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Review

Clearing the path: Unraveling bisphenol a removal and degradation mechanisms for a cleaner future

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ABSTRACT

Bisphenol A (BPA) is a prevalent chemical found in a range of consumer goods, which has raised worries about its possible health hazards. Comprehending the breakdown pathways of BPA is essential for evaluating its environmental consequences and addressing associated concerns. This review emphasizes the significance of studying the degradation/removal of BPA, with a specific focus on both natural and artificial routes. It explores natural processes such as photolysis, hydrolysis, and biodegradation, as well as manmade methods including advanced oxidation processes (AOPs) and enzymatic degradation. Examining the decomposition of BPA helps to understand how it behaves in the environment, providing valuable information for managing risks and addressing pollution. Furthermore, comprehending degradation mechanisms aids in the creation of more secure substitutes and regulatory actions to reduce BPA exposure and safeguard human health. This review emphasizes the need of promptly addressing this environmental and public health concern through the research of BPA degradation.

1. Introduction

Bisphenol A (BPA) is a chemical compound commonly utilized (over 95%) in the production of polycarbonate plastics and epoxy resins, prevalent in various consumer products such as food containers, beverage cans, and thermal paper receipts (Liu et al., 2021). BPA is primarily utilized in manufacturing polycarbonate plastics and epoxy resins, constituting 65% and 30% of total BPA production. Additionally, it finds application in thermal paper, sulfides and pesticides, leather tanning agents, dye dispersants, fiber additives, medical devices, and electronic products (Huelsmann et al., 2021). The estimated size of the Bisphenol A Market in 2024 is 7.96 million tons, with a projected growth to reach 10.76 million tons by 2029 in Asia Pacific, North America, Europe, and South America. This growth is anticipated to occur at a compound annual growth rate (CAGR) of 6.23% during the forecast period of 2024–2029 (www.mordorintelligence.com). Despite its widespread industrial applications, concerns have emerged regarding the potential adverse health effects associated with environmental BPA exposure (Catenza et al., 2021; Ramakrishna et al., 2021; Tarafdar et al., 2022; Manzoor et al., 2022; Xing et al., 2022). BPA and its derivatives are prevalent in aquatic environments, significantly influencing aquatic ecosystems. Research has linked BPA to various health risks, including disruptions to hormone function (Shamhari et al., 2021; Miyagawa et al., 2021; Wang et al., 2021a,b; Rubin and Seebacher, 2022; Guo et al., 2023; Xue et al., 2024), reproductive abnormalities (Biswas et al., 2020; den Braver-Sewradj et al., 2020; Pivonello et al., 2020; Reis et al., 2022), and developmental issues (Gyimah et al., 2021; Sabry et al., 2021; Ji et al., 2022; Huang et al., 2023; Wang et al., 2023; Lee et al., 2024), prompting increased scrutiny and calls for regulatory action.

In 2015, the European Food Safety Authority (EFSA) set a temporary tolerated daily intake (t-TDI) of 4 μg/kg body weight (bw) per day for BPA. In 2016, the European Commission ordered the EFSA to reassess the potential hazards to public health arising from including BPA in food products and to determine a TDI (EFSA Panel on Food Contact MaterialsEnzymesFlavourings and Processing Aids, 2015). Given these circumstances, the CEP Panel determined that an extra uncertainty factor (UF) of 2 was required to establish the TDI. The TDI of 0.2 ng BPA/kg bw per day was calculated by applying an overall UF of 50 to the reference point (RP). Upon comparing the TDI with the dietary exposure estimates provided in the 2015 EFSA opinion, it was seen that both the average and 95th percentile dietary exposures across all age groups surpassed the TDI by a factor of two to three (EFSA Panel on Food Contact

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MaterialsEnzymesFlavourings and Processing Aids, 2023).

Understanding the degradation pathways and fate of BPA is crucial in comprehending its environmental impact and mitigating potential risks to human health and ecosystems. The degradation of BPA can occur through various processes, both natural and engineered, which break down the compound into less harmful substances (Umar et al., 2013; Chouhan et al., 2014; Pahigian and Zuo, 2018; Reddy et al., 2018; Ohore and Zhang, 2019; Godiya and Park, 2022). Natural degradation mechanisms include photolysis, hydrolysis, and biodegradation, while engineered methods such as advanced oxidation processes (AOPs) and enzymatic degradation offer promising strategies for BPA remediation. For this analysis, we employed VOSviewer software (version 1.6.20) to visually represent the body of literature on the degradation of BPA over the past four decades. This approach allows us to identify patterns and areas of emphasis in research within this domain (Fig. 1).

Investigating the degradation of BPA holds significant importance for several reasons. Firstly, it aids in assessing the environmental fate of BPA and its potential to accumulate in ecosystems, thereby informing risk assessment and management strategies. Secondly, understanding degradation pathways enables the development of effective remediation technologies for contaminated sites, contributing to environmental restoration efforts. Furthermore, elucidating BPA degradation mechanisms supports the design of safer alternatives and regulatory measures to reduce BPA exposure and safeguard public health.

In this context, this review article explores the degradation pathways of BPA, highlighting the importance of studying its fate and environmental behaviour, including the knowledge gaps across the studies. By examining the current knowledge on BPA degradation, we aim to underscore the significance of addressing this pressing environmental and public health concern.

2. Removal using physicochemical methods

Adsorption is widely recognized as an economical method for removing BPA, and it is one of several adsorbents that have been studied for this purpose (Zhou et al., 2020). This technique is regarded by the USEPA (U.S. Environmental Protection Agency) as the utilization of non-destructive physicochemical methods has proven to be highly efficient in removing organic and inorganic contaminants during wastewater treatment. (Kargi and Pamukoglu, 2004; Rivera-Utrilla et al., 2012). Adsorbents' high efficiency has gotten much attention because of their economic viability. The effectiveness of adsorption is closely linked to its capacity for adsorption (Liang et al., 2015). Carbon-based adsorbents such as activated carbon, carbon nanotubes, and graphene are widely used due to their stability, mechanical properties, and large surface areas, according to Alhokbany et al. (2020). The notable characteristics of activated carbon are its ample presence of functional groups, capacity to withstand high temperatures, favourable porosity, chemical stability, and significant surface area (Supong et al., 2019).

Activated carbon is one of the most widely used sorbent, processed with oxygen to increase its microporosity and surface area (Kamarudin et al., 2022). The term "activated" refers to the process where charcoal is heated to high temperatures or chemically treated, both of which significantly increase its surface area (Cao et al., 2011). Despite its effectiveness, activated carbon production is energy-intensive, requiring additional heat and processing. In contrast, biochar has emerged as a more cost-effective alternative, offering comparable adsorptive capabilities (Tan et al., 2017; Kamarudin et al., 2022). Biochar is a carbon-rich material commonly produced through the thermal degradation (350–800 °C) of waste biomass (organic matter from plants) viz., wood, crop residues, manure, leaves, and municipal waste under low-oxygen environments (Inyang and Dickenson, 2015; Qiu et al., 2022). Biochar production generally demands lower energy input compared to activated carbon, resulting in reduced overall energy consumption and lower production costs. This makes biochar an attractive option for sustainable contaminant removal in water and soil treatment (Qiu et al., 2022).). In recent years, the application of biochar and activated carbon, has gained attention for removing both trace organic and inorganic contaminant from wastewater (Mohan et al., 2014; Huggins et al., 2016; Lefèvre et al., 2018).

2.1. Removal using activated carbon

Activated carbon is recognized as a highly effective adsorbent for water treatment, mainly due to its enormous surface area, distinctive surface chemistry, and chemical composition (Rivera-Utrilla et al., 2012; Méndez-Díaz et al., 2010). One key factor that influences the adsorption process is the pH level of the solution. The pH controls the chemical form of ionizable chemicals and affects the surface chemistry and charge of the activated carbon (Rivera-Utrilla et al., 2009). Researchers have prepared various types of activated carbon in the laboratory, each with unique characteristics tailored for specific applications. This diversity in preparation methods and resulting properties highlights the versatility and adaptability of activated carbon in different water treatment contexts.

In a study by Bautista-Toledo et al. (2005), the adsorption capacity of the carbons (Xm) and their relative adsorbent-adsorbate affinity (BXm) were determined from the isotherms using Langmuir's equation. Three types of carbon-carbon S (129.6 mg/g), carbon A (188.9 mg/g), and carbon M (263.1 mg/g) showed a relatively high capacity to adsorb BPA. This is due to the textural and chemical characteristics of these carbons and the hydrophobic nature of BPA. The adsorption capacity (Xm and X'm) and the relative affinity of the carbons increased in the order: carbon S < carbon A < carbon M. In all three systems, adsorption was maximal at acidic or mildly basic pH values. However, beyond a certain pH, the amount adsorbed decreased with rising pH. This behavior can be explained by the net surface charge of the carbon and the BPA species at different pH values. BPA is found in its molecular form at pH values below 8, and deprotonation to bisphenolate monoanion occurs significantly around pH 8. Therefore, the reduction in adsorption capacity at very basic pH values is partly due to repulsive electrostatic interactions between the negatively charged carbon surface and the bisphenolate anion. Activated carbon samples become more hydrophobic with a reduction in mineral matter (such as metallic ions, especially calcium, sulfate, and phosphate ions), resulting in increased BPA adsorption. The BPA adsorption was greater in the presence of an electrolyte. The presence of NaCl in solution causes a salting-out effect, decreasing the solubility of BPA and thereby enhancing its adsorption on the activated carbons. This effect contributes to the increased adsorption capacity observed when NaCl is present.

Martín-Lara et al. (2020) showed good adsorptive behavior of AC-40 (commercially available activated carbon) for BPA removal in batch systems in single- and binary-solute adsorption. The maximum adsorption capacity of AC-40 was close to 90 mg/g pH did not significantly affect the BPA adsorption at low pH values. However, when the acidity of the medium was increased, a slight improvement in the removal efficiencies was observed. In the case of the mixtures of Pb (II) and BPA, the results seemed to indicate that both Pb (II) and BPA can be efficiently removed from wastewater using AC-40 (Martín-Lara et al., 2020). Additionally, Bautista-Toledo et al. (2014) highlighted the effectiveness of activated carbon derived from olive-mill waste. This particular activated carbon exhibited several remarkable attributes, including a substantial surface area of up to 1641 m^2/g, a varied distribution of micropores, and a chemical composition that is particularly effective for the removal of BPA from wastewater. This comparison underscores the versatility and potential of different types of activated carbon in addressing various contaminants in water treatment processes.

Naganathan et al. (2021) conducted a study to assess the efficacy of inexpensive activated carbon derived from coffee residuals in removing BPA. They activated coffee residues using phosphoric acid and iron (III) chloride, then analyzed the textural characteristics, surface chemistry, and surface morphology of the obtained activated carbons. Their

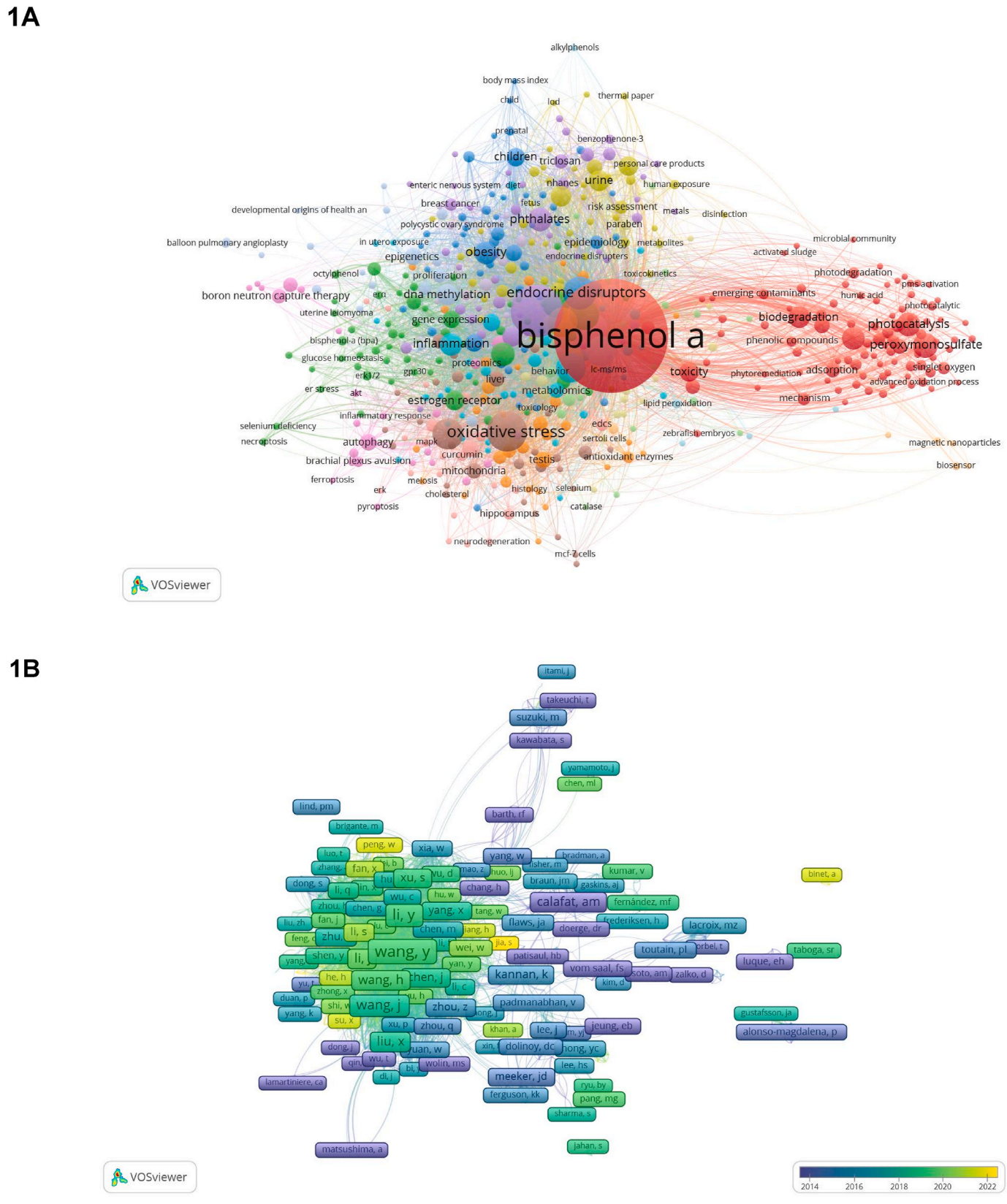

Fig. 1. Network and overlay visualization diagram of BPA Degradation. A. Network visualization of co-occurrence of MeSH keywords for "BPA degradation" and B. Overlay visualization of co-occurrence of authors for "BPA degradation".

findings indicate that AC-CoR I, activated with H_3PO_4, has a significant surface area of 1030 m^2/g and a mesopore size of 2.13 nm, making it well-suited for removing BPA at a concentration of 105 mg/g. The adsorption results aligned well with the pseudo-second-order and Langmuir models, suggesting that coffee residue is a promising precursor for producing activated carbon for wastewater treatment.

In a related study, Gómez-Serrano et al. (2021) used activated carbon made from PET waste activated by KOH at different weight ratios (1:1, 1:3, and 1:5) to adsorb BPA from aqueous solutions. Their data showed that the adsorption of BPA fit better with the Ho and McKay second-order kinetic model compared to the Lagergren first-order kinetic model. Furthermore, the Langmuir equation demonstrated a better fit than the Freundlich equation, indicating that the adsorption process favors these models.

Additionally, Lopez-Ramon et al. (2019) explored the use of activated carbon clothing to adsorb bisphenol A and S in the presence of bacteria, while Wirasnita et al. (2014) treated an aqueous medium with activated carbon derived from empty fruit bunches of oil palm residues to eliminate BPA. The equilibrium data from this study, represented by the Langmuir isotherm, showed a maximum monolayer adsorption capacity of 41.98 mg/g.

Table 1 summarizes the types of activated carbon and their capacities to remove BPA, highlighting the versatility and potential of different activated carbon sources and activation methods in wastewater treatment.

Activated carbon, known for its high surface area and unique surface chemistry, is highly effective in adsorbing contaminants like BPA and BPS from wastewater. Various studies have demonstrated that different forms of activated carbon, such as those derived from almond shells, coffee residue, and PET waste, exhibit significant adsorption capacities. These capacities can be further enhanced by factors such as mineral content and specific surface modifications. However, while activated carbon adsorption is highly efficient, practical challenges for large-scale applications remain. For instance, Bautista-Toledo et al. (2005) found that the presence of hydrophilic mineral matter in the activated carbon reduced its adsorption capacity, highlighting the need for precise control of pH and ionic strength to optimize adsorption conditions. Additionally, the pore texture of the particles can sometimes result in low efficiency of BPA adsorption due to inappropriate π-π dispersion interactions.

Future research could focus on optimizing the chemical properties and surface modifications of activated carbon, including graphene layer density and surface functionalization, to enhance BPA adsorption. Reducing mineral content and tailoring surface functional groups could also improve performance. Furthermore, investigating the effects of various electrolytes and solution chemistries can provide insights that may enhance adsorption efficiency and inform the design of more effective water treatment systems.

2.2. Removal using biochar

Biochar is an economical renewable resource that mitigates multiple environmental issues, including pollution and remediation in sediment, water, and the atmosphere. The International Biochar Initiative (IBI) characterizes biochar as "a solid material derived from the thermochemical conversion of biomass in an oxygen-restricted environment" (Sharma et al., 2023; IBI, 2024). Biochar possesses multiple potential applications, including i) pollution remediation, attributed to its elevated cation exchange capacity (CEC) and specific surface area, ii) enhancement of soil fertility, facilitated by its liming effect, enrichment in volatile matter, and augmented pore volume, and iii) carbon sequestration, resulting from its carbon and ash content. The characteristics of biochar are affected by several technological factors, chiefly the pyrolysis temperature and the feedstock type employed. These characteristics can lead to products exhibiting a diverse array of pH levels, specific surface areas, pore volumes, cation exchange capacity, volatile matter, ash content, and carbon content. It is extensively utilized for BPA breakdown and its adsorption (Inyang and Dickenson, 2015; Lefèvre et al., 2018; Kamarudin et al., 2022; Qiu et al., 2022).

Lehmann (2007) and Chen et al. (2008) stated that biochars are solid particles with a high carbon content produced from biomass via oxygen-limited pyrolysis at a very low temperature of approximately 700 °C. Recently, there has been an increased focus on using biochar for various purposes, such as soil amendment, carbon sequestration, climate change mitigation, and pollution removal (Mohan et al., 2014; Tan et al., 2015). According to Tan et al. (2015), numerous research has demonstrated that biochars exhibit significant sorption capabilities for various contaminants, such as heavy metals and organic pollutants, when present in aqueous solutions. Most of this research examined the porosity composition and surface characteristics of low-mineral biochars, commonly referred to as deashed biochars (treated with HCl or HCl/HF), concerning their sorption capabilities. The term "super--sorbent" is often used to describe biochar because of its notable attributes, including a significant specific surface area, unique surface chemistry properties (such as the presence of oxygen-containing groups and highly graphitized carbon surfaces), and its capacity to immobilize detrimental heavy metal ions and adsorb persistent pollutants. As a result, biochar has significant promise in soil and wastewater remediation, as evidenced by studies conducted by many workers (Cao et al., 2009; Chen et al., 2015; Shimabuku et al., 2016).

The study utilized four biomass substrates, including corncob, pomelo peel, eucalyptus globulus, and silkworm excrement, as the primary raw materials. These biomasses were designated as CC, PP, EG, and SE, respectively. The materials underwent multiple washes to eliminate dust particles, followed by air drying for several days and oven-drying for 12 h at a temperature of 70–80 °C. Biochars were generated through pyrolysis under oxygen-limited circumstances in a muffle furnace, with temperatures ranging from 200 to 500 °C. BPA was quantified in the supernatants using an HPLC (Agilent Technologies 1200) equipped with a reversed-phase C8 column (5 mm, 4.6–150 mm) and a UV detector. BPA was quantified at a wavelength of 280 nm. The biochars produced demonstrated the existence of oxalates, carbonates, and KCl crystals, with variations observed based on the specific feedstocks and temperatures employed. At temperatures ranging from 200 to 300 °C, oxalates and KCl are created, while carbonates often form at pyrolysis temperatures over 400 °C. The observed sorption of BPA is minimally affected by the presence of insoluble crystal particles and dissolved salts (Li et al., 2017).

Nevertheless, it has been observed that the elimination of ash content impacts the sorption of BPA. The sorption of BPA is influenced by the inorganic content, which can be linked to the inherent features of biochar. Based on an analysis of the biochar and a comparison of its sorption capabilities prior to and following ash removal, it is proposed that the inclusion of inorganic mineral compositions within the biochar particles may have impeded the functionality of the inner pores, hence diminishing the significance of these sorption sites. Therefore, the association between BPA and biochar was mostly determined by the functional groups on the biochar's surface. The application of acid

Table 1
Types of Activated Carbon and their capacity to remove BPA.

Sl. No.	Activate Carbon Derived from	Surface area	Pore Size	BPA Removal	References
1	Coffee Residue	1030 m^2/g	2.13 nm	10 mg/g	Naganathan et al. (2021)
2	Olive-mill waste	1641 m^2/g	–		Bautista-Toledo et al. (2014)
3	Commercial Activated Carbon (AC-40)	–	–	90 mg/g.	Martín-Lara et al. (2020)
4	Graphen or AC	–	–	103 μg/g	Wang et al. (2017) a,b

treatment successfully removed a significant portion of the inorganic constituents, resulting in the identification of supplementary sorption sites and consequently augmenting the sorption capacity of BPA. Enhancing the accessibility of the inner pores of biochar has the potential to improve its sorption ability.

Biochar as a soil amendment is a cheap and easy way to dispose of organic waste. The study examined how biochar affects soil sorption, leaching, and dissipation of BPA and 17α-ethynylestradiol (EE2). The maize stalk-derived biochar underwent a thermal treatment at a temperature of 500 °C for 1.5 h. Therefore, biochar was produced with a distinct fragrance and a microporous composition, displaying a diverse array of functional groups on its outer layer. In the batch sorption trials, incorporating 4 wt% biochar into the soil significantly enhanced the solid-water distribution coefficients. At a pollutant equilibrium value of 0.01 mg/L, the coefficients for BPA increased by 263%, and for EE2 increased by 298%. By putting biochar at concentrations of 1 wt%, 2 wt %, and 4 wt% into the soil during the leaching experiment, the total quantity of BPA was reduced by 19%, 28%, and 53%, respectively.

Additionally, the quantity of EE2 dropped by 42%, 58%, and 77% compared to the soil without biochar. Notably, adding biochar did not significantly impact the dissipation of BPA and EE2 during the 90-day incubation period. Nevertheless, notable decreases were observed in $CaCl_2$ extractable BPA and EE2 quantities. The study by Xu et al. (2015) revealed that the biochar exhibited a distinctive ability to reduce the mobility of BPA and EE2 in soil while simultaneously preserving the degradation of both pollutants without any adverse effects.

According to Wang et al. (2019)a,b, the physical and chemical properties of the biochar (Peanut Shell) can be influenced by the pyrolysis temperature. The adsorption of BPA by biochars is enhanced at elevated temperatures owing to their increased surface area, pore volume, hydrophobicity, and aromaticity. The adhesion of BPA onto Peanut Shell biochars is mostly attributed to three mechanisms: the hydrophobic effect, electric double-angle (EDA) interaction, and hydrogen bonding. The presence of surfactants may impact the adsorption behavior of BPA onto biochars. Surfactants of various natures (cationic, anionic, and non-ionic) were discovered to hinder the adsorption of BPA. This study focuses on examining the adsorption characteristics of BPA onto biochars and analyzing the distinct effects of these surfactants. The study's findings revealed that biochars derived from peanut shells at different temperatures (300 °C, 500 °C, and 700 °C) exhibited a significant capacity to adsorb BPA. Additionally, it was noted that the adsorption affinity of the biochars showed a positive correlation with the rise in pyrolysis temperature. The recorded logarithmic Kd values for BC300, BC500, and BC700 were 2.83°C3.71, 2.91°C4.57, and 3.24°C5.50, correspondingly. The observed influence of cetyltrimethyl ammonium bromide (CTAB) on the adsorption of BPA on BC300 was found to be negligible. However, when the pyrolysis temperature of biochar increased, the inhibitory effect of CTAB became more prominent. The study demonstrated that the inhibitory impact of Tween 20 and sodium dodecyl benzene sulfonate (SDBS) was more significant compared to CTAB, specifically with regards to BC300. This phenomenon may be attributed to the fact that the inhibitory effect caused by the competition of CTAB may be counterbalanced by the enhancement resulting from the partitioning effect of adsorbed CTAB and the bridge effect between the $-NH^{4+}$ group of CTAB and the phenol group on BPA/O-functional groups of biochars. However, it should be noted that Tween 20 and SDBS are not showing this advantage concerning the bridge effect, as indicated by Wang et al. (2019)a,b. In their study, Choi and Kan (2019) showed that the alfalfa biochar generated at 650 °C had a remarkable maximum adsorption capacity of 38 mg/g for BPA. In their study, Kim et al. (2016) found that the ability of BPA to adsorb onto biochars is more potent than its adsorption capability on powdered activated carbon. Others have investigated the impact of aqueous chemistry conditions on the adsorption behaviour of biochars in wastewater treatment (Chen et al., 2007; Sun et al., 2016).

Lu and Chen (2018) introduced significant findings by combining biochar with biofilter to remove BPA from stormwater effectively. The study aimed to characterize and investigate the adsorption of BPA by biochars derived from wood dust (BC0) at various pyrolytic temperatures (300, 500, and 700 °C, denoted as BC300, BC500, and BC700, respectively). The investigation was conducted using batch sorption and fixed-bed column experiments with different pH levels and humic acid concentrations. The study involved the construction of microcosm biofilters that were planted with phragmites australis and supplemented with various biochars. These biofilters were then utilized to remove BPA at varying hydraulic loading rates (HLRs). BC700 exhibited a superior adsorption rate and capacity compared to other biochars, primarily attributed to its elevated specific surface area and pore volume. BC700 exhibited a notable ability to effectively eliminate BPA from aqueous solutions, as evidenced by its rapid sorption rate and substantial adsorption capacity. A consistently high removal efficiency, consistently above 98.4%, was observed, even when the HLR values increased. In addition, the addition of biochar also stimulated the growth of *Phragmites australis* and increased the effectiveness of removing *E. coli* and wastewater parameters (TOC, TSS, N, and P). In general, biochar exhibits significant promise in eliminating BPA and other organic and inorganic pollutants from stormwater, as well as preserving plant health in stormwater biofilter systems, when compared to traditional substrates such as sand, gravel, and soil, considering the affordability and accessibility of biochar (Lu and Chen, 2018).

The study utilized a CuO-Fe_3O_4-BC nanocomposite, consisting of iron and copper oxide nanoparticles placed atop biochar, as a heterogeneous catalyst for activating peroxymonosulfate(PMS) in the breakdown of BPA. The CuO-Fe_3O_4-BC/PMS system achieved a 100% removal efficiency of BPA within 30 min by employing 2.0 g/L CuO- Fe_3O_4-BC and 5 mM PMS at a pH of 9.0. The presence of SO_4^{-3} significantly facilitated the breakdown process. The combined influence of copper ions and iron ions resulted in an enhanced flow of Fe (II)/Fe (III) and Cu (I)/Cu (II), hence facilitating electron transfer on the catalyst surface and augmenting the production of free radicals. In the meantime, biochar adsorption facilitated enhanced interaction and reactivity between BPA molecules and free radicals, hence promoting the breakdown of BPA. The stability and reusability of the CuO-Fe_3O_4-BC nanocomposite were demonstrated by the sustained BPA degradation efficiency of over 80% after four iterations (Zhen et al., 2021).

Activated biochar (Ag-Fe@BAB) made from bamboo and doped with Ag_3PO_4 and Fe_3O_4 was created by Talukdar et al. (2020) using a co-precipitation method. There was a 95.6% degradation rate for BPA within 60 min using the Vis/Ag-Fe@BAB/PDS method. At a pH of 6.5 and a peroxydisulfate (PDS) concentration of 0.5 mM, this degradation took place with a photocatalyst concentration of 1.0 g/L. Researchers discovered that the presence of $\bullet O_2^-$, which shows photocatalytic characteristics when p-benzoquinone is used as a scavenger, was the main factor responsible for the breakdown of BPA in the Vis/Ag-Fe@BAB/PDS system. Furthermore, the author used electron spin resonance to determine which radical species were produced in the Vis/Ag-Fe@BAB/PDS system.

The mechanism underlying the nonradical pathway involved the production of intermediates through the binding interactions between the nanocomposites and sodium persulfate (PS). The presence of lactones and aromatic structures within the nanocomposites was crucial in facilitating these events. The degrading process of BPA involves the transfer of electrons from contaminants to PS through the formation of electron transfer intermediates resulting from the binding interactions between CuO/BC [Copper (II) oxide-Biochar Nanocomposites] and PS. Hence, a notable disparity was seen in the alteration of the O-element between the nonradical pathway and the radical pathway. This disparity can be attributed to the formation of intermediates resulting from unsaturated bonds, such as C=O and lactones, facilitating the amalgamation of nanocomposites and PS.

Furthermore, the CuO/BC-PS system showed a remarkable

mineralization rate of 100% for BPA. Additionally, the CuO/BC system exhibited a high activity level in breaking down BPA even after being reused five times. In addition, our research presented a swift degradation technique for aromatic pollutants using a nonradical pathway. Furthermore, we devised a straightforward and efficient approach to repurpose biochar derived from solid waste generated by factories (Luo et al., 2020).

The study conducted by Birer et al. (2021) provided evidence that the pyrolysis of sewage sludge, utilizing a straightforward and economically viable method, can yield biochars that are well-suited for the extraction of hydrophobic analytes in solid-phase applications. The comprehensive analysis revealed that the alteration increased three hydrophobic samples and one hydrophilic sample compared to the initial biochar. The solid-phase extraction of the developing contaminant Bisphenol A from aqueous solutions was conducted to evaluate all samples. KOH-SSB (potassium hydroxide-sewage sludge biochar) and KOH/MeOH-SSB (potassium hydroxide/Methanol-sewage sludge biochar) had the most favourable performance, reaching recoveries of 88.1% at a dosage of 0.1 g at the pH of the BPA solution (pH 6.5). Following the use of all five samples in the solid-phase extraction of BPA, it was ascertained that the biochar treated with hydrophobic KOH/-MeOH exhibited the most favourable performance, resulting in the maximum recovery of BPA. The interaction process involved a combination of hydrogen bonding and interaction, although it is essential to acknowledge the possibility of physical sorption into the surface pores. Their study proved that hydrophobic biochars are highly effective in the solid-phase extraction of pollutants from aqueous solutions.

Additional investigations into the adsorption mechanism supported the observation that Pb (II) binding onto BCMW-β-CD (BioCharMicroWave-β-cyclodextrin) was mostly influenced by complexation and electrostatic interactions. Conversely, the removal of BPA was primarily attributed to the host-guest supramolecular and–- stacking interactions. Furthermore, the BPA and Pb (II) pollutants that were adsorbed onto the BCMW-β-CD were effectively separated successively using ethanol and HCl. However, there was a slight decrease in the adsorptive capacity of BCMW-β-CD after undergoing five cycles. According to Qu et al. (2020), the BCMW- β-CD has demonstrated its efficacy as a customized adsorbent for concurrently removing organic and inorganic contaminants in wastewater. Types of biochar used for BPA removal have been summarized in Table 2.

In summary, various types of biochar, including those derived from maize stalks, peanut shells, apricot shells, wood, walnut shells, and bamboo, have been extensively studied for their BPA removal capabilities. This biochar exhibits significant adsorption properties due to its high surface area, diverse functional groups, and optimized production conditions, such as specific pyrolysis temperatures. BPA sorption is enhanced through modifications like acid treatment, composite formation, and surfactant interactions. Potential limitations include the need for further investigation into the stability and reusability of the photocatalyst over multiple cycles, as well as the potential environmental impacts of residual photocatalyst materials. Future research could focus on scaling up the synthesis of Ag-Fe@BAB for industrial applications, exploring its effectiveness against a broader range of contaminants, and optimizing the photocatalytic system for enhanced durability and long-term use. Again, in Luo et al., (2020) study may face challenges related to the long-term stability and potential environmental impacts of the CuO/BC nanocomposite. The scalability of the method for industrial applications needs further evaluation. It could explore the application of this nonradical pathway degradation method to a broader range of pollutants and optimize the reuse process of biochar from various waste sources to enhance its practicality and cost-effectiveness.

Table 2
Types of Biochar and their ability to remove BPA.

Biochar Derived from	Method used in the experiment	% of BPA extraction	References
Peanut shell biochars	Electric double-angle ($\pi-\pi$ EDA) interaction	–	Wang et al. (2019)a,b
CuO-Fe_3O_4-BC Biochar	CuO-Fe_3O_4-BC/PMS system	100 %	Zhen et al. (2021)
Ag_3PO_4/Fe_3O_4 co-doped bamboo-derive activated biochar	Co-precipitation method	95.6%	Talukdar et al. (2020)
Sewage sludge biochar	Solid-phase extraction	88.1%,	Birer et al. (2021)
Biochar with biofilter from stormwater	Batch sorption and Fixed-bed column experiments	>98.4%	Lu and Chen (2018)
Alfalfa biochar	Thermogravimetric analysis	–	Choi et al., 2019

3. Degradation using chemical methods

Substances that impede the endocrine system's control over hormone production, release, transport, metabolism, and elimination are known as endocrine-disrupting chemicals (EDCs). Because of its widespread usage in consumer products and its negative effects on health, BPA has garnered a lot of attention as an EDC. The plastic industry's heavy reliance on BPA has led to a rise in the chemical's concentration in water bodies. Chemical techniques such as adsorption, oxidation, and precipitation are commonly used to extract, break down, or isolate BPA molecules from water. Each method has its advantages and limitations, depending on factors like effectiveness, cost, and environmental impact. The choice of the best approach for BPA removal from water depends on the concentration of BPA, the required level of treatment efficiency, and the available infrastructure and resources. Different chemical methods for removing BPA offer varying removal efficiencies. These approaches are summarized in Table 3, providing an overview of the options and helping to guide the selection of the most suitable method for specific circumstances.

3.1. Fenton/Fenton-like method

3.1.1. Heterogeneous sono-Fenton process with Fe_3O_4 magnetic nanoparticles

The degradation of BPA using a heterogeneous sono-Fenton process with Fe_3O_4 magnetic nanoparticles shows a synergistic effect of ultrasound. The catalysis of BPA degradation was investigated, and promising results were found. The study provides insights into efficiently removing BPA using advanced oxidation processes. The Fe_3O_4 magnetic nanoparticles, combined with ultrasound and H_2O_2 in a heterogeneous sono-Fenton process, showed effective removal of bisphenol A. The method exhibited its optimum efficacy in breaking down BPA, and even after multiple recycling cycles, the Fe_3O_4 nanoparticles remained stable and active. Following the initial recycling, the removal efficiency of BPA remained constant, demonstrating the effectiveness of the process in breaking down BPA. The BPA removal efficiencies in this method were remarkable, with values exceeding 95% in the US + Fe_3O_4 + H_2O_2 system at different pH levels (pH 3, pH 7, and pH 9). The method significantly accelerated the degradation of BPA, with removal efficiencies ranging from 77.4% to 100%, When compared to other processes (Huang et al., 2012).

The heterogeneous sono-Fenton process using Fe_3O_4 magnetic nanoparticles offers several advantages for removing BPA, such as effectiveness, reusability, and wide pH range. However, there are a few limitations to consider. The slow reaction rate may cause the process to take longer, necessitating additional optimization for quicker degradation. Fe_3O_4 nanoparticles may need to be modified or doped to increase the reaction rate. More research is required to completely comprehend the process and maximize its effectiveness for large-scale applications.

Table 3
Summarized approaches using chemical methods for BPA removal.

Methods used for removal of BPA	BPA removal efficiency	Advantages	Limitations	References
Heterogeneous sono-Fenton process with Fe_3O_4 magnetic nanoparticles	The removal efficiencies of BPA in the system exceeded 95% in the US + Fe_3O_4 + H_2O_2 system at different pH levels (pH 3, pH 7, and pH 9)	• Fe_3O_4 nanoparticles can be reused multiple times without significant loss of activity, and exhibit good stability even after several recycles • Maintain good activity within a wide pH range from 3 to 9	It may take longer due to the low reaction rate, requiring further optimization for faster degradation	Huang et al. (2012)
Ethylenediamine-N, N'disuccinic acid (EDDS) on Fenton and photo-Fenton processes using goethite as an iron source	Optimal conditions with low concentrations of H_2O_2 (0.1 mM) and EDDS (0.1 mM) at pH 6.2 resulted in the complete removal of BPA.	EDDS enhances the photo-Fenton degradation of BPA, showing potential for water treatment technologies	The presence of EDDS inhibits the heterogeneous Fenton degradation of BPA and the formation of hydroxyl radicals, impacting the reactivity of goethite toward H_2O_2	Huang et al. (2013)
Bio-synthesized schwertmannite as a catalyst in a sono-Fenton-like system	After 60 min of reaction, 98.2% of BPA was degraded.	• Combines ultrasonic technology with bio-synthesized schwertmannite, leading to enhanced degradation of BPA • Intermediates produced during the degradation process are less toxic	The process is much complex, involving multiple components (schwertmannite, ultrasonic technology, hydrogen peroxide) which may require careful optimization and control for efficient operation	Li et al. (2018)
Fe^{2+}/Fe^{3+} layered double hydroxide (LDH) material	The Fe-Al-LDH catalyst was able to achieve nearly 100% removal of BPA within 30 min, indicating high efficiency.	The heterogeneous Fenton-like catalysts like Fe-Al-LDH and $CuFeO_2$ can be more easily separated and reused in homogeneous Fenton systems.	The presence of scavengers like carbonate ions can consume the hydroxyl radicals (OH), lowering the degradation efficiency of the Fenton-like process	Zhong et al. (2019)
Inorganic materials as heterogeneous cocatalysts	Inorganic cocatalysts like C-Boron have shown a high removal efficiency of 95% of 20 mM phthalate in 20 min	The addition of WO_3 to the $Fe_3H_2O_2$ system enhances OH and Fe(IV) activity, significantly boosting the degradation performance of 4-chlorophenol		Xiang et al. (2022)

3.1.2. Ethylenediamine-N, 'disuccinic acid (EDDS) on fenton and photo-fenton processes

The impact of ethylenediamine-N, 'disuccinic acid (EDDS) on Fenton and photo-Fenton processes using goethite as an iron source, showing that EDDS inhibits the heterogeneous Fenton degradation of BPA but enhances the photo-Fenton degradation through the formation of a photochemically efficient Fe-EDDS complex. Low concentrations of H_2O_2 (0.1 mM) and EDDS (0.1 mM) at pH 6.2 have been proven to be optimal for the complete removal of BPA, indicating the potential of the EDDS/goethite system in boosting heterogeneous photo-Fenton oxidation for water treatment methods. Optimal conditions for complete BPA removal include low concentrations of H_2O_2 and EDDS at pH 6.2, indicating cost-effectiveness and environmental friendliness. On the other hand, the reactivity of goethite towards H_2O_2 is affected by the inhibition of hydroxyl radical production and heterogeneous Fenton degradation of BPA in the presence of EDDS. Optimal conditions with low concentrations of H_2O_2 (0.1 mM) and EDDS (0.1 mM) at pH 6.2 resulted in complete BPA removal, showcasing high efficiency (Huang et al., 2013).

However, the total prevention of BPA degradation and hydroxyl radical formation in the presence of EDDS in the heterogeneous Fenton system employing goethite as an iron source is the area of research that needs more investigation. The substantial adsorption of EDDS on goethite surfaces, which modifies catalytic sites and decreases goethite reactivity towards H_2O_2, which results in the insignificant contribution of the homogenous Fenton process. As this research gap highlights, More study is needed to maximize the utilization of EDDS in heterogeneous Fenton and photo-Fenton processes for effective organic pollutant degradation.

3.1.3. Bio-synthesized schwertmannite as a catalyst in a sono-fenton-like system

The use of bio-synthesized schwertmannite as a catalyst in a sono-Fenton-like system for degrading BPA highlights the synergistic effect of ultrasonic technology and schwertmannite in activating hydrogen peroxide, leading to enhanced degradation of BPA. The schwertmannite catalyst exhibits good reusability in the recycling study, and ecotoxicity tests reveal lower toxicities of intermediates in comparison to BPA. However, the method generates organic intermediates during BPA degradation, which may require further treatment or monitoring for potential environmental impact. The process is more complex, involving multiple components (schwertmannite, ultrasonic technology, hydrogen peroxide) may require careful optimization and control for efficient operation. Further characterization is necessary since producing amorphous precipitates as potential byproducts throughout the reaction cycles may impact schwertmannite's catalytic activity. The efficiency percentage of the method for the removal of BPA in the study was not explicitly mentioned. However, it is reported that 98.2% of BPA was eliminated within 60 min of the reaction.

Furthermore, the recycling study found that the BPA elimination efficiency remained above 95% after five reaction cycles. These outcomes show that removing BPA is highly effective (Li et al., 2018). Exploration of the stability and reusability of bio-synthesized schwertmannite in the sono-Fenton-like system is an area that has not been extensively investigated.

3.1.4. Fe^{2+}/Fe^{3+} layered double hydroxide (LDH) material

A practical method for breaking down BPA with a Fe^{2+}/Fe^{3+} layered double hydroxide (LDH) material is illustrated by Zhong et al. (2019). The process involves both homogeneous Fenton and heterogeneous Fenton reactions. The highly reactive hydroxyl radical (•OH) is produced when H_2O_2 combines with Fe^{2+} in the homogeneous Fenton reaction, which breaks down BPA. To continue the breakdown of BPA, the Fe^{3+} generated may also take part in the heterogeneous Fenton reaction on the LDH surface. It is demonstrated that combining homogeneous and heterogeneous Fenton processes is an effective method of BPA degradation (Zhong et al., 2019). The Fe-Al-LDH catalyst showed high efficiency, removing nearly 100% of BPA in 30 min. The Fe^{2+}-based Fenton-type systems, like the Fe-Al-LDH and nZVI catalysts, showed rapid elimination of BPA by completely degrading it in 30–120 min. Comparatively, heterogeneous Fenton-like catalysts such as Fe-Al-LDH and $CuFeO_2$ are easier to separate and repurpose than homogeneous Fenton systems. However, the higher concentrations of BPA (e.g., 100 mg/L) resulted in lower degradation rates and efficiencies for the Fe-Al-LDH/H_2O_2 system. The hydroxyl radicals (•OH) can be consumed by scavengers such as carbonate ions, which reduces the effectiveness of degradation. Complexity in the degradation mechanism and kinetics might result from variables such as catalyst dosage, H_2O_2 concentration, and initial pH.

The study addresses the drawbacks of the homogeneous Fenton

process, which usually needs a small pH range of 2–3 to degrade BPA effectively. Its narrow pH range limits the homogeneous Fenton process's practical applicability. The activity of existing iron-bearing catalysts is lower than that of homogeneous Fe^{2+}, and they may need extra energy sources like UV light or ultrasonography, which would raise treatment costs. By overcoming the drawbacks of conventional Fenton procedures, this innovative method provides a more effective and reliable catalyst for the breakdown of BPA. These gaps in the research highlight the need for more effective and sustainable methods for BPA degradation, which the study aims to address through the use of Fe-Al-LDHs.

3.1.5. *Inorganic heterogeneous cocatalysts utilized in fenton/fenton-like processes*

In Fenton/Fenton-like wastewater treatment systems, inorganic heterogeneous cocatalysts improve efficiency and address challenges related to conventional Fenton reactions. Cocatalysts include transition metals like Mo, MoS_2 (Molybdenum disulfide), and MoO_2 and non-metals such as carbon, boron, and phosphorus, each with unique benefits and drawbacks in practical applications. A high elimination efficiency of 95% of 20 mM phthalate in 20 min has been demonstrated using inorganic cocatalysts such as C-Boron. Adding WO_3 to the Fe^{3+}/H_2O_2 system enhances OH and Fe(IV) activity, significantly enhancing the degradation performance of 4-chlorophenol. However, carbon-based materials like BC can decrease redox potential and promote Fe^{3+}/Fe^{2+} cycling, aiding in removal. Inorganic cocatalysts such as C-Boron have demonstrated a high removal efficiency of 95% of 20 mM phthalate in 20 min. BC combined with H_2O_2 and Fe^{3+} removed 95% of the 20 mM sulfamethoxazole in 60 min (Xiang et al., 2022) (Fig. 2).

Various methods have been explored for the degradation of BPA using advanced oxidation processes. These include heterogeneous sono-Fenton processes with Fe_3O_4 magnetic nanoparticles, Fenton and photo-Fenton processes with EDDS, and bio-synthesized schwertmannite as a catalyst. The heterogeneous sono-Fenton process with Fe_3O_4 magnetic nanoparticles significantly accelerated the degradation of BPA, with removal efficiencies ranging from 77.4% to 100%, compared to other processes (Huang et al., 2012). Bio-synthesized schwertmannite as a catalyst in a sono-Fenton-like system degrades 98.2% of BPA within 60 min of the reaction. Fe^{2+}/Fe^{3+} layered double hydroxide (LDH) materials have also been used, showing high efficiency in BPA degradation, completely degrading it in 30–120 min. Inorganic heterogeneous co-catalysts have also been utilized to improve efficiency in Fenton/Fenton-like processes. Inorganic cocatalysts such as C-Boron have demonstrated a high removal efficiency of 95% of 20 mM phthalate in 20 min. C-Boron combined with H_2O_2 and Fe^{3+} removed 95% of the 20 mM sulfamethoxazole in 60 min. However, further research is needed to optimize and scale up these processes for practical applications.

3.2. *Ozone oxidation method*

BPA can be eliminated from water using ozone oxidation, and a higher removal efficiency can be achieved at greater ozone dosages (Xu et al., 2007). Most research on the oxidation of BPA by ozone has concentrated on the effectiveness of BPA removal in terms of BPA disappearance and the impact of various parameters like pH, contact time, and ozone feed rate. A pH range of 5–7 is ideal for BPA degradation (Umar et al., 2013). Several studies have demonstrated that ozone (O_3) possesses potent oxidizing and disinfecting properties (Acero et al., 2000; Huber et al., 2003) that can selectively oxidize and degrade micro-pollutants such as BPA, which facilitates their removal throughout the treatment process from water and wastewater (Xu et al., 2007).

Ozonation effectively breaks down BPA in sewage effluent, even when competing organics are present (Umar et al., 2013). First-order kinetics regulate the ozonation-mediated removal of BPA, and the dissolved ozone concentration influences the rate of removal. Depending

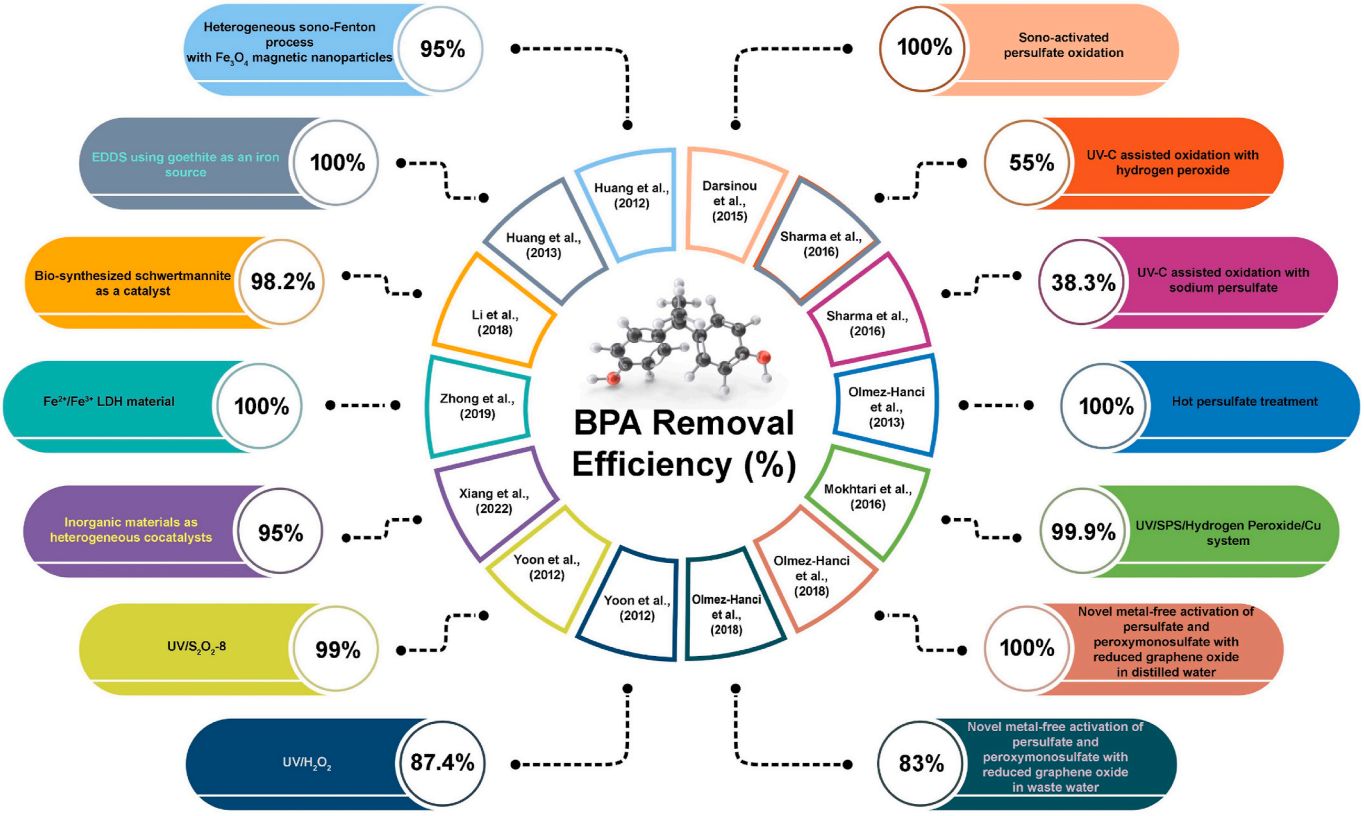

Fig. 2. Diagrammatic representation of BPA removal efficiency (%) based on different processes and authors.

on the parameters of the ozonation process, various by-products are formed when BPA is oxidized. Due to the presence of the phenolic ring in BPA, similar mechanisms and by-products can be anticipated (Snyder et al., 2006). Identifying the by-products generated during the ozone oxidation process by employing UV wavelength scanning provides insight into the degree of BPA breakdown (Xu et al., 2007). During ozonation, BPA has shown several significant transformation products, such as benzoquinone, 2-(4-hydroxyphenyl)-propan-2-ol, orthoquinone, and catechol, as well as muconic acid derivatives. However, the composition of the water matrix and other organic matter can affect the detection and properties of the by-products produced when BPA is treated with ozone. More investigation is required to completely comprehend the properties and possible effects of the very limited by-products that are formed when BPA is oxidized by ozone (Umar et al., 2013). BPA can be removed with greater efficiency at higher ozone dosages; removal efficiencies of up to 70%, 82%, and 90% can be attained at 1, 1.5, and 2 mg/L, respectively (Xu et al., 2007). The study highlights the influence of organic matter content and treatment units on ozone oxidation efficiency, suggesting a gap in understanding the relationship between water composition and BPA degradation processes. At an initial 5–50 mg/L dosage, ozonation can completely remove BPA (Umar et al., 2013). Even yet, the study emphasize the need for more investigation into the formation and breakdown of oxidation by-products that arise from BPA ozonation in water and wastewater.

The authors highlighted the need for more research to determine suitable ozone-to-BPA stoichiometric ratios because most previous studies mainly focus on the disappearance of BPA without considering the breakdown products. More research is necessary to address the economic feasibility of attaining complete mineralization, as the report emphasizes the difficulties in getting complete mineralization of BPA, particularly at higher beginning BPA concentrations. More investigation is needed to fully comprehend how pH, temperature, water matrix, initial BPA concentration, and ozone dosage affect stoichiometric ratios and by-product production during BPA ozonation. Snyder et al. (2006) have observed ozone (O_3) and O_3 combined with hydrogen peroxide (O_3/H_2O_2) eliminated a wide range of trace organic pollutants, including BPA, from wastewater and surface water, with the majority of the chemicals removed with over 90% efficiency.

H_2O_2 may not significantly boost the removal of BPA, but it may slightly increase the elimination of several other compounds when added to ozone treatment. According to Wang et al. (2021a,b), nanocomposite of graphene oxide (GO)-Fe_2O_3 enhanced BPA removal and showed 4.3–7.3 times higher BPA adsorption capacity than GO and rGO, with improved thermal stability and solid/liquid separation.

Endocrine-disrupting chemicals (EDCs), such as BPA, have been successfully removed when ozone treatment is used with conventional treatment (Borikar et al., 2015). However, the study has a research gap in water treatment. Most previous studies focused on bench-scale experiments with deionized water, lacking real-world applicability. The impact of various water characteristics like organics, bicarbonates, carbonates, and particles on the removal efficiency of contaminants needs further exploration. The study addresses the necessity of thorough investigations into the effectiveness of various treatment methods to satisfy legal obligations and improve the acceptability of water treatment. Jasim et al. (2006) do not explicitly address the possibility of BPA elimination through ozone oxidation but have shown the potential to eliminate it. Despite that, most known EDC oxidation byproducts, including those resulting from BPA ozonation, are entirely obscured. The development and existence of by-products during water treatment operations should be carefully assessed to ascertain the overall safety and effectiveness of the treatment method. Therefore, the precise efficacy of ozone oxidation for eliminating BPA requires more investigation.

3.3. Sulfate radical oxidation method

Several investigations have been conducted on coupling the sulfate radical oxidation technique with different oxidizing agents. However, these methods of BPA degradation through a complex reaction pathway involve several intermediate products such as Dehydroxylated benzene derivatives, Hydroxylated benzene derivatives, Catechols, Dicatechols, Quinones, Aldehydes, Carboxylic acids, and Carbon dioxide. The various sulfate radical oxidation techniques for BPA removal are illustrated in Table 4.

3.3.1. Oxidation of bisphenol a by UV/$S_2O_2^{-8}$: comparison with UV/H_2O_2

BPA was decomposed using the UV/$S_2O_2^{-8}$ process with the main oxidizing agent sulfate radical, which showed higher performance for BPA degradation and mineralization than the UV/H_2O_2 process, which used OH radical as an oxidizing agent. The efficiency of BPA removal by UV/$S_2O_2^{-8}$ was influenced by factors such as $S_2O_2^{-8}$ concentration, BPA concentration, pH levels, and the presence of humic acid (Yoon et al., 2012). Sulfate radical was a more effective oxidant for BPA removal than the OH radical, leading to better remediation performance. However, there were certain limitations to the process. Humic acid was observed to have an inhibitory effect on BPA oxidation using the UV/$S_2O_2^{-8}$ process. Factors such as pH levels and $S_2O_2^{-8}$ concentrations influenced the efficiency of BPA removal, which requires careful optimization. Compared to UV/H_2O_2, the UV/$S_2O_2^{-8}$ method had a greater BPA degradation efficiency, with BPA removal efficiencies of 98.8%, 85.3% in 2 min, and 99.0% and 87.4% in 6 min, respectively. For BPA mineralization, UV/$S_2O_2^{-8}$ was more effective than UV/H_2O_2, with mineralization efficiencies of 68.6% and 55.7% in 60 min, respectively (Yoon et al., 2012).

UV/$S_2O_2^{-8}$ method utilizes sulfate radicals generated from persulfate under UV light, showing high efficiency in BPA degradation with removal rates of 98.8% in 2 min and 99.0% in 6 min. It outperforms the UV/H_2O_2 method which relies on hydroxyl radicals, particularly in mineralization, with 12.9 % greater efficiency.

3.3.2. Sono-activated persulfate oxidation of bisphenol A

Sono-activated persulfate oxidation of bisphenol A involves sulfate and hydroxyl radicals contributing to degradation, affected by various factors like temperature, pH, and the water matrix, influencing the overall efficiency of the removal method. A hybrid process of low-frequency ultrasound and sodium persulfate was tested for BPA degradation, showing a synergistic effect for degradation. BPA degradation occurs through a complex reaction pathway involving hydroxylation, oxidation, and direct cleavage reactions. Twelve by-products were identified, and a reaction pathway was proposed for the degradation process.

However, the presence of radical scavengers in environmental matrices may affect the degradation kinetics, necessitating modifications to the operating parameters. Temperature, pH, and the composition of the water matrix can all impact the sonochemical processes that break down BPA. The elimination of BPA occurs within 6–8 h of the reaction, suggesting the generation of transformation by-products that are resistant to complete oxidation (Darsinou et al., 2015).

However, the impact of various water matrices on the degrading process has not been thoroughly explored. Understanding how varying water compositions impact the kinetics and pathways of BPA degradation could provide valuable insights. Examining the precise function of pH in the degradation process might benefit the research. Exploring how different pH levels affect the generation of radicals and subsequent BPA degradation kinetics would enhance the study's comprehensiveness. Although the survey reports that twelve by-products were identified using LC-MS/TOF analysis, there may be a research gap regarding a more thorough examination of these and their possible environmental effects. The study might also look at its scalability and larger-scale efficiency to better understand the difficulties and practical applications of the process for treating BPA-contaminated water sources.

Table 4
Summary of Sulfate Radical Oxidation Method for BPA removal.

Methods used for removal of BPA	BPA removal efficiency	Advantages	Limitations	References
UV/$S_2O_2^{-8}$ and UV/H_2O_2	UV/$S_2O_2^{-8}$ was more effective than UV/H_2O_2, with BPA removal efficiencies of 98.8% and 85.3% in 2 min, and 99.0% and 87.4% in 6 min, respectively	The UV/$S_2O_2^{-8}$ process using sulfate radical showed higher BPA degradation and mineralization efficiency than the UV/H_2O_2 process, leading to better remediation performance	• The presence of humic acid was observed to have an inhibitory effect on BPA oxidation using UVt UV/$S_2O_2^{-8}$ process • Factors such as pH levels and S_2O_2- $S_2O_2^{-8}$ concentrations influenced efficiency of BPA removal, which needs meticulous optimization	Yoon et al. (2012)
Sono-activated persulfate oxidation	Complete BPA removal can occur after 6–8 h of reaction	• Involves sulfate and hydroxyl radicals contributing to BPA degradation, showing efficient removal capabilities • The hybrid process of low frequency ultrasound and sodium persulfate for BPA removal shows a synergistic effect, enhancing degradation efficiency	• The presence of radical scavengers in environmental matrices may hinder the degradation kinetics, requiring adjustments in operating conditions • BPA degradation through sonochemical processes can be affected by factors like temperature, pH, and the water matrix, influencing the overall efficiency of the removal method	Darsinou et al. (2015)
UV-C assisted oxidation with hydrogen peroxide and sodium persulfate	UV-C assisted oxidation with hydrogen peroxide and sodium persulfate showed a removal efficiency of 55% and 38.3% respectively	• UV-C assisted oxidation with hydrogen peroxide and sodium persulfate effectively removes BPA from water, showing enhanced degradation with decreasing BPA concentration • The process generates highly reactive radicals like hydroxyl and sulfate, leading to the decomposition of BPA into biodegradable products	• Higher concentrations of BPA can compete for reaction with radicals, decreasing the removal efficiency • Some intermediates with smaller and higher molecular weights than BPA are formed during the process, indicating the complexity of the degradation pathway	Sharma et al. (2016)
Hot persulfate treatment	Complete BPA removal in a short time, with the highest removal rates observed at specific initial pH value	Hot persulfate treatment effectively removes BPA and its oxidation products, with complete BPA removal achieved in a short time	The formation of toxic oxidation products during treatment poses a challenge, as some of these intermediates were found to be more toxic than BPA itself	Olmez-Hanci et al. (2013)
UV/SPS/H_2O_2/Cu system	Effectively removes BPA from aqueous solutions, achieving up to 99.99% removal in optimal conditions	The process involves the generation of sulfate and hydroxyl radicals, leading to the degradation and mineralization of BPA, reducing toxicity in the effluent	Excessive hydrogen peroxide concentration can act as a radical scavenger, reducing the reaction rate and BPA removal	Mokhtari et al. (2016)
Novel metal-free activation of persulfate and peroxymonosulfate with reduced graphene oxide	Complete BPA degradation was achieved in distilled water with the persulfate/reduced graphene oxide treatment after 10 min, while in wastewater, 83% removal was obtained after 30 min	• Efficiently degrades Bisphenol A in water samples, achieving complete degradation in distilled water and significant removal in wastewater • The process is environmentally benign	• The stability of reduced graphene oxide as a catalyst needs improvement for reusability, as it was found to be deactivated after the second cycle in the study. • Higher concentrations of persulfate can lead to self-quenching and recombination reactions, affecting the efficiency of BPA removal.	Olmez-Hanci et al. (2018)
VUV/UV/PMS system	Shows high efficiency in BPA removal, achieving significant degradation rates	The process offers synergistic effects from the combination of VUV, UV, and PMS, leading to enhanced BPA elimination	• The efficiency of BPA degradation can be influenced by factors such as solution pH, with higher pH levels potentially reducing degradation rates • The presence of inorganic ions and organic matter in the solution may also impact the effectiveness of the removal process	Lin et al. (2020)a,b

3.3.3. UV-C assisted oxidation with hydrogen peroxide and sodium persulfate

UV-C-assisted oxidation with hydrogen peroxide and sodium persulfate efficiently removes BPA from water, which shows enhanced degradation with decreasing BPA concentration. The degradation pathways involve hydroxylation, dehydration, coupling, and ring-opening reactions, with the formation of hydroxylated by-products and quinones indicating different oxidation pathways. UV-C-assisted oxidation with hydrogen peroxide and sodium persulfate efficiently removes BPA from water, which shows enhanced degradation with decreasing BPA concentration. The process produces highly reactive radicals like hydroxyl and sulfate, which cause BPA to break down into biodegradable products. Confident intermediates with smaller and higher molecular weights than BPA are produced during the process, showing the intricacy of the degradation pathway. Higher amounts of BPA can compete for reaction with radicals, reducing the removal efficiency. Hydrogen peroxide and sodium persulfate elimination efficiencies using UV-C aided oxidation were 55% and 38.3% for BPA removal (Sharma et al., 2016).

However, the lack of exploration into the effects of different initial BPA concentrations on the degradation process and efficiency of BPA under UV-C/H_2O_2 and UV-C/SPS systems represents a research gap in this work. This discrepancy is significant because it may provide insight into the effectiveness and kinetics of BPA removal at various starting concentrations, which could help to improve the treatment procedure. Furthermore, the study does not delve into the influence of different oxidant/BPA molar ratios on the degradation pathway and by-product formation during photooxidation. Comprehending how oxidant concentrations affect the breakdown could provide essential insights for creating effective BPA removal plans.

3.3.4. Hot persulfate treatment

Olmez-Hanci et al. (2013) studied the fact that after BPA was treated with hot persulfate, harmful oxidation products were formed, with the

early-stage compounds being more destructive than the BPA. A relationship was found between the formation of 2,3-dimethyl benzoic acid during treatment and acute toxicity. BPA and its oxidation products can be efficiently removed by hot persulfate treatment with rapid removal of BPA at specific initial pH values.

Though, the effect of different initial pH values on BPA oxidation utilizing the hot persulfate method was not investigated. The study did not examine the possible synergistic benefits of reducing the toxicity of oxidation by-products and improving BPA removal efficiency by combining hot persulfate treatment with other advanced oxidation techniques. The economic viability and cost-effectiveness of using hot persulfate treatment for BPA removal compared to alternative traditional or advanced treatment techniques were also not addressed. Additionally, this work did not explore the long-term environmental implications of hot persulfate treatment, such as the persistence of oxidation by-products and their possible ecological impacts. The hot persulfate process's scalability and practicality for treating BPA-contaminated water on larger scales were not discussed, even though they are essential for remediation techniques and real-world implementation.

3.3.5. UV/SPS (sodium persulfate)/H_2O_2/Cu system

BPA is efficiently removed from aqueous solutions by the UV/SPS/H_2O_2/Cu system; under ideal circumstances, removal rates can reach 99.99%. Sulfate and hydroxyl radicals are produced during the process, which breaks down and mineralizes BPA and reduces its toxicity in wastewater. A high quantity of hydrogen peroxide (H_2O_2) can function as a radical scavenger, consequently decreasing the reaction rate and eliminating BPA. Since BPA molecules will always be accessible for reaction, increasing the concentration of sodium persulfate (SPS) might not significantly impact BPA degradation (Mokhtari et al., 2016).

However, the lack of discussion on the long-term impacts of the UV/SPS/H_2O_2/Cu system on the aquatic ecosystem and its sustainability represents a research gap. The study does not examine the suggested system's possible ecological effects or scalability in practical applications; instead, it focuses on optimizing and modeling BPA removal. More investigation is required to determine whether using the UV/SPS/H_2O_2/Cu system on a broader scale to remove BPA from natural aquatic systems is possible, cost-effective, and environmentally safe. Future studies could also investigate the efficiency of this system in treating BPA-contaminated wastewater from industrial sources and its feasibility for widespread implementation in water treatment facilities.

3.3.6. Novel metal-free activation of persulfate and peroxy-mono sulfate with reduced graphene oxide

BPA is effectively degraded in water samples by a novel metal-free activation of persulfate and peroxy-monosulfate with reduced graphene oxide. This leads to complete degradation in distilled water and considerable elimination of effluent during short treatment periods. The study emphasizes that SO_4^{-2} predominates in the activation process, with OH making a minor contribution. This underscores the need for additional research to improve reduced graphene oxid''s stability as a catalyst. The method is safe for the environment and provides details on activating persulfate and peroxy-monosulfate with decreased graphene oxide to remove BPA. The effectiveness of BPA removal may be impacted by self-quenching and recombination processes induced by higher persulfate concentrations. In wastewater, 83% elimination of BPA was accomplished after 30 min. However, complete BPA breakdown was achieved after 10 min with the persulfate/reduced graphene oxide treatment in distilled water. Using hydrogen peroxide and decreased graphene oxide, the overall BPA removal efficiency was 60%, comparable to the efficiency of adsorption experiments. After 30 min, the BPA removal effectiveness dropped from 100% to 96% in the presence of 0.25 mM persulfate and 0.02 g/L reduced graphene oxide. The BPA removal rate increased from 81% to 100% with increased persulfate content in wastewater samples from 0.125 mM to 0.25 mM (Olmez-Hanci et al., 2018).

3.3.7. VUV/UV/peroxy-mono sulfate system

In a VUV(vacuum UV)/UV/peroxy-monosulfate (PMS) system, the study focuses on the kinetics and mechanism of bisphenol A degradation. The study investigates the relative contributions of reactive radicals and second-order rate constants in degradation. Electron paramagnetic resonance (EPR) spectroscopy characterization and radical quenching experiments validated the identification and transition of reactive radicals. High removal efficiencies across a broad spectrum of pH levels are demonstrated by the effectiveness of BPA degradation in the VUV/UV/peroxy-monosulfate system at various pH values.

The BPA removal efficacy of the VUV/UV/peroxy-monosulfate system is high, with notable degradation rates. The technique has synergistic actions that combine VUV, UV, and PMS to improve BPA removal. However, variables like solution pH might affect the BPA degradation; higher pH values may slow down the degradation rate. The efficiency of the removal process may also be impacted by the presence of organic matter and inorganic ions in the solution (Lin et al., 2020a,b) (Fig. 2).

3.4. Electroenzymatic oxidation method

An electrochemical process is used with enzymes in the electro-enzymatic technique of BPA removal from water to degrade BPA molecules into less hazardous materials. Electro-enzymatic oxidation can remove BPA from water through the following steps.

i. Oxidation
ii. Substitution and Radical coupling
iii. Hydroxylation
iv. Precipitation

Electro-enzymatic oxidation is a flexible and adaptive method for various water treatments since it can function at low concentrations throughout a wide pH and temperature range (Ohore and Zhang, 2019). The efficiency of this approach can differ based on some variables, including the specific type of enzymes utilized, the concentration of BPA present in the water, and the operating conditions of the electrochemical cell (Husain, 2019).

Electro-enzymatic oxidation requires extracellular enzymes like laccase and peroxidase, highly reactive, non-specific free radicals with strong oxidative potential and the ability to break down BPA (Ohore and Zhang, 2019). With the help of oxygen or hydrogen peroxide, enzymes like horseradish peroxidase (HRP) catalyze the transformation of BPA into phenoxy free radicals, which is achieved through the self-polymerization and cross-coupling reactions of BPA. Following their coupling, these radicals can produce low-solubility polymers that can be precipitated or coagulated out of water (Du et al., 2016; Zhao et al., 2016).

Peroxidase catalyses the oxidation of BPA in the presence of hydrogen peroxide (H_2O_2), producing phenyl radicals that form insoluble oligomers. The breakdown of BPA is caused by the easy removal of these oligomers (Ohore and Zhang, 2019). However, the study lacks some detailed discussion on a few specific areas, viz; a comparison of the effectiveness and affordability of several BPA removal methods, the possible effects of BPA pollution on the environment in water bodies, investigation of multidisciplinary strategies for more effective BPA elimination. The electro-enzymatic system does not require extra chemicals since dioxygen reduction on the cathode provides a constant H_2O_2 supply. Additionally, the electro-enzymatic system promotes BPA intermediate hydroxylation, which produces hydroxylated compounds (Zhao et al., 2016; Du et al., 2016). Though the electro-enzymatic approach effectively removes BPA and other organic micropollutants from water by combining the reactivity and selectivity of enzymes with

the electro-generation of H_2O_2, it has few challenges in terms of practical application.

Targeted and hidden-targeted screening techniques are necessary due to the intricate and complex investigation of the transformation, products, and intermediates of BPA and its derivatives in the presence of humic acid. However, practical implementation may necessitate additional investigation and consideration of H_2O_2 supply (Zhao et al., 2016). Additionally, most of the studies do not examine the long-term stability and reusability of the enzymatic system, which could be critical for its implementation in continuous treatment procedures. The economic viability and cost-effectiveness of scaling up the electro-enzymatic approach for treating industrial wastewater is also not explored in the research, which is crucial for determining the system's suitability for large-scale applications. Future research could address these gaps by investigating the optimization of operational parameters for continuous treatment assessing the stability of the enzymatic system over extended periods.

Another study found that enzyme loss can occur continually with treated wastewater, leading to instability and discontinuity in using enzymes in electro-enzymatic oxidation (Ohore and Zhang, 2019). According to diverse studies, the removal efficacy of enzymes can vary depending on how they are immobilized on various surfaces or materials. Conclusively, more investigation is required to maximize the electro-enzymatic oxidation process and scale it up for large-scale BPA removal from water.

3.5. Photocatalytic method

BPA is one of the most widely produced compounds and an endocrine disruptor (Czarny-Krzymińska et al., 2023). Primarily utilized in the manufacturing of epoxy and polycarbonate resins for various products like water containers, infant bottles, and medical devices, BPA contamination diffuses all environmental domains, including air, water, and soil (Sharma and Shah, 2021)

With projections indicating a substantial increase in BPA utilization, it is anticipated that 92% of BPA contamination will be concentrated in water bodies, thus emerging as a significant water pollutant in the future (Gavrilescu et al., 2015). Traditional water treatment methods like chlorination and ozonation have proven ineffective in removing many hazardous water pollutants. Consequently, recent research has focused on photocatalysis-based approaches for BPA treatment.

Jia et al. (2012) studied the photodegradation of BPA in aqueous solution under UV irradiation at 253.7 nm using nano titanium dioxide (TiO_2) as a photocatalyst in a batch photocatalytic reactor. The impact of degradation was examined under several circumstances, including pH, irradiation duration, TiO_2 dosage, and initial BPA content, and it was found that the degradation efficiency increases with irradiation time and decreases with increasing BPA initial concentration having alkaline conditions ideal for the breakdown (Tran et al., 2017). compared the photocatalytic activity of different titania polymorphs (brookite, anatase, and rutile), where brookite exhibited higher photocatalytic activity, and its performance was comparable to anatase whereas Rutile showed lower activity. Further, various modification techniques were adopted in which TiO_2-based photocatalyst were metal doped to enhance the photocatalytic efficiency. It was reported that using Fe-loaded TiO_2 in the presence of H_2O_2 shows significant BPA destruction, UV/H_2O_2/5.0 mol% Fe-TiO_2 system completely removed 10.0 ppm BPA after 2 h (Kang et al., 2015). Many results suggest that the change in pH significantly affects the degradation rate, where alkaline conditions greatly enhance the rate due to alterations in surface charge, while acidic conditions negatively impact degradation. Additionally, the amount of photocatalyst carrier influences the degradation rate, with the rate constant peaking at a 1% ratio, then decreasing as the ratio increases to 1.5%, 2%, or 3%. Temperature has a minimal effect on enhancing BPA degradation because of the already rapid pace of photocatalytic degradation (Wang et al., 2009). Another promising photocatalyst is ZnO, which shows high photocatalytic efficiency in various wastewater types (Lee et al., 2016). Increased BPA degradation has resulted from doping inner transition metals like Ce, 2% Ce-ZnO achieve 100% BPA degradation and 61% BPA mineralization after 24 h of UV irradiation (Bechambi et al., 2016). Photocatalysts based on bismuth that comprise either Bi^{3+} or Bi^{5+} provide improved photocatalytic activity under visible illumination (Meng and Zhang, 2016). Bismuth tungstate (Bi_2WO_6) catalysts at pH 11 at 1.0 g/L remove 100% BPA after 30 min of irradiation (Wang et al., 2010). Ag-based photocatalysts have garnered significant interest in recent research because of their high photocatalytic activity and visible reaction. Ag-based photocatalysts of various types, such as Ag_2O, Ag_2S, AgX (Cl, Br, I), Ag_3AsO_4, $AgPO_4$, and $AgAlO_2$, are found. Among many photocatalysts, Ag_3PO_4 crystals exhibit excellent photooxidative capabilities of which the crystal shape, Rhombic dodecahedrons with (110) facets, exhibit much higher photocatalytic activities mainly due to their higher surface energy (Bi et al., 2011). Recently, a carbon-based photocatalyst has been used for assessing the efficiency of BPA degradation, in which Palladium mesoporous graphite carbon nitride (Pd/mpg-C_3N_4) leads to photodegradation of 100% BPA @ 20mg/L after 360 min under stimulated sunlight (Chang et al., 2013).

This review section aims to shed light on the adverse effects of BPA exposure and the necessity for photocatalytic BPA removal. A list of classifications for the agents used in photocatalysis has been depicted in Fig. 3. We discussed the performance of various potent materials, including TiO_2, ZnO, Bi-/Ag-based graphene, carbon nanotubes, and their composites, in detail, which has been summarized in Table 5. Furthermore, the degradation mechanism of BPA and photocatalyst' efficacy in tackling BPA contamination have also been discussed. The efficiency of the photocatalytic process depends on several factors, including the type and morphology of the photocatalyst, light intensity, pH of the solution and the presence of electron acceptors or scavengers such as hydrogen peroxide (H_2O_2). Studies have revealed that modified TiO_2, doped with metals and non-metals, enhances the photocatalytic activity under visible light by narrowing the bandgap and reducing the recombination of photo-generated electron-hole pairs. The degradation kinetics of BPA generally follow Pseudo first order behaviour, indicating a dependence on catalyst surface interaction and light absorption (Aljaafari, 2022). Moreover, the process of photocatalytic degradation involves several complex pathways viz. carbon-carbon bonds, hydroxylation and ring opening as the primary mechanisms. Very recently, using a typical iron-based metal-organic framework, MIL-88B (Fe), Lin et al. (2020)a,b constructed a MIL-88B (Fe)/persulfate/visible light (M88/PS/Vis) system, and with this, BPA in aqueous solution was entirely degraded within 25 min with 0.6 g/L M88 and 2 mM PS under visible light. Their result demonstrated that the removal rates with individual M88/Vis or M88/PS were only 26.0% and 34.1%, respectively. Photocatalysis is performed using sunlight, UV, Backlight lamps or LEDs offer significant sustainability benefits. LED photocatalysis, in particular, provides high performance and environmental safety, making it ideal for removing emerging micro-pollutants in areas with insufficient sunlight. LEDs can also be a backup for solar systems during cloudy periods or peak influent loads (Davididou et al., 2018). While lab-scale experiments have demonstrated the potential of photocatalytic methods for BPA removal but translating this technology into large-scale, real--world applications faces several challenges. The efficiency of photocatalysis is often reduced in actual wastewater due to the presence of natural organic matter, inorganic ions and turbidity, which can compete for ROS or hinder light penetration (Iervolino et al., 2020). Future research should evaluate the process efficiency in wastewater with relevant pollutant concentrations and assess the economic and environmental impacts to determine its suitability as a tertiary treatment step in wastewater treatment plants before scaling up. While photocatalytic degradation presents a promising green solution for the removal of BPA from contaminated waters, its practical implementation requires addressing several technical challenges. Optimizing catalyst

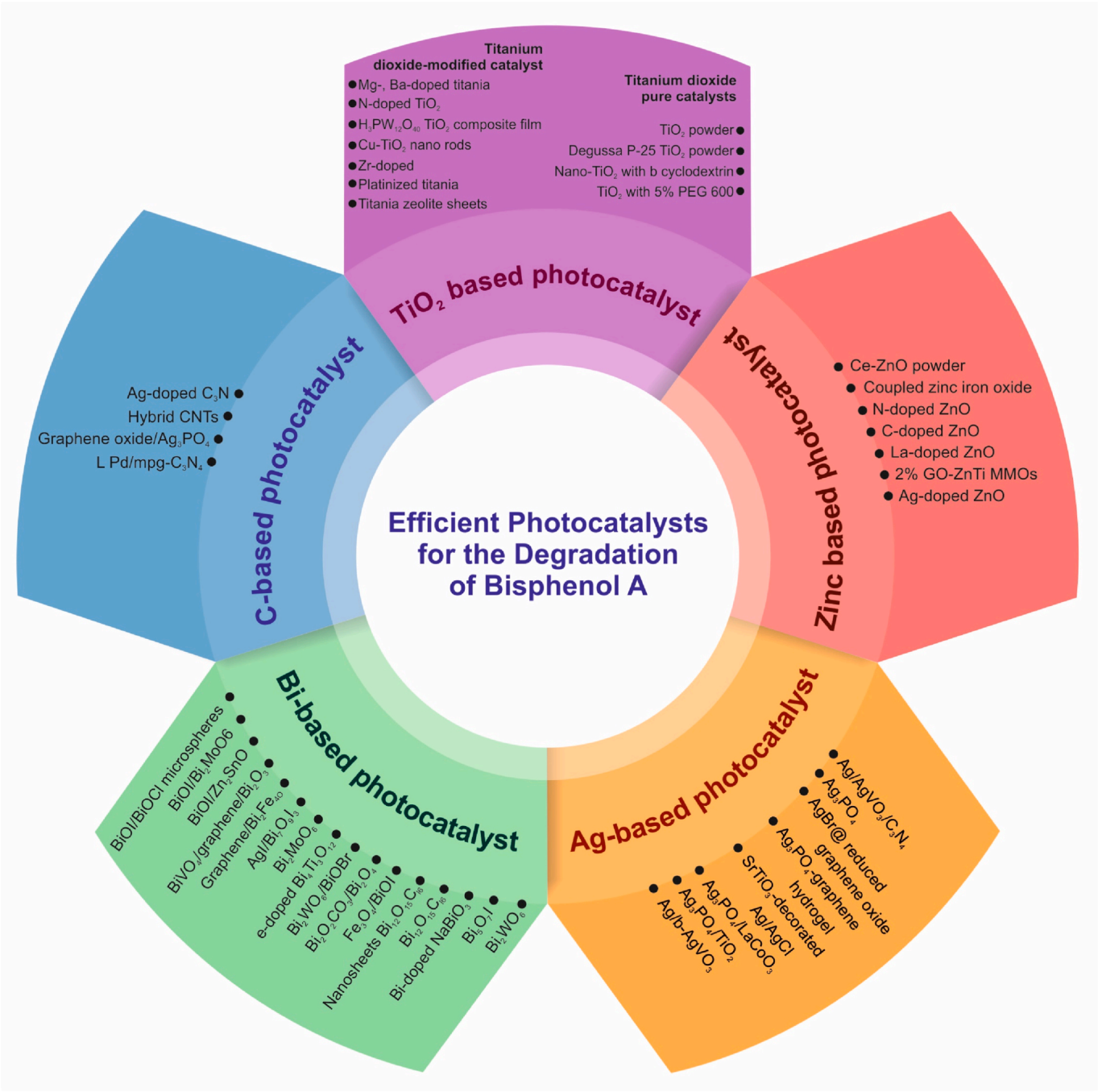

Fig. 3. Classification of different photocatalysts used for the degradation of BPA.

design, enhancing the selectivity of degradation pathways and improving process scalability are essential steps toward making photocatalytic treatment a viable technology for widespread environmental remediation.

4. Degradation using biological methods

4.1. Microbial remediation

Among all remediation methods, microbial remediation of BPA has emerged as the most essential and significant method (Zhang et al., 2007; Eltoukhy et al., 2020). This is primarily due to its cost-effectiveness and minimal disruption to the contaminated environment, especially compared to alternative degrading methods (Eltoukhy et al., 2020). Microbial metabolism plays a significant role in the biodegradation of BPA in the natural environment (Choi and Lee, 2017; Li et al., 2020; Yang and Zhao, 2023). Several research studies have identified bacterial strains capable of BPA degradation across diverse environments, including saltwater, rivers, wastewater, soil, desert soil, leachates, sludges, and plant roots (Sasaki et al., 2005; Toyama et al., 2009; Fischer et al., 2010; Kang et al., 2015; Suyamud et al., 2018; Louati et al., 2019; Zühlke et al., 2020; López-Moreno et al., 2021; Das et al., 2023). In the scientific literature, 109 bacterial strains have been identified as capable of degrading BPA. The genera *Pseudomonas, Sphingomonas, Bacillus, Sphingobium*, and *Cupriavidus* are most efficient in degrading BPA (de Morais Farias and Krepsky, 2022). Bacterial strains isolated from sediment environments, such as *Novosphingobium, Pseudomonas, Alcaligenes, Sphingomonas, Nitrosomonas,*

Table 5
BPA removal performance by Photocatalysts.

Photocatalysts	Method	Characterization	Photocatalytic Activity and Efficiency	References
Ag_2O/Bi_5O_7I	Modifying Ag_2O on porous Bi_5O_7I nanosheets, they extended the optical absorbance range and improved charge separation efficiency.	XRD, TEM	• Ag_2O and Bi_5O_7I, achieving 7.23 and 4.39 times higher BPA degradation, respectively. • Excellent photocorrosion resistance.	Li et al. (2020)
$Ag_3PO_4/g\text{-}C_3N_4$	Calcination and precipitation methods	XRD, XPS SEM, TEM, Photoluminescence spectroscopy (PL), UV–vis DRS, BET surface area test	92.8% bisphenol A degradation	Mei et al. (2018)
$Bi_{12}O_{15}C_{16}$	Facile solvothermal method	XRD	Degrading BPA 13.6 and 8.7 times faster compared to BiOCl and TiO_2	Wang et al. (2016).
$Bi_{12}O_{17}C_{l2}$	Solvothermal route	XRD	Degrade BPA 20 and 40 fold higher than those by BiOCl and TiO_2 (P25) respectively	Wang et al. (2017)a,b
$Bi_2WO_6/CoFe_2O_4$	Two-step hydrothermal method	XRD	Efficiency of $Bi_2WO_6/CoFe_2O_4$ is high compared to pure Bi_2WO_6 after 120 min	Wang et al. (2013)
$Bi_7O_9I_3$	Pseudo first-order kinetics according to the Langmuir–Hinshelwood model.	SEM, LC–MS	• 99% BPA degradation in 60 min • Perform 16 times greater than that of P25 catalyst based on TiO_2	Xiao et al. (2012b)
BiOI/BiOCl composite	One-pot, solvothermal method	LC–MS	• 100% photodegradation efficiency	(Xiao et al., 2012a)
Bismuth Ferric Nanomagnetic Photocatalyst (BFO NMPs)	Sol-gel method	FE-SEM, TEM, PL, XRD, UV–Vis DRS, VSM, EDX, and FTIR	• BPA removal more than 82%	Mahmoudian et al. (2022)
C-doped ZnO	Hydrothermal method.	XRD, Nitrogen physisorption, Raman spectroscopy, FTIR, UV–vis DRS, and photoluminescence spectra	100% BPA degradation and 70% BPA mineralization after 24 h.	Bechambi et al. (2015)
CdS/COF	Facile Sonochemical irradiation method	SEM, HR-TEM, XPS, Raman spectra, XRD, BET surface area test	85.68% BPA removal in 3 h	Sun et al. (2021)
Ce–ZnO	Sol–gel method	XRD, FTIR, UV–Visible spectroscopy, photoluminescence spectra (PL), and Raman spectroscopy	100% BPA degradation and 61% BPA mineralization after 24 h of UV irradiation	Bechambi et al. (2016)
Co Codoped TiO_2	Wet impregnation method	XRD, FTIR SEM, TEM, UV–vis spectrophotometer and XPS	• 1.5% Co and 0.5% N-codoped TiO_2 shows higher activity than commercial TiO_2. • Total organic carbon (TOC) removal reached 97%, indicating complete BPA mineralization	Garg et al. (2019)
Cobalt and nitrogen co-doped TiO_2 nanoparticles	Wet impregnation	XRD, Raman Spectra, FTIR Spectroscopy, SEM, TEM, UV–vis spectrophotometer, and XPS	97% removal of total organic carbon (TOC) indicating complete BPA mineralization	Garg et al. (2019)
Co-doped BiOCl	Hydrothermal process	XRD	Degradation rate 3.5 times faster than pure BiOCl	Wang et al. (2018)
$CuOx/BiVO_4$	Efficient separation of photogenerated electron-hole pairs occurred at the p–n heterojunction between n-type $BiVO_4$ and p-type CuO (or Cu_2O) semiconductors	XRD, SEM–EDS, HR-TEM, and UV–vis DRS	• Pure $BiVO_4$ showed BPA degradation. • Addition of copper improved photocatalytic performance • Optimal results were achieved with the catalyst containing 0.75 wt% Cu	(Kanigaridou et al., 2017)
Fe_2O_3-doped TiO_2	Sol-gel method	FTIR, FESEM-EDX, XRD, and DRS	90.33% BPA removal efficiency	(Asadi et al., 2020)
Me/TiO_2 (Me: Pt, Ru, Pd, Rh)	Wet impregnation method	H_2 chemisorption, XRD, BET and UV–vis DRS	• Pt/TiO_2 catalyst shows higher efficiency under solar irradiation. • Rh/P25 catalyst show increased activity in the presence of 20 mg/L humic acid (HA), which is 2.5 times higher than that obtained in ultrapure water	Repousi et al. (2017)
MIL-101-NH_2@TpMA and UiO-66-NH_2@TpMA	Step-by-step assembly method	SEM, TEM, XRD and FT-IR	99% degradation efficiency	Lv et al. (2020)
MIL-88B (Fe)/persulfate/visible light (M88/PS/Vis)	ECOSAR system	XRD	• BPA removal rate: 26% with M88/Vis; 34.1% with M88/PS • BPA degradation is 4.7 times higher in M88/PS/Vis than that of M88/PS	Lin et al. (2020)a,b
$NaBiO_3$	Chemical oxidation	XRD	99.8% BPA degradation and 86% total organic carbon removal	Ding et al. (2016)
Nano $Fe_xZn_{1-x}O$ (x = 0.01, 0.03, 0.05)	Solution combustion method	X-ray photoelectron spectroscopy, GC-MS	• 99.1% of Bisphenol A was degraded within 90 min • 45.3% of total organic carbon was removed, and chemical oxygen demand decreased to 11.2%.	Dhiman et al. (2017)

(*continued on next page*)

Table 5 (*continued*)

PI-g-C_3N_4	Amidation reaction between perylene tetracarboxylic dianhydride (PTCDA) and graphitic carbon nitride (g-C_3N_4)	XRD	96% of BPA degraded within 60 min	Zhang et al. (2018)
Reduced graphene oxide–titanium dioxide photocatalyst (rGO–TiO_2)	Hydrothermal method	XRD, SEM, TEM, UV–vis DRS	0.5 g/L 1% rGO–P25 degrade 100% BPA in 30 min under sunlight	Yu et al. (2019)
Rhombohedral α-Fe_2O_3	P123 soft template assisted method.	XRD, BET, SEM and HRTEM	Degrade 91% of BPA	Ye et al. (2019)
TiO_2@nanodiamond	Water-based precipitation	XRD	• Degrade 10 ppm of bisphenol A within 100 min • Solar energy-driven photocatalysis.	Hunge et al. (2021)
Titanium dioxide (TiO_2)	Horizontal circulating bed photocatalytic reactor (HCBPR)	XRD	Removal of 95% total organic carbon (TOC) and 97% BPA after 6 h of UV radiation	Wang et al. (2009)
Tm^{3+}: CeO_2/Palygorskite (Pal) nanocomposites	Hydrothermal-deposition method	XRD, SEM, TEM, Photoluminescence spectroscopy (PL) and Mott-Schottky analysis	Tm^{3+}: CeO_2/Pal provide active site for direct Z-scheme for photocatalytic degradation of BPA in waste water.	Wang et al. (2019)a,b
ZnAlTi-LDO supported C_{60}@AgCl	Coprecipitation-light-induced method	XRD, FTIR SEM, TEM	90% BPA degradation rate	Ju et al. (2018)
ZnO wrapped ZnHCF	Nanofabrication of ZnO@ZnHCF with *Azadirachta indica*	GC–MS analysis	• BPA degradation followed first-order kinetics, achieving 97% removal. • Reduced the BPA's half-life compared to bare ZnHCF and ZnO.	Rani and Shanker (2018)
Zr-doped TiO_2	Multi-step sol–gel process using metallo-organic chemicals as the precursors.	XRD	Improved performance by an upward shift of the conduction bands due to increasing Zr content, enhancing photogenerated electron reduction power	Gao et al. (2010)
Z-scheme biochar@$CoFe_2O_4$/Ag_3PO_4	Visible light irradiation ($\lambda \geq 420$ nm)	TEM, XRD, FT-IR, XPS, UV–Vis BET, EIS and VSM analysis.	73.94% photocatalytic activity and 58.96% removal rate of TOC	Zhai et al. (2020)
Titanium dioxide (TiO_2)	Horizontal circulating bed photocatalytic reactor (HCBPR)	XRD	Removal of 95% total organic carbon (TOC) and 97% BPA after 6 h of UV radiation	Wang et al. (2009)

Achromobacter, Serratia, Klebsiella, Bordetella, Pandoraea, Streptomyces, Bacillus, and Cupriavidus, have also shown potential in decomposing BPA (Tang et al., 2008; Zhang et al., 2013; Huang et al., 2017). The persistent contamination of BPA in the environment has prompted many bacteria to adapt to these pollutants (Zühlke et al., 2017; de Morais Farias and Krepsky, 2022), promoting specific enzymatic pathways in bacteria to degrade and use biphenyl as a growth substrate, carbon, and an energy source (Zhang et al., 2013; Zühlke et al., 2017).

Bacteria split BPA at the carbon bridge, resulting in monoaromatic hydrocarbons, metabolized further within bacterial cells (Zhang et al., 2013; Zühlke et al., 2017). Microorganisms respond to biological stress caused by BPA exposure by regulating the expression of genes related to xenobiotic degradation, flagellin production, and biofilm formation (Cydzik-Kwiatkowska et al., 2021). Bacteria can initiate biodegradation by utilizing various catabolic biochemical reaction types. They undergo two main biodegradation mechanisms: oxidative skeletal rearrangement, which involves an aliphatic methyl group in the BPA molecule, and hydroxylation of phenolic rings followed by aromatic ring detachment (Noszczyńska and Piotrowska-Seget, 2018). Enzymes secreted by microorganisms, such as spore laccase of *Bacillus* and cytochrome P450 monooxygenase of *Sphingomonas bisphenolicum* strain AO1, are efficient contributors to BPA degradation (Das et al., 2018; Jia et al., 2020). BPA degradation by bacteria is rapid and efficient under aerobic conditions, with minimal degradation (less than 10%) observed under anaerobic conditions (Kang and Kondo, 2002). A study by Li et al. (2023) revealed that Pseudomonas sp. P1 exhibited robust tolerance to diverse environmental factors at the genetic level, enhancing our understanding of the mechanisms involved in BPA degradation.

Degradation of BPA is time-consuming; researchers have turned to meta-omics approaches to identify the active microbiota and microbial dynamics involved in BPA mitigation (Sharma et al., 2022). Multi-omics (includes metatranscriptomics, metaproteomics, metagenomics, and metabolomics) approaches have been crucial and practical tools for understanding the mechanism of action of xenobiotics and mitigating the toxicity of BPA exposure (Ewald et al., 2021; Sharma et al., 2022; Fan et al., 2022). These approaches have helped identify active microbiota involved in BPA degradation and highlighted the impact of processing activities on BPa transit in food items (Nagarajan et al., 2022). Bioaugmentation with a consortium has been demonstrated to improve the removal of BPA and BPS in river water-sediment microcosms (Chang et al., 2014). In the aerobic degradation of BPA, adding various compounds such as yeast extract, sodium chloride, cellulose, Brij 30, Brij 35, rhamnolipid, and surfactin enhanced the process. Among these additives, rhamnolipid demonstrated superior efficacy in promoting BPA degradation compared to others. Additionally, the accumulation of 2, 4-bis (1,1-dimethyl ethyl) phenol, an intermediate product of BPA degradation, was observed in sediments (Chang et al., 2011). Microbial remediation rates can be slow and often depend on the bioavailability of compounds and the specific bacterial species involved (Godiya and Park, 2022; de Morais Farias and Krepsky, 2022).

However, most studies relied on a single microorganism. They examined omics alterations at only one or a few BPA concentrations, primarily due to the high costs and complexity of the omics analyses. Future research should explore a broader range of BPA concentrations and varying time points to better understand microbial communities' dose-response relationships and temporal dynamics during BPA degradation. Integrating multi-omics data with advanced computational models could provide a deeper understanding of the biological networks and pathways involved in BPA remediation. Additionally, enhancing the efficiency of BPA bioremediation strategies by including diverse environmental settings and microbial consortia will be crucial for predicting and improving the effectiveness of BPA bioremediation strategies. The Microbial remediation species capable of BPA removal are summarized in Supplementary Table 1. Heat map showing the degradation of BPA from different species (Fig. 4).

4.2. Phytoremediation

The presence of typical endocrine-disrupting compounds (EDCs), such as Bisphenol A (BPA), has detrimental effects on aquatic organisms, prompting a shift in the focus of water quality management towards the removal or reduction of BPA to non-hazardous levels (Gattullo et al., 2012). Researchers facing the challenge of eradicating environmental BPA encounter numerous obstacles. Conventional remediation techniques are often costly and environmentally unsustainable (Ghosh and Singh, 2005; Phouthavong-Murphy et al., 2020). Recent biological

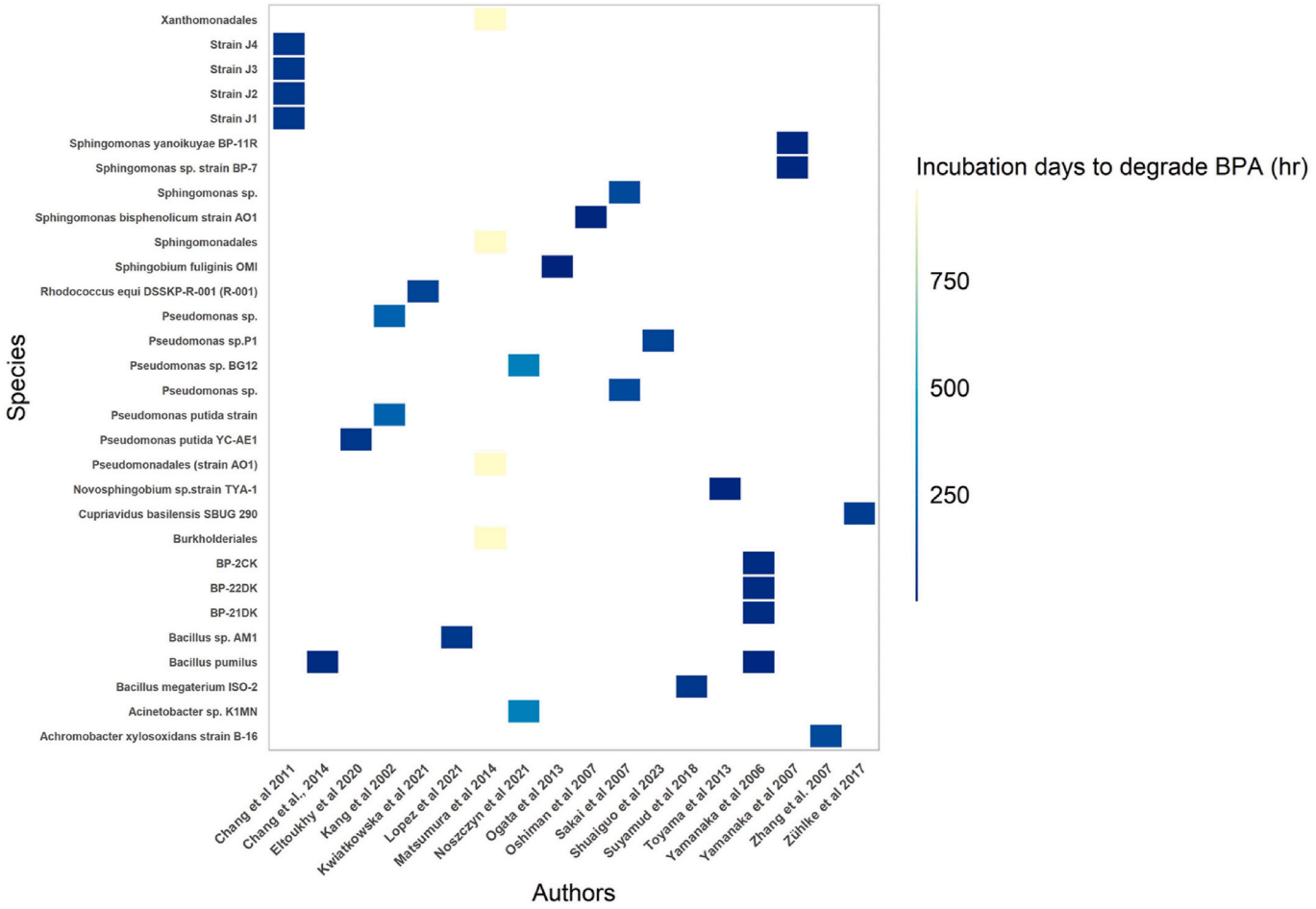

Fig. 4. Heat map showing the degradation of BPA from different species.

methods, both in situ and ex-situ, offer promising solutions. These methods include bioaugmentation, phytobial remediation, phytoremediation, flocculation, bio flocculant cationization, nano phytoremediation, biostimulation, and genetic modifications of microbes and plants, all recognized as viable approaches for cleaning up Bisphenol contaminants (Mohammed et al., 2024). Previous research demonstrates that BPA degradation can occur through microbial metabolism, biodegradation, and enzymatic processes within flora and fauna (Mohapatra et al., 2010; C. Y. Wang et al., 2017a,b). Strategies for BPA treatment encompass the utilization of bacterial strains and communities, fungi, cultured plant cells, and microalgae (Hirano et al., 2000; Chai et al., 2003; Hamada et al., 2002; Hirooka et al., 2005; Nakajima et al., 2007). Recent advancements in bioremediation, such as employing bacterial consortia for BPA biodegradation, have demonstrated effectiveness (Zhao et al., 2008; Roh et al., 2009; Eio et al., 2015).

Phytoremediation emerges as a green biotechnology method, offering an economical, sustainable, and socially acceptable means to sequester BPA from contaminated soil and water. This method utilizes plant and microbial associations to extract, stabilize, transfer, and decompose hazardous contaminants from the environment (Kristanti and Hadibarata, 2023; Kristanti et al., 2023a; Kristanti et al., 2023b). Phytoremediation mechanisms include phytostabilization, phytodegradation, phytoextraction, phytovolatilization, phytostimulation, and rhizofiltration, tailored to the contaminant type and medium (Fu et al., 2022). However, natural adaptation periods and high contaminant concentrations may hinder phytoremediation efficacy, which can impede plant growth, survival, and yield (Issac et al., 2024). Specific algal and herbaceous species show potential for BPA removal from aqueous environments, albeit with limited practical application due to inherent characteristics (Loffredo et al., 2010; Gattullo et al., 2012; Zhao et al., 2021). In contrast, submerged macrophytes are increasingly recognized as effective agents for phytoremediation of organic pollutants in aquatic systems (Zhao et al., 2021).

In phytoremediation, various species across different groups have demonstrated the ability to degrade BPA. Microalgae such as *Chlorella fusca*, *Monoraphidium braunii*, *Pseudokirchneriella subcapitata*, *Scenedesmus acutus*, and *Coelastrum reticulatum* have shown significant potential in BPA degradation (Hirooka et al., 2005; Gattullo et al., 2012). Among grasses, species like *Cynodon dactylon*, *Festuca arundinacea*, and *Lolium perenne* have also proven effective (Loffredo et al., 2010). Legumes such as *Trifolium repens* and Glycine max have shown BPA tolerance and degradation capabilities (Ferrara et al., 2006). Additionally, crops like *Cucumis sativus* and *Triticum aestivum* contribute to remediation efforts (Loffredo et al., 2010). Aquatic plants, such as *Dracaena sanderiana*, and trees like *Eucalyptus perriniana*, are also highly effective (Saiyood et al., 2010; Hamada et al., 2002) while flowering plants like *Digitalis purpurea* and *Datura stramonium* extend the diversity of species used in phytoremediation (Toyama et al., 2013).

Microalgae, sensitive to various micropollutants, including EDCs, heavy metals, and hydrophobic organic contaminants (K. Guo et al., 2017a,b; Zhang et al., 2019) serve as reliable indicators for ecotoxicological evaluations (Nakajima et al., 2007). Among microalgae, *Chlorella fusca* removed 85% of BPA (40 μM) under light conditions and 22% under dark conditions within 120 h, indicating that light enhances its degradation capabilities (Hirooka et al., 2005). Similarly, *Chlorella vulgaris* successfully eliminated BPA at 20 mg/L within seven days (Gulnaz and Dincer, 2009), while *Stephanodiscus hantzschii* showed BPA removal rates of 88%–99% at low concentrations (0.01–0.10 mg/L) over 16 days

(Li et al., 2009). Additionally, *Monoraphidium braunii* removed 35%–48% of BPA (2–10 mg/L) within two days (Gattullo et al., 2012), further emphasizing the potential of microalgae for rapid BPA remediation. Cyanobacteria, particularly effective in reducing bisphenol toxicity, highlight the importance of biological techniques in mitigating BPA effects (Shimoda and Hamada, 2009; Hakim and Alghanmi, 2024). Blue-green algae ability to glycosylate BPA into less harmful forms revealed their significance in environmental toxicology (Nakajima et al., 2007). Other submerged aquatic plants have also shown impressive results such as *Ceratophyllum demersum* and *Myriophyllum spicatum* could completely remove BPA (0.5–5.0 mg/L) within three days (Zhao et al., 2021). Furthermore, aquatic weeds such as *Lemna* sp. and *Spirogyra* sp. achieved 68%–95% BPA removal in planted reactors during the first ten days (Garcia-Rodríguez et al., 2015). In the case of higher plants, *Panicum virgatum* (switchgrass) degraded 40.4%–46.1% of BPA (20 mg/L) over a period of 84–85 days (Phouthavong-Murphy et al., 2020), showcasing the long-term potential of terrestrial plants in phytoremediation. Additionally, fungi have demonstrated high BPA degradation efficiencies, with species like *Fusarium sporotrichioides* and *Aspergillus terreus* MT-13 achieving over 99% BPA removal (40 mg/L) in the dark within 14 days (Chai et al., 2005). Various botanical species offer significant phytoremediation potential for organic pollutants, though some are constrained by invasive tendencies (Loffredo and Traversa, 2016). Phouthavong-Murphy et al. (2020) reported that switch grass (*Panicum virgatum*) was able to remove between 40.4% and 46.1% of BPA from an initial concentration of 20 mg/L over a period of 84–85 days. Additionally, mangrove species like *Bruguiera gymnorhiza* can remove complete (100%) BPA with in 51 days (Saiyood et al., 2013). The Phytoremediation species capable of BPA removal are summarized in Fig. 5. (Supplementary Table 2).

Despite its potential, natural phytoremediation processes can be slow and may be hindered by high costs, high contaminant concentrations, the generation of toxic byproducts, and the requirement for large areas of land, all of which can affect plant growth and survival (Issac et al., 2024). To address these limitations, future research should focus on enhancing phytoremediation efficiency through genetic modifications and synthetic amendments that improve plant's ability to tolerate and degrade xenobiotics (Kristanti and Hadibarata, 2023). Additionally, artificially constructed wetlands, which leverage phytoremediation mechanisms to treat industrial effluents, sewage effluents, and medical residues, represent a promising application of this technology (Sharma et al., 2022). Understanding the underlying mechanisms is essential to develop new and more efficient management strategies. Optimizing bioremediation processes to enhance cost-effectiveness, minimize toxic byproducts, and reduce land use requirements should be key focus areas for future research. These advancements could significantly improve the removal rates of BPA and other contaminants, offering a viable and eco-friendly solution for environmental remediation.

4.3. Horseradish peroxidase (HRP)-mediated degradation

Enzyme-mediated oxidizing treatment has emerged as a promising biological method for the rapid and selective degradation of BPA, even at trace concentrations (Hong-Mei and Nicell, 2011; Liu et al., 2020; Cai et al., 2021). Enzymes, isolated from their native organisms, exhibit specificity towards particular compounds, high stoichiometric efficiencies, and reaction rates (Karam and Nicell, 1997). Naturally occurring enzymes, such as peroxidases and laccase, have shown promise in degrading BPA. Researchers have explored surface action additives to protect and enhance enzyme activity during BPA degradation, namely, Rhamnolipid, cationic (Hexadecyl trimethyl ammonium bromide), anionic (Sodium dodecyl benzenesulfonate), polymeric (Polyethylene glycol), and non-ionic (Triton X-100) additives showed improvement in improvement in BPA removal from wastewater (Alshabib and Onaizi, 2020). Horseradish peroxidase (HRP), a heme protein with an iron porphyrin active center, stands out as an effective catalyst for BPA oxidation and degradation in the presence of hydrogen peroxide (Pylypchuk et al., 2020). The oxidative transformation of substrate

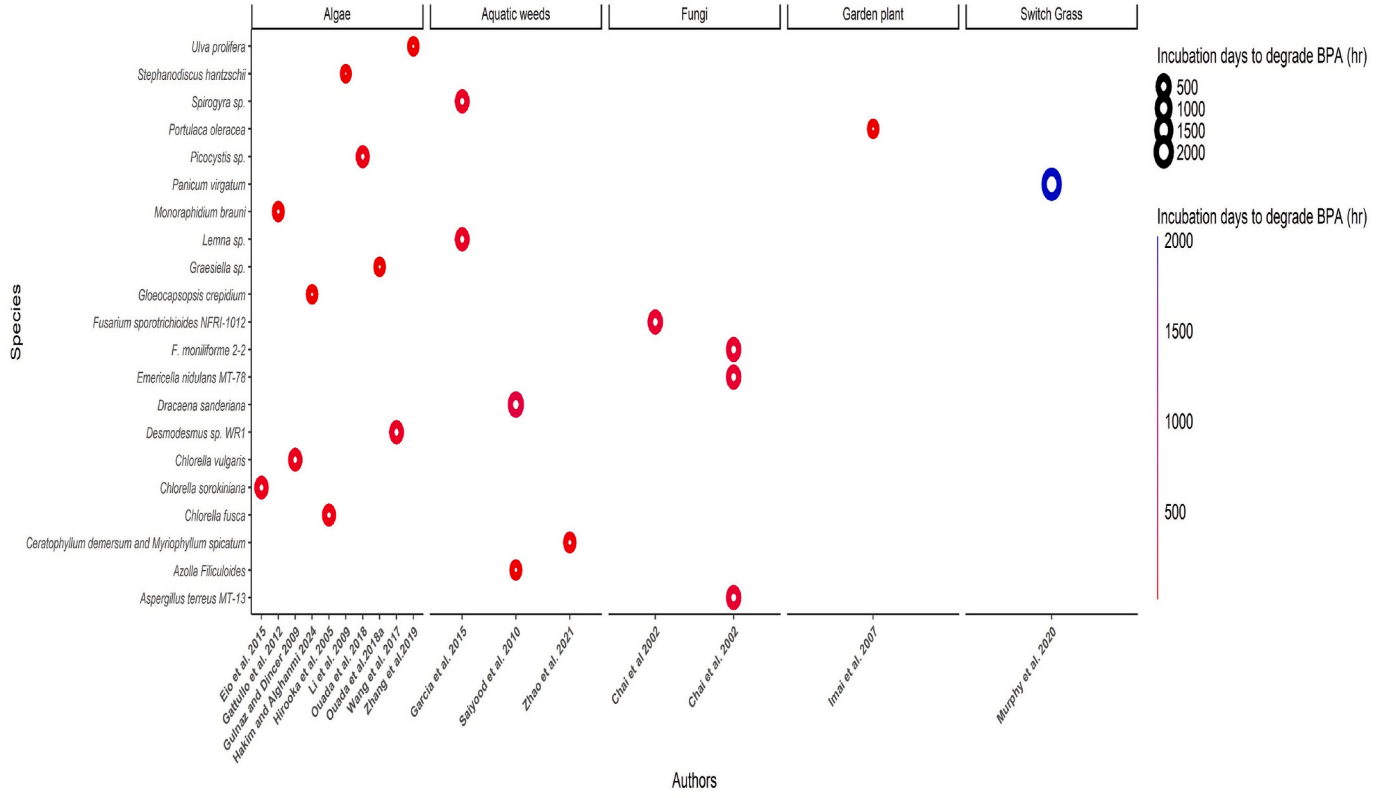

Fig. 5. Bubble plot analysis showing the degradation of BPA using phytoremediation process using different species.

molecules by HRP results in non-toxic polymers and other compounds that are easily removable from water (Cai et al., 2021; Klibanov et al., 1983).

HRP acts as a biocatalyst when combined with hydrogen peroxide, facilitating the oxidation of phenolic compounds to generate free radicals or quinones. These reactive species interact with other phenolic molecules, forming oxidized products, typically water-insoluble polymers and oligomers. These products can be removed through sedimentation or filtration (Klibanov et al., 1983).

Hong-Mei and Nicell (2008) demonstrated the catalytic oxidation of BPA by HRP in a reverse micelle system, where factors such as water-to-surfactant ratio, pH, temperature, and BPA concentration significantly influenced transformation efficiency. Moreover, a hybrid system combining a photocatalyst and an enzyme sustains enzymatic catalysis without causing enzyme inactivation, as shown by Xu et al. (2013) and Du et al. (2024). This hybrid approach effectively treats phenolic Endocrine Disrupting Chemicals (EDCs), showcasing potential for environmental remediation. Cai et al. 2021 incorporated HRP into the Fe-based metal-organic framework MIL-88B(Fe), achieving a remarkable removal efficiency of BPA, reaching up to 99.2% within just 1 h, especially with the addition of the hydrophilic agent, polyethylene glycol. Similarly, Liu et al., 2020 observed improved performance of HRP when encapsulated within nano gels, resulting in enhanced removal efficiencies of phenol and BPA while improving the biodegradability of phenolic compounds through leveraging their redox potentials and binding affinities with enzymes. Adequate conditions for the oxidative degradation of BPA by HRP have been identified, including a pH of 9.0, a temperature of 25 °C, and maintaining an appropriate molar ratio of hydrogen peroxide to BPA. However, it is noted that the activity of HRP directly influences the conversion rate of BPA, with higher levels of HRP correlating with higher conversion rates.

Nevertheless, the residual activity of HRP tends to decline gradually over time, possibly due to the formation of polymer products during the oxidation process of BPA (Hong-Mei and Nicell, 2011). Furthermore, Xu et al. (2013) demonstrated the effectiveness of immobilized HRP, achieving a loading of 285 mg/g with 70% enzyme activity through adsorption on a modified poly (methyl methacrylate-co-ethyl acrylate) (PMMA CEA) microfibrous membrane support. This immobilized form exhibited improved stability and reusability, retaining about 50% of its initial activity after six repeated runs. Importantly, it showed significantly higher BPA removal efficiency (93% in 3 h) compared to free HRP (61%) and PMMA CEA alone (42%).

However, despite the advantages enzymes offer over traditional treatment methods, their high cost remains a significant challenge for full-scale application. Aromatic pollutants, often found at low concentrations, necessitate substantial amounts of biocatalysts for effective treatment, coupled with the issue of continuous discharge of biocatalysts when treating contaminants in an aqueous phase (Karam and Nicell, 1997; Hong-Mei and Nicell, 2008). These challenges underscore the need for further research to optimize enzyme-based approaches for practical environmental remediation applications.

5. Degradation using mechanical methods

One well-known endocrine disruptor is BPA, a diphenylmethane derivative that has abilities similar to hormones and is consumed globally each year by more than 3.8 million tons (Gies, 2011). Additionally, due to their harmful impacts on both the environment and human health, EDCs have been getting more attention in recent years (Umar et al., 2013; Molkenthin et al., 2013; Chen et al., 2016; Liu et al., 2018; Diao et al., 2018). Throughout the world's aquatic environments, endocrine disruptors have been discovered in drinking water, groundwater, and surface water (Gies, 2011).

There is literature on BPA removal methods using end-of-pipe techniques, which can be categorized into two categories: technologies based on processes that do not include chemical transformation, such as adsorption and filtering, and biochemical processes, which are driven mainly by reactive oxygen species (ROS). The latter comprise electrochemical, photocatalytical, photoelectrochemical, and other advanced oxidation processes (AOPs), including ultrasonic degradation, Fenton, Photo Fenton, and Ozonation. Advanced oxidation processes are identified by the direct formation of reactive oxygen species, such as per hydroxyl and hydroxyl radicals, which are highly reactive with organic contaminants due to their high oxidation potential (Ren et al., 2013). Of the techniques mentioned above, the most promising ones for reducing environmental effects are those that don't require extra chemicals, such as sonolysis and electrochemical treatment.

5.1. Degradation using sonolysis (ultrasound-induced chemical reaction)

Sonolysis is the technique of producing HO• in an aqueous medium by using ultrasonic irradiation without the need for catalysts. It is one of the effective methods for breaking down organic pollutants in water (Ollis et al., 1991). Ultrasound, which is defined as a frequency range of 18 kHz to 10 MHz, has a wide range of chemical and physical effects.

In Sonolysis, Ultrasound frequencies (20 kHz–2 MHz) are used (Mason, 2002). Acoustic cavitation occurs in this frequency range. The acoustic cavitation bubbles, which are essentially growing, pulsating, and collapsing microreactors, are the main components of the ultrasonic activity. On a microsecond, an '*ultrasonic cavitation bubble*' compresses adiabatically when it pulses or collapses, creating a hot nucleus (temp: 5000K) with pressures (100 Pa), causing the decomposition of water and organic pollutants (Meng et al., 2019; Naddeo et al., 2010; Bang and Suslick, 2010; Suslick et al., 1990). Highly reactive radicals such as OH, H, and H_2O_2 radicals are created during the breakdown of water molecules, and these radicals damage the organic matrix and break down the molecules in pollutants to achieve the degradation effect. A low-volatility hydrophilic or hydrophobic molecule cannot enter the bubble; instead, it will react with °OH radicals within the bulk or boundary region and become hydroxylated (Meng et al., 2019), resulting in the detection of H_2O_2, HNO_2, and HNO_3 in the solution. (Inoue et al., 2008).

$$H_2O + US \rightarrow HO\bullet + H\bullet$$

$$O_2 + US \rightarrow 2O\bullet$$

$$H\bullet + O_2 \rightarrow \bullet OOH$$

$$O\bullet + H_2O \rightarrow 2HO\bullet$$

$$HO\bullet + HO\bullet \rightarrow H_2O_2$$

According to Suslick et al. (1981), 580 kHz yields the best sonochemical degradation in an aqueous solution. The breakdown occurs in the subsequent sequence within 30 min longer time period is 580 kHz (92–97%) > 1000 kHz (90–94%) > 28 kHz (62–67%). The best TOC reductions and the fastest bisphenol A degradation were produced at high US intensities. According to Guo and Feng's (2009) study, BPA degradation is facilitated by increasing ultrasonic intensity.

Aeration slows down the rate of BPA degradation as a small number of radicals are created at the bubble's surface due to aeration (Zhang et al., 2011). It has been demonstrated that oxygen appears to provide superior outcomes than air for removing organic compounds in the high-frequency range (Mead et al., 1976). However, BPA is eliminated more quickly when oxygen is substituted for air. The use of oxygen in sonochemical treatment makes sense because it prevents the creation of unwanted NOx species and yields the best outcomes in terms of BPA eradication (Torres et al., 2007a,b).

5.2. Degradation using sonoelectrochemical treatment

The sonoelectrochemical treatment demonstrates significant degradation within 30 min (Dietrich et al., 2017). Ozone, oxygen, and

hydrogen peroxide are produced as byproducts of hydroxyl radical electrochemical generation, which takes place at the anode through an electron transfer. To prevent the production of undesirable oxygen, a large overpotential is required for the anode material to produce oxygen. For this, substances such as boron-doped diamond (BDD) are applied.

$$BDD + H_2O \rightarrow BDD(\bullet OH)\ Adsorbed + H^+ + e^-$$

5.3. Degradation using sonocatalysts

The occurrence of HO during the water degradation process under ultrasound irradiation makes it possible to degrade BPA by only 20% using ultrasound alone. However, BPA degradation can be enhanced by adding an effective oxidizing agent, catalyst, or Fenton-like reagent. ElShafei et al. (2014) and Khataee et al. (2017) stated that reactive radicals couldn't be generated from water in sonolysis efficiency due to the absence of an oxidant, meaning ultrasound could not eliminate BPA alone.

In the study of Dietrich et al. (2017), it was observed that when two processes - ultrasound and electrochemical oxidation were combined, it was discovered that over 90% of BPA could be eliminated in 30 min at a starting concentration of 1 mg/L and low-frequency ultrasound (24 kHz, amplitude: 25 μm and 125 μm) at 5 V or 10 V is an effective method of eliminating bisphenol A in an aquatic medium by electrochemical, sonochemical, and sonoelectrochemical approaches.

Diao et al. (2020) demonstrated, under ultrasound (US) irradiation, the viability of using sludge biochar catalyst (BC) as a persulfate (PS) activator to accelerate the breakdown of BPA. At 20 mg/L of BPA concentration, approximately 98% degradation could be accomplished in 80 min. It was discovered that humic acid (HA) and HCO_3 exhibited potent inhibitory effects on the breakdown of BPA, but coexisting chemicals like Cl^-, SO_4^{-2}, and NO_3 showed no discernible inhibition.

According to previous research, ultrasonic/photocatalysis coupling is more efficient for mineralizing organic pollutants (Berberidou et al., 2007; Torres et al., 2008; Stock et al., 2000). According to Torres-Palma et al. (2010), Ultrasound, Fe^{2+}, and TiO_2, combination photoassisted technique shortened the time needed for removal of BPA are 75 and 60 min, respectively, using TiO_2 (conc: 10 and 50 mg/L, respectively). Combining the three systems results in efficient and fast complete mineralization of BPA. Synergistic effects, however, were not noted. The synergy among the systems addresses difficulties associated with individual AOP applications, such as high catalyst and oxidant loading in photo-Fenton and TiO_2 photocatalysis or prolonged irradiation times in ultrasound. While the study outlines the synergy among the three systems, a deeper mechanistic understanding of how the combination enhances BPA degradation and mineralization is needed.

In an experiment conducted by Guo et al., in 2009, 50 mL of 100 g/L BPA was treated with US/O_3 at various flow rates, and degradation efficiencies were also compared. He also prepared a 50 mL mixture containing 100 g/L BPA and 25 g/L CCl_4, which was then exposed to ultrasonic irradiation at an ultrasonic intensity of 60W/cm^2. In both cases, he observed higher degradation efficiency than in a single system alone. Additionally, the study identifies •OH radical-mediated oxidation as the primary pathway for BPA degradation during sonochemical processes. Furthermore, the identification of key intermediates, such as monohydroxylated BPA, phenol, 4-isopropenylphenol, hydroquinone, 4-hydroxyacetophenone, 2-hydroxypropionic acid, and glycerol, provides valuable insights into the degradation mechanisms involved. Overall, this research contributes to understanding effective methods for treating BPA-contaminated water and sheds light on the underlying chemical processes driving its degradation.

When BPA is exposed to ultrasonic radiation, some of the radicals that typically generate these chemicals are employed in the processes that break down BPA. In contrast, higher concentrations of H_2O_2 and HNO_3 are produced when water is exposed to UV radiation. The addition of $FeSO_4$ facilitates BPA degradation, and the amount of time needed for BPA to break down was not shortened by the gradual addition of $FeSO_4$, but the degree of mineralization was much enhanced (Inoue et al., 2008).

However, in 2011, Zhang et al. showed that low concentrations of H_2O_2 could effectively promote the ultrasonic breakdown of BPA. Nevertheless, it was demonstrated that the breakdown efficiency of BPA was reduced by further increasing the dose of H_2O_2 (the mole ratio H_2O_2: BPA >200:1). Because H_2O_2 can generate more OH when exposed to ultrasonic irradiation (Gogate and Pandit, 2004), the breakdown of BPA is enhanced. However, because H_2O_2 acts as an OH-scavenger and competes with BPA for OH, an excessively high concentration of H_2O_2 may prevent radical-induced oxidation. The study should evaluate the environmental and health impacts of additives like H_2O_2 at various concentrations to ensure safety and sustainability.

Pahontu et al., (2023) used three distinct frequencies - 1146 kHz, 864 kHz, and 580 kHz to study the effects of frequency as well as several additional substances, including Carbon tetrachloride, $FeSO_4$ $7H_2O$, and Ethyl anthraquinone. The efficiency of ultrasonic degradation exceeds that of photocatalytic oxidation processes, which require longer exposure times and expensive catalysts. It also compares favorably with ultraviolet light irradiation. Degradation processes under aerobic or anaerobic conditions show lower efficiencies and longer durations, especially at lower initial BPA concentrations.

Torres et al. (2007) studied BPA mineralization using the synergetic effect of ultrasound, UV, and Fe (II) treatment. To increase the effectiveness of BPA degradation and decrease the creation of byproducts, more study is required to optimize the ultrasonic-UV-iron (II) process parameters, such as Fe^{2+} concentration, UV intensity, and ultrasound duration.

In 2019, Jung et al. showed that the removal of BPA by ultrasound in addition to catalyst systems such as US + PBC (pristine biochar), α-MnO_2/BCs, or δ-MnO_2/BCs and was found to be more effective than by the single systems alone (PBC, α-MnO_2/BCs, or δ-MnO_2/BCs). In ideal circumstances, the entire BPA is removed in 20 min. The results point to a broad range of potential applications for different organic contaminants' removal from the environment. Further research is needed to understand the detailed mechanisms underlying the enhanced catalytic activity of the urchin-like α-MnO_2/BCs. The feasibility and cost-effectiveness of scaling up this synthesis method for industrial-scale environmental remediation have not been explored. The study could benefit from a comparative analysis with other commonly used catalysts to highlight the advantages and limitations of urchin-like α-MnO_2/BCs.

Zhang et al. (2018) studied BPA degradation by adding Schwertmannite (Sch), a Fenton-like catalyst. They concluded that when the catalytic system was coupled with ultrasound, Sch, and H_2O_2 together, the rate of BPA degradation was amplified to 98%, suggesting that US and Sch had a synergistic effect on H_2O_2 activation.

According to the study of Zhang et al. (2011), humic acid and BPA may compete for OH, which would cause a side reaction that would slow down the breakdown of BPA. This discovery should coincide closely with the study of Laughrey et al. (2001).

The BPA degradation increased in the following orders of magnitude when CCl_4 was present: 0.01/0.1 mM (98%), 1 mM (99.7%), 10 mM (99.8%), and no addition (97%) at a 30-mins reaction period. However, adding t-BuOH, an effective scavenger of hydroxyl radicals, led to a slight reduction in BPA degradation at low concentrations but a significant drop at high concentrations (Park et al., 2011). While the study provides insights into a deeper understanding of the complete reaction mechanisms at various frequencies and conditions, it is needed. Further research could explore the effects of a broader range of conditions (e.g., different pH levels, gas injections, and concentrations) on BPA degradation. Although the study focuses on BPA, it would be beneficial to investigate the sonodegradation efficiency and mechanisms for a

broader range of EDCs and related compounds. The environmental and health impacts of additives like CCl_4 and t-butanol need further investigation to ensure the process is safe and sustainable.

Gültekin and Ince (2008) also experimented and observed the addition of t-butanol at a concentration of 1, 5, and 10 mM caused a 15%, 51.4%, and 74.4% reduction in the degradation process, respectively. The lower rate of hydrogen peroxide accumulation in BPA solutions compared to ultrapure deionized water suggests OH radical-mediated oxidation as the primary degradation pathway. Carbonate and t-butanol have an insignificant impact on BPA decomposition at low concentrations. Still, these scavengers significantly inhibit the reaction at high concentrations, with t-butanol showing a more considerable degree of inhibition than carbonate. Large amounts of t-butanol indicate a significant interfacial effect on the decomposition process. The synergistic effects of several catalysts and ultrasound treatment for BPA degradation are summarized in Table 6. This section of the review mentions various synergistic approaches for BPA removal, such as sonoelectrochemical treatment and combined ultrasound with adding additives, whether salts, oxidizing species, or inorganic particles, as well as using various ultrasound frequencies. However, there may be a need for more comprehensive studies to understand the mechanisms and optimize these synergistic effects further. Numerous investigations have been conducted to determine the specific process of pollution degradation by ultrasonic waves and to find techniques to maximize the impact. Ultrasound is unquestionably an effective means in the field of advanced oxidation processes. The efficiency of the process of ultrasonic degradation has been significantly increased over time. There is potential to investigate novel catalyst materials or combinations that could enhance BPA degradation efficiency and minimize the formation of harmful byproducts. Comparative studies that assess the performance of various BPA removal methods under controlled circumstances may offer insightful information about their relative efficacy, enabling decision-makers to select the best approach for given applications. Despite many studies concentrating on laboratory-scale investigations, research on the scalability and practical use of BPA removal strategies is lacking. The work focuses on BPA, but more investigation is required to evaluate how well other EDCs and related contaminants can be broken down using ultrasonic degradation.

6. Degradation using other methods

BPA is present in the air, and it is highly recommendable for air-degradation of this harmful compound or there is a chance of BPA precipitation in the water bodies. Using gel permeation chromatography, Abbås, 1980 has shown that BPA polycarbonate can be thermally degraded in a rheometer barrel within the temperature range between 300 and 330 °C with the samples harvested after 20, 40, 60, and 80 min (Abbås, 1980). The thermal degradation of BPA polycarbonate has been examined using high-resolution thermogravimetry with a variable heating rate in both nitrogen and air environments. The study included a temperature range from room temperature to 900 °C and focused on monitoring changes in the sample's degradation rate. A previously undisclosed degrading process of polycarbonate has been discovered, including either three steps in a nitrogen environment or four steps in an air environment. This process was not easily detected using typical thermogravimetry methods (Li and Huang, 1999). The degradation of BPA polycarbonate end-capped with t-butyl phenol in air has been analyzed using TGA/FTIR and chromatography combined with mass spectrometry. This analysis has allowed for the identification of significantly evolved products (Jang and Wilkie, 2004, 2005). They showed that thin films of BP polycarbonate break down quickly under 200 °C sustained pumping vacuum. Molecular weight increases gel formation and gelation timings and pre-gelation molecular weight fluctuations match the Davis-Golden process, which includes simultaneous condensation and branching. About 0.8 dm^3/mol/hour is the second-order condensation rate constant. Trifunctional branch points need one chain scission and are generated at 10^5/g of polymer/hour. Extractable substance inhibition and low molecular weight polymer amplification are complications. In 2020, Wu et al. demonstrated that the heat breakdown process of hydrogenated BPA involves decarboxylation, disproportionation of the C–H transfer and β–H transfer, and the Fries rearrangement. The researchers determined that synthesizing high-molecular-weight hydrogenated BPA polycarbonate was challenging (Wu et al., 2020).

7. Conclusion & future direction

To summarize, studies on the breakdown of BPA in aquatic systems have revealed encouraging approaches to reduce its environmental consequences. Several studies have investigated different methodologies, such as using microorganisms for biological degradation and implementing advanced oxidation processes (AOPs) for chemical degradation. The approaches mentioned above have effectively degraded BPA molecules, decreasing their occurrence within aquatic

Table 6
Synergistic effects of several catalysts along with ultrasound treatment for BPA degradation.

Additional substances (Catalyst)	Effect on BPA degradation	BPA degradation (%)	Frequency (kHz)	References
Cl-	Inhibition at 10 mM conc.	–	–	Guo et al. (2017)a,b; Diao et al. (2018)
NO_3^-	No visible effect	–	–	Diao et al. (2020)
SO_4^-	No visible effect	–	–	
HCO_3^-	Degradation efficiency decline at 1,5, 10 mM	93.5%, 72.5%, 59.5%	–	Sharma et al. (2015); Zhou et al. (2016)
Humic acid	Degradation efficiency decreased at 1, 5, 10 mM		–	Wu et al. (2019); Zhang et al. (2011)
CO_3^{2-}	At conc. 1,5,10 mM degradation	18.5%, 41%, 40%		Gültekin and Ince (2008)
Fe^{2+}/TiO_2	Degradation increased	–	300 kHz	Torres-Palma et al. (2010)
TBA (tert-butanol)	Inhibition at 60 mM conc.	12%		Diao et al. (2018)
CCl_4	Degradation efficiency increased at 25μl/100 ml BPA within 15 min	70%	580/864 kHz	Pahontu et al. (2023)
EAC (ethyl anthraquinone)	Degradation increased within 60 min	72%	580 kHz	
$FeSO_4$ $7H_2O$	Dose-20 mL/80 mL starting solution, degradation increased within 60 min	72%	580 kHz	
H_2O_2	Degradation increased (after 120 min)	75%	20 kHz	Jung et al. (2019)
$CuS/BaWO_4/K_2S_2O_8$	Degradation increased	–	–	Liu et al. (2023)
$US/Sch/H_2O_2$	Degradation increased	98%	–	Li et al. (2018)
US/UV/Fe (II)	Degradation increased	95%	300 kHz	Zhang et al. (2011)
US+α-MnO_2/BCs + H_2O_2	BPA removal within 20 min	100%	20 kHz	Jung et al. (2019)

ecosystems. Nevertheless, it is imperative to do more research on difficulties such as the production of potentially detrimental by-products and the continued existence of BPA alternatives, such as bisphenol S (BPS) and bisphenol F (BPF). Although progress has been achieved in comprehending the mechanisms of BPA degradation, more investigation is essential to enhance degradation methodologies, evaluate environmental hazards, and formulate comprehensive approaches for managing endocrine-disrupting substances in aquatic environments. To effectively tackle the issue of BPA contamination, it is imperative to foster multidisciplinary collaboration and adopt a thorough strategy that considers the intricate interplay of pollutants, organisms, and environmental elements.

The ubiquitous presence of BPA in the environment, especially in aquatic systems, presents considerable threats to human health and ecosystems. As we progress into the future, the significance of efficient BPA degradation and removal technologies will escalate, propelled by heightened awareness of environmental sustainability and public health.

7.1. Ecological importance

Ecosystem Health: BPA disrupts endocrine systems in aquatic creatures, resulting in reproductive and developmental problems. The lack of biodiversity leads to a reduction in ecosystem resilience, impacting food webs and ecosystem services. The efficient elimination of BPA is essential for safeguarding aquatic biodiversity and sustaining environmental equilibrium.

Water Quality: Pristine water is essential for human consumption and ecological stability. The presence of BPA and other pollutants in water bodies can make sources unfit for drinking and recreational use. Advanced degradation technologies will be crucial for guaranteeing safe and clean water supplies for future generations.

Climate Change Mitigation: Polluted aquatic environments may intensify the effects of climate change. For example, algal blooms exacerbated by nutrient pollution can be intensified by the presence of organic contaminants such as BPA. Eliminating BPA can enhance the stability of aquatic ecosystems, rendering them more tolerant to the effects of climate change.

7.2. Risks to human health

Exposure Pathways: BPA can infiltrate the human body via multiple routes, including the ingestion of contaminated water, consumption of aquatic creatures, and direct skin contact during recreational activities. The forthcoming focus on BPA elimination will aid in reducing exposure hazards, especially for at-risk groups like youngsters and pregnant women.

Chronic Health Effects: BPA is associated with numerous health complications, such as hormone disruptions, reproductive abnormalities, and metabolic diseases. As research progresses in revealing the comprehensive health effects of BPA, the necessity for efficient removal techniques will intensify, harmonizing public health policies with environmental conservation initiatives.

Public Awareness and Advocacy: Enhancing public consciousness of the hazards of BPA will stimulate demand for purer water and more stringent laws on its utilization and disposal. The advancement of effective degrading technologies will be crucial to fulfill these expectations and safeguard public health.

7.3. Technological advancements

Advanced Treatment Solutions: Future innovations in water treatment technologies, including photocatalysis, bioremediation, and membrane filtering, will improve our capacity to eliminate BPA from aquatic environments. Investment in research and development will be essential for creating scalable, cost-efficient solutions.

Monitoring and Regulation: The implementation of rigorous monitoring systems will facilitate the prompt identification of BPA concentrations in aquatic environments. Augmented rules and policies designed to diminish BPA influx into ecosystems will collaborate with removal technology to foster a more sustainable future.

Circular Economy: Incorporating BPA degrading solutions within a circular economy framework can reduce waste and enhance sustainable materials management. This strategy can promote advancements in recycling methods and substitute materials, diminishing dependence on BPA-containing items.

7.4. Final assessment

The future of water quality and public health is fundamentally connected to the efficient breakdown and elimination of BPA from aquatic environments. Addressing the difficulties of pollution and environmental deterioration necessitates prioritizing the elimination of BPA, which will defend ecosystems and protect human health. Cooperative initiatives among scientists, policymakers, and the public will be essential in formulating sustainable solutions that guarantee a healthy planet for future generations.

CRediT authorship contribution statement

Sourav Kundu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Basanta Kumar Das:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Abhilash Wodeyar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Poonam Majumder:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Susmita Jana:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Ayan Biswas:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Sagarika Das:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Rinku Besra:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123558.

Data availability

Data will be made available on request.

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