Genthe, B.; Steyn, M. Health Risk Assessment Protocol for Endocrine Disrupting Chemicals; WRC Project No KV 206/08 ; Report to the Water Research Commission by B Genthe and M Steyn, CSIR, Natural Resources and the Environment Stellenbosch. https://www.wrc.org.za/wp-content/uploads/mdocs/KV-206-08.pdf (accessed 2023-09-27).

(49) Van Zijl, M. C.; Aneck-Hahn, N. H.; Swart, P.; Hayward, S.; Genthe, B.; De Jager, C. Estrogenic Activity, Chemical Levels and Health Risk Assessment of Municipal Distribution Point Water from Pretoria and Cape Town, South Africa. *Chemosphere* **2017**, *186*, 305−313.

(50) Zheng, C.; Liu, J.; Ren, J.; Shen, J.; Fan, J.; Xi, R.; Chen, W.; Chen, Q. Occurrence, Distribution and Ecological Risk of Bisphenol Analogues in the Surface Water from a Water Diversion Project in Nanjing, China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3296.

(51) Teixeira, L. C. G. M.; das Chaves, J. R.; Mendonça, N.; Sanson, A. L.; Alves, M. C. P.; Afonso, R. J. C. F.; Aquino, S. F. Occurrence and Removal of Drugs and Endocrine Disruptors in the Bolonha Water Treatment Plant in Belém/PA (Brazil). *Environ. Monit. Assess.* **2021**, *193* (5), 246.

(52) Santos, J. M.; Putt, D. A.; Jurban, M.; Joiakim, A.; Friedrich, K.; Kim, H. Differential BPA levels in Sewage Wastewater Effluents from Metro Detroit Communities. *Environ. Monit. Assess.* **2016**, *188* (10), 585.

(53) FDA Regulations on Bisphenol A (BPA) 2023. Use in Food Contact Application. https://www.fda.gov/food/food-additives-petitions/bisphenol-bpa-use-food-contact-application#regulations (accessed 28/07/2024).

(54) Food Safety New (FSN), (2010). https://www.foodsafetynews.com/2010/09/canada-first-to-list-bpa-as-toxic/#google_vignette (accessed 28/072024).

(55) Health Canada (2014). Bisphenol A: Update on the Food Directorate's Risk Management Commitments for Infant Formula. https://www.canada.ca/en/health-canada/services/food-nutrition/food-safety/packaging-materials/bisphenol/update-food-directorate-risk-management-commitments-infant-formula.html (accessed 28/07/2024).

(56) ECHA (2018). Use of bisphenol A and its alternatives in thermal paper in the EU from 2014 to 2017. https://echa.europa.eu/documents/10162/22863068/bpa_in_thermal_paper_report_en.pdf/0d93cd76-345e-2ed4-698f-a3beaea6d755 (accessed 28/07/2024).

(57) SGS (2011). China bans BPA in infant feeding bottles. https://newsletter.sgs.com/eNewsletterPro/uploadedimages/000006/SGS-Safeguards-10311-China-bans-BPA-in-infant-feeding-bottles-A4-EN-11.pdf (accessed 28/07/2024).

(58) AIST (National Institute of Advanced Industrial Science and Technology, Japan) (2007). "Bisphenol A Risk Assessment Document (AIST Risk Assessment Document Series No. 4)." https://unit.aist.go.jp/riss/crm/mainmenu/BPA_Summary_English.pdf (accessed on 28/07/2024).

(59) FSANZ (Food Standards Australia New Zealand) (2010). "Bisphenol A (BPA)." Available at: https://www.foodstandards.gov.au/consumer/chemicals/bpa (accessed 28/07/2024).

(60) National Health Surveillance Agency - Anvisa. Bisphenol A. https://www.gov.br/anvisa/pt-br/setorregulado/regularizacao/alimentos/bisfenol-a. (accessed 28/07/2024).

(61) CANSA (Cancer Association of South Africa), 2011. Fact Sheet on Bisphenol A. https://cansa.org.za/files/2011/11/BPA-Fact-Sheet-Oct2011.pdf (accessed 28/07/2024).

(62) Environment Protection and Heritage Council, National Health and Medical Research Council, Natural Resource Management Ministerial Council. Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) - Augmentation of Drinking Water Supplies. Water Quality Australia. 2008, https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-augmentation-drinking-22.pdf (accessed 2023-09-23).

(63) Minnesota Department of Health. Bisphenol A in Drinking Water: Environmental Health Division. Environmental Health Division, 2014 https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/bpainfosheet.pdf (accessed 2023-09-27).

(64) European Union. Directive (Eu) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the Quality of Water Intended for Human Consumption. European Union, 2020. https://faolex.fao.org/docs/pdf/eur201243.pdf (accessed 2023-09-28).

(65) Tian, L.; Zheng, J.; Pineda, M.; Yargeau, V.; Furlong, D.; Chevrier, J.; Bornman, R.; Obida, M.; Goodyer, C. G.; Bayen, S. Targeted Screening of 11 Bisphenols and 7 Plasticizers in Food Composites from Canada and South Africa. *Food Chem.* **2022**, *385*, No. 132675.

(66) Mahomed, S. I.; Voyi, K. V. V.; Aneck-Hahn, N. H.; de Jager, C. Oestrogenicity and Chemical Target Analysis of Water from Small-Sized Industries in Pretoria, South Africa. *Water SA*, **2008**, *34* (3), https://journals.co.za/doi/pdf/10.10520/EJC116533 (accessed 2023-09-27).

(67) de Jager, C.; Aneck-Hahn, N. H.; Swart, P.; Truebody, B.; Van Zijl, M. C. Estrogenic Activity and Endocrine Disrupting Chemical (EDC) Status in Water Obtained from Selected Distribution Points in Pretoria and Cape Town; WRC Report No. KV 317/13, ; 2013. https://www.wrc.org.za/wp-content/uploads/mdocs/KV%20317-13.pdf (accessed 2023-09-27).

(68) Olorundare, O. F.; Msagati, T. A.; Krause, R. W.; Okonkwo, J. O.; Mamba, B. B. Preparation and use of Maize Tassels' Activated Carbon for the Adsorption of Phenolic Compounds in Environmental Wastewater Samples. *Environ. Sci. Pollut.* **2015**, *22* (8), 5780−5792.

(69) Archer, E.; Petrie, B.; Kasprzyk-Hordern, B.; Wolfaardt, G. M. The Fate of Pharmaceuticals and Personal Care Products (ppcps), Endocrine Disrupting Contaminants (EDC), Metabolites and Illicit Drugs in A WWTW and Environmental Waters. *Chemosphere* **2017**, *174*, 437−446.

(70) Wanda, E. M. M.; Nyoni, H.; Mamba, B. B.; Msagati, T. A. M. a. Occurrence of Emerging Micropollutants in Water Systems in Gauteng, Mpumalanga, and North West Provinces, South Africa. *Int. J. Environ. Res. Public Health* **2017**, *14* (1), 79.

(71) Wooding, M.; Rohwer, E. R.; Naudé, Y. Determination of Endocrine Disrupting Chemicals and antiretroviral compounds in surface water: A disposable sorptive sampler with comprehensive gas chromatography - Time-of-flight mass spectrometry and large volume injection with ultra-high performance liquid chromatography-tandem mass spectrometry. *J. Chromatogr. A* **2017**, *1496*, 122−132.

(72) Wanda, E. M. M.; Nyoni, H.; Mamba, B. B.; Msagati, T. A. M. Application of Silica and Germanium Dioxide Nanoparticles/Polyethersulfone Blend Membranes for Removal of Emerging Micropollutants from Water. *Phys. Chem. Earth A/B/C* **2018**, *108*, 28−47.

(73) Adoons, M. Water Quality of the Fonteinspruit Stream on the Outskirts of Bloemfontein, Free State, South Africa. MSc Dissertation, Central University of Technology, Free State BLOEMFONTEIN, 2020. http://ir.cut.ac.za/bitstream/handle/11462/2332/Adoons,%20Mongezi.pdf?sequence=1 (accessed 2023-09-23).

(74) Ligavha-Mbelengwa, L.; Madzivire, G.; Nolakana, P.; Coetzee, H.; Gomo, M. Potential Use of Emerging Organic Contaminants as Pollution Source Tracers. IMWA 2022 − "Reconnect". Proceedings of International Mine Water Association, Chrustchurch, New Zealand 2022; Pope, J.; Wolkersdorfer, C.; Rait, R.; Trumm, D.; Christenson, H.; Wolkersdorfer, K.; Eds. Pp 223−228; https://www.imwa.info/docs/imwa_2022/IMWA2022_Ligavha-Mbelengwa_223.pdf.

(75) Archer, E.; Holton, E.; Fidal, J.; Kasprzyk-Hordern, B.; Carstens, A.; Brocker, L.; Kjeldsen, T. R.; Wolfaardt, G. M. Occurrence of Contaminants of Emerging Concern in the Eerste River, South Africa: Towards the Optimisation of an Urban Water Profiling Approach for Public- and Ecological Health Risk Characterization. *Sci. Total Environ.* **2023**, *859* (Part 1), No. 160254.

(76) Dotan, P.; Godinger, T.; Odeh, W.; Groisman, L.; Al-Khateeb, N.; Rabbo, A. A.; Tal, A.; Arnon, S. Occurrence and Fate of Endocrine Disrupting Compounds in Wastewater Treatment Plants in Israel and the Palestinian West Bank. *Chemosphere.* **2016**, *155*, 86−93.

(77) Department of Water Affairs. Municipal Wastewater Treatment Base Information for Targeted Risk − Based Regulation. Department of Water Affairs, 2009. https://www.humansettlements.fs.gov.za/wp-content/uploads/2012/07/Municipal-Wastewater-Treatment-Status-July-2009.pdf (accessed 2023-09-27).

(78) Olujimi, O. O.; Fatoki, O. S.; Odendaal, J. P.; Okonkwo, J. O. Endocrine Disrupting Chemicals (Phenol and Phthalates) in the South African Environment: A Need for More Monitoring. *Water SA* **2010**, *36* (5), 671−682. http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1816-79502010000500017&lng=en&tlng=en.

(79) Dueñas-Moreno, J.; Mora, A.; Cervantes-Avilés, P.; Mahlknecht, J. Groundwater Contamination Pathways of Phthalates and Bisphenol A: Origin, Characteristics, Transport, and Fate − A Review. *Environ. Int.* **2022**, *170*, No. 107550.

(80) Gumbo, J. R.; Malaka, E. M.; Odiyo, J. O.; Nare, L. The Health Implications of Wastewater Reuse in Vegetable Irrigation: A Case Study from Malamulele, South Africa. *Int. J. Environ. Health Res.* **2010**, *20* (3), 201−11.

(81) Mora, A.; Torres-Martínez, J. A.; Capparelli, M. V.; Zabala, A.; Mahlknecht, J. Effects of Wastewater Irrigation on Groundwater Quality: An Overview. *Curr. Opin. Environ. Sci. Health.* **2022**, *25*, No. 100322.

(82) South African National Bottled Water. Bottled Water Bottles Do Not Contain BPA, Are Reusable. https://www.sanbwa.org.za/

bottled-water-bottles-do-not-contain-bpa-are-reusable.html (accessed 2023-09-27).

(83) Ginter-Kramarczyk, D.; Zembrzuska, J.; Kruszelnicka, I.; Zając-Woźnialis, A.; Ciślak, M. Influence of Temperature on the Quantity of Bisphenol A in Bottled Drinking Water. *Int. J. Environ. Res. Public Health.* **2022**, *19* (9), 5710.

(84) What is Bottled Water, and what is not? https://www.sanbwa.org.za/categories-of-bottled-water.html (accessed 12/09/2024).

(85) Momba, M. N. B.; Obi, C. L.; Thompson, P. Survey of disinfection efficiency of small drinking water treatment plants: challenges facing small water treatment plants in South Africa. *Water SA* **2009**, *35* (4), 485−493. http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1816-79502009000400014&lng=en&tlng=en.

(86) Bottled Water South Africa. https://www.statista.com/outlook/cmo/non-alcoholic-drinks/bottled-water/south-africa (accessed 2023-09-27).

(87) Ojemaye, C. Y.; Pampanin, D. M.; Sydnes, M. O.; Green, L.; Petrik, L. The Burden of Emerging Contaminants Upon an Atlantic Ocean Marine Protected Reserve Adjacent to Camps Bay, Cape Town, South Africa. *Heliyon* **2022**, *8* (12), No. e12625.

(88) Karalius, V. P.; Harbison, J. E.; Plange-Rhule, J.; van Breemen, R. B.; Li, B.; Huang, K.; Durazo-Arvizu, R. A.; Mora, N.; Dugas, L. R.; Vail, L.; Tuchman, N. C.; Forrester, T.; Luke, A. Bisphenol A (BPA) Found in Humans and Water in Three Geographic Regions with Distinctly Different Levels of Economic Development. *Environ. Health Insights.* **2014**, *8*, 1−3.

(89) Edokpayi, J. N.; Enitan, A. M.; Mutileni, N.; Odiyo, J. O. Evaluation of Water Quality and Human Risk Assessment Due to Heavy Metals in Groundwater Around Muledane Area of Vhembe District, Limpopo Province, South Africa. *Chem. Cent. J.* **2018**, *12* (1), 2.

(90) Musvoto, E.; Mgwenya, N.; Mangashena, H.; Mackintosh, A. Energy Recovery from Wastewater Sludge − A Review of Appropriate Emerging and Established Technologies for the South African Industry; WRC Report No. TT 752/18; Report to the Water Research Commission, 2018. https://www.wrc.org.za/wp-content/uploads/mdocs/TT%20752-18.pdf (accessed 2023-09-28).

(91) Katibi, K. K.; Yunos, K. F.; Man, H. C.; Aris, A. Z.; Mohd; Nor, M. Z.; Azis, R. S. An Insight into a Sustainable Removal of Bisphenol A from Aqueous Solution by Novel Palm Kernel Shell Magnetically Induced Biochar: Synthesis, Characterization, Kinetic, and Thermodynamic Studies. *Polymers (Basel).* **2021**, *13* (21), 3781.

(92) Adesina, M. O.; Block, I.; Günter, C.; Unuabonah, E. I.; Taubert, A. Efficient Removal of Tetracycline and Bisphenol A from Water with a New Hybrid Clay/TiO_2 Composite. *ACS Omega.* **2023**, *8* (24), 21594−21604.

(93) Dura, A. M.; Stefan, D. S.; Chiriac, F. L.; Trusca, R.; Nicoara, A. I.; Stefan, M. Clinoptilolite—A Sustainable Material for the Removal of Bisphenol A from Water. *Sustainability* **2023**, *15*, 13253.

(94) Chatir, E. M.; El Hadrami, A.; Ojala, S.; El Mouhri, G.; Brahmi, R. Removal of chromium (VI) and bisphenol A from water using a novel spoilt milk-derived adsorbent: material characterisation and adsorption mechanisms. *Int.J. Environ. Anal. Chem.* **2023**, 1−20.

(95) Lingamdinne, L. P.; Angaru, G. K. R.; Pal, C. A.; Koduru, J. R.; Karri, R. R.; Mubarak, N. M.; Chang, Y. Y. Insights into Kinetics, Thermodynamics, and Mechanisms of Chemically Activated Sunflower Stem Biochar for Removal of Phenol and Bisphenol-A from Wastewater. *Sci. Rep.* **2024**, *14* (1), 4267.

(96) Stojanović, S.; Rac, V.; Mojsilović, K.; Vasilić, R.; Marković, S.; Damjanović-Vasilić, L. Photocatalytic Degradation of Bisphenol A in Aqueous Solution using TiO_2/clinoptilolite Hybrid Photocatalyst. *Environ. Sci. Pollut. Res. Int.* **2023**, *30* (35), 84046−84060.

(97) Aiyelabegan, T. D.; Shafie, S. N. A.; Hizam, S. M.; Nordin, N. A. H. The Removal of Bisphenol-A from Synthetic Wastewater Using Thin-Film Composite Membrane. *MJAS* **2022**, *26* (3), 507−519.

(98) Sun, J.; Jiang, X.; Zhou, Y.; Fan, J.; Zeng, G. Microfiltration Membranes for the Removal of Bisphenol A from Aqueous Solution: Adsorption Behavior and Mechanism. *Water* **2022**, *14*, 2306.

(99) Frankowski, R.; Zgoła-Grześkowiak, A.; Smułek, W.; Grześkowiak, T. Removal of Bisphenol A and Its Potential Substitutes by Biodegradation. *Appl. Biochem. Biotechnol.* **2020**, *191* (3), 1100−1110.

(100) Wang, S.; Wu, Q.; Yan, B.; Guo, Y.; Xia, W.; Li, J.; Cui, F.; Tian, J. A Novel Integrated Process of Ceramic Membrane Filtration Coupled with Peroxymonosulfate Activation and Adsorption for Water Treatment. *Sep. Purif. Technol.* **2022**, *291*, 120874.

(101) Tijani, J. O.; Mouele, M. E. S.; Fatoba, J. O.; Babajide, O. O.; Petrik, L. F. Degradation of Bisphenol-A by Dielectric Barrier Discharge System: Influence of Polyethylene Glycol Stabilized Nano Zero Valent Iron Particles. *Adv. Nat. Sci.: Nanosci. Nanotechnol.* **2017**, *8*, No. 035013.

(102) Sambaza, S.; Maity, A.; Pillay, K. Enhanced Degradation of BPA in Water by PANI Supported Ag/TiO_2 Nanocomposite Under UV and Visible Light. *Journal of Environmental Chemical Engineering* **2019**, *7* (1), 102880.

(103) Sambaza, S. S.; Maity, A.; Pillay, K. Polyaniline-Coated TiO_2 Nanorods for Photocatalytic Degradation of Bisphenol A in Water. *ACS Omega.* **2020**, *5* (46), 29642−29656.

(104) Mafa, P. J.; Malefane, M. E.; Opoku, F.; Mamba, B. B.; Kuvarega, A. T. Visible light Responsive MoS_2/Ag@WO_3/EG Photoanode with Highly Stable Z-Scheme Induced Circular Electron Motion Pioneered by Exfoliated Graphite for Bisphenol a Photoelectrodegradation. *Chem. Eng. J.* **2023**, *464*, No. 142462.

(105) Ama, O. M.; Khoele, K.; Ray, S. S. TiO_2/Ag_2O-Exfoliated Graphite as Visible Light-Responsive Nanostructure for Improved Photoelectrochemical Degradation of BPA. *Int. J. Nanosci. Nanotechnol.* **2021**, *17* (1), 1−10. https://www.ijnnonline.net/article_242798.html.

(106) Umejuru, E. C.; Prabakaran, E.; Pillay, K. Coal Fly Ash Decorated with Graphene and Polyaniline Nanocomposites for Effective Adsorption of Hexavalent Chromium and Its Reuse for Photocatalysis. *ACS Omega.* **2023**, *8* (20), 17523−17537.

(107) Kruid, J.; Fogel, R.; Limson, J. Unsubstituted Metallophthalocyanine Catalysts for the Removal of Endocrine Disrupting Compounds Using H_2O_2 as Oxidant. *Environ. Sci. Pollut. Res.* **2018**, *25* (32), 32346−32357.

(108) Wanda, E. M. M.; Mamba, B. B.; Msagati, T. A. M. Nitrogen-Doped Carbon Nanotubes/Polyethersulfone Blend Membranes for Removing Emerging Micropollutants. *Clean − Soil, Air, Water* **2017**, *45* (4), No. 1500889.

(109) Koloti, L. E.; Gule, N. P.; Arotiba, O. A.; Malinga, S. P. Laccase-immobilized Dendritic Nanofibrous Membranes as a Novel Approach Towards the Removal of Bisphenol A. *Environ. Technol.* **2018**, *39* (3), 392−404.

(110) Rovani, S.; Santos, J. J.; Guilhen, S. N.; Corio, P.; Fungaro, D. A. Fast, Efficient and Clean Adsorption of Bisphenol-A Using Renewable Mesoporous Silica Nanoparticles from Sugarcane Waste Ash. *RSC Adv.* **2020**, *10* (46), 27706−27712.

(111) de Farias, M. B.; Silva, M. G. C.; Vieira, M. G. A. Adsorption of Bisphenol A from Aqueous Solution onto Organoclay: Experimental Design, Kinetic, Equilibrium and Thermodynamic Study. *Powder Technol.* **2022**, *395*, 695−707.

(112) Lazim, Z. M.; Salmiati; Hadibarata, T.; Yusop, Z.; Nazifa, T. H.; Abdullah, N. H.; Nuid, M.; Salim, N. A. B.; Zainuddin, N. A.; Ahmad, N. Bisphenol A Removal by Adsorption Using Waste Biomass: Isotherm and Kinetic Studies. *Biointerface Res. Appl. Chem.* **2021**, *11* (1), 8467−8481.

(113) Wang, F.; Zeng, Q.; Su, W.; Zhang, M.; Hou, L.; Wang, Z. L. Adsorption of Bisphenol A on Peanut Shell Biochars: The Effects of Surfactants. *J. Chem.* **2019**, *2019*, 2428505.

(114) Mphahlele, K.; Onyango, M. S.; Mhlanga, S. D. Kinetics, Equilibrium, and Thermodynamics of the Sorption of Bisphenol A onto N-CNTs-β-Cyclodextrin and Fe/N-CNTs-β-Cyclodextrin Nanocomposites. *J. Nanomater.* **2015**, *2015*, 214327.

(115) Orimolade, B. O.; Adekola, F. A.; Mohammed, A. A.; Idris, A. O.; Saliu, O. D.; Yusuf, T. Removal of Bisphenol-A from Aqueous Solution Using Rice Husk Nanosilica: Adsorption Kinetics,

Equilibrium and Thermodynamic Studies. *J. Appl.. Chem. Res.* **2018**, *12* (3), 8−21. https://jacr.karaj.iau.ir/article_540396_92b25525fe35264b365b5d503d035ba8.pdf.

(116) Hlekelele, L.; Nomadolo, N. E.; Setshedi, K. Z.; Mofokeng, L. E.; Chettya, A.; Chauke, V. P. Synthesis and Characterization of Polyaniline, Polypyrrole and Zero-Valent Iron-Based Materials for the Adsorptive and Oxidative Removal of Bisphenol-A from Aqueous Solution. *RSC Adv.* **2019**, *9*, 14531−14543.

(117) Rochester, J. R.; Bolden, A. L. Bisphenol S and F: A Systematic Review and Comparison of the Hormonal Activity of Bisphenol A Substitutes. *Environ. Health Perspect.* **2015**, *123* (7), 643−650.

(118) Rotimi, O. A.; Olawole, T. D.; De Campos, O. C.; Adelani, I. B.; Rotimi, S. O. Bisphenol A in Africa: A review of environmental and biological levels. *Sci. Total Environ.* **2021**, *764*, No. 142854.