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Review

Managing Bisphenol A Contamination: Advances in Removal Technologies and Future Prospects

Hassimi Abu Hasan [1,2,*], Mohd Hafizuddin Muhamad [1,*], Setyo Budi Kurniawan [3], Junaidah Buhari [1] and Osama Husain Abuzeyad [1]

1 Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia; junaidah1611@gmail.com (J.B.); p100560@siswa.ukm.edu.my (O.H.A.)
2 Research Centre for Sustainable Process Technology (CESPRO), Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia
3 Laboratory of Algal Biotechnology, Centre Algatech, Institute of Microbiology of the Czech Academy of Sciences, Opatovický mlýn, Novohradská 237, 379 81 Třeboň, Czech Republic; kurniawan@alga.cz
* Correspondence: hassimi@ukm.edu.my (H.A.H.); ir_din84@yahoo.com.my (M.H.M.)

Abstract: Increasing levels of bisphenol A (BPA), classified as an endocrine-disrupting compound, in the environment have raised concerns because of its detrimental impact on human and animal health. BPA has been detected in soil and water and even as a volatile compound in the air primarily because of improper disposal and its extensive use in the production of polycarbonate plastics and epoxy resins. This review comprehensively surveyed recent research focusing on the removal of BPA from water through physicochemical and biological treatments, covering articles published from 2002 to 2023. A range of conventional and non-conventional methods employed for BPA removal is examined, and their limitations in completely degrading BPA in water are acknowledged. Hybrid or integrated treatment systems have been explored, capitalising on the distinctive removal potential of various treatment processes. The literature spanning from 2002 to 2023 underscores the efficacy of hybrid or integrated treatment systems in yielding promising results for BPA removal from water. Furthermore, future directions for BPA removal are outlined, and advancements in treatment technologies developed over the past decade are incorporated.

Keywords: bisphenol A; water treatment; physicochemical; biological; hybrid system; integrated system

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Citation: Abu Hasan, H.; Muhamad, M.H.; Budi Kurniawan, S.; Buhari, J.; Husain Abuzeyad, O. Managing Bisphenol A Contamination: Advances in Removal Technologies and Future Prospects. *Water* **2023**, *15*, 3573. https://doi.org/10.3390/w15203573

Academic Editor: Anastasios Zouboulis

Received: 21 August 2023
Revised: 28 September 2023
Accepted: 2 October 2023
Published: 12 October 2023

1. Introduction

Bisphenol A (BPA) has emerged as a significant environmental pollutant of concern [1,2]. The widespread presence of BPA in the environment is closely linked to its use as a raw material in plastic production [3], and BPA serves as a monomer for plastics utilised in bottles, food packaging, and piping [3–5]. Two of the most commonly used compounds containing BPA are polycarbonate and epoxy resin [6]. The improper handling of BPA and its derivatives often leads to soil contamination. Concern about the transfer of BPA from soil to water is growing, which poses a potential threat to aquatic ecosystems [7].

The global regulatory framework for BPA widely varies. In the United States, regulations prohibit the sale of products with BPA levels exceeding 0.1 ppb and bans BPA-based epoxy resin coatings in children's products [8]. Meanwhile, Japan has no restrictions because it has low BPA levels, and several regions in Southern and Central America, Africa and Southeast Asia lack regulatory standards. South Korea identifies cosmetics and receipts as BPA sources but remains below exposure limits [9]. BPA wastewater treatment aligns with regulations by reducing BPA in discharged water. Recommendations include stricter discharge limits, support for research and global cooperation.

BPA transfers from soil to water because of changes in environmental conditions and degradation by soil microbiomes [1,7,10]. The degradation of BPA releases intermediate compounds with high hydrophilicity, rendering them soluble in water [7]. Lin et al. [11] reported that BPA concentrations in surface water reached up to 5.68 µg/L, and another study observed levels of up to 6.37 µg/L [10]. The presence of BPA in water can have chronic or even acute effects on aquatic organisms [12], and the bioaccumulation and biomagnification of BPA in aquatic organisms potentially disrupt the food web [13,14]. The utilisation of BPA-coated metal cans for food storage has shown a positive correlation with BPA concentration in food [15]. The BPA concentrations in canned fish and beef are 26.3 and 21.3 ng/g, respectively [14]. Additionally, Gys et al. [16] detected BPA concentrations in human urine as a result of dietary BPA intake from food.

Most BPA treatment technologies are primarily physicochemical, including adsorption [17,18], membrane technology [19,20] and advanced oxidation processes [19,21]. These methods are highly effective in treating BPA-contaminated water. For instance, magnetic biochar has been successfully employed for BPA adsorption [22], and nanofiltration (NF) has exhibited nearly complete removal (>98%) of BPA from wastewater [23]. Advanced oxidation processes completely degrade (100%) BPA from wastewater [24]. However, these methods consume significant amounts of energy and generate chemical residues [25–27], prompting the exploration of alternative green solutions. In this context, biological treatment emerges as a promising environmentally friendly approach to address BPA-contaminated water [26,28].

Biological treatment harnesses natural mechanisms to effectively treat pollutants [29] and are often optimised through engineering strategies [30,31]. In the context of BPA, activated sludge and its modifications have demonstrated efficacy in BPA degradation. Activated sludge methods have shown successful BPA removal in laboratory-scale experiments [32,33]. The integration of treatment methods, referred to as hybrid systems, can enhance BPA removal performance [34]. Although a limited number of studies have investigated hybrid systems for treating BPA-contaminated water [35], hybrid systems are emerging as effective tools for treating pollutants [36], but their application to BPA removal remain limited [34,37]. This review provides valuable insights into the recent developments in hybrid BPA treatment technologies for contaminated water. By harnessing the synergy of diverse treatment methodologies, hybrid systems can enhance pollutant removal, a critical consideration for real-scale contaminated environments. Moreover, our comprehensive comparative analysis bridges the gap between established treatment technologies and the potential use of hybrid systems for efficient BPA removal from contaminated water. Ultimately, this review aims to enhance understanding of BPA removal techniques and introduce eco-friendly alternatives for treating BPA-contaminated water, establishing it as a valuable resource for researchers and practitioners.

2. BPA Application and Occurrence in Environment

BPA, with the chemical formula $C_{15}H_{16}O_2$, is a white crystalline compound with a melting point of approximately 158–159 °C, a boiling point of about 359.1 °C and moderate solubility in water but high solubility in organic solvents. This compound is extensively employed in polycarbonate plastics, epoxy resins and fire-retardant materials [6,38]. BPA-derived products are integral to various daily activities, encompassing the creation of protective coatings for metals, pipes, bottles, cans, medical devices and digital equipment [3,5,39]. Due to its widespread use, the demand for BPA exceeded 7.7 million metric tons in 2015, with projections indicating it will surpass 10 million metric tons by 2020 [3]. In terms of consumption, Asia, led by Mainland China, is the largest consumer of BPA products [40]. BPA has varying decay times in different environmental conditions. BPA has a variable half-life in aerobic soil, typically 3 to 37.5 days, signifying relatively rapid biodegradation. However, in anaerobic soil, BPA does not degrade during the 70 day experiments, suggesting that it can persist under these conditions. In aquatic environments, photolysis breaks down BPA in the presence of light above 290 nm and does not tend to persist. Thus, its decay time depends on factors, such as aeration and light exposure [41].

The maximum allowable content of BPA varies depending on the type of water source. In freshwater, seawater and wastewater, maintaining BPA concentrations within 1–15 µg/L is crucial to the protection of aquatic ecosystems and prevention of contamination [42]. Different countries have established varying limits for the presence of BPA in drinking water quality according to the US ANSI/NSF-61 standard [43]: 100 ng/L in France, 30 µg/L in Germany, 100 mg/L in Japan and 200 mg/L. These limits aim to regulate BPA concentrations and ensure safety in various environmental contexts.

Given its substantial consumption, the presence of BPA in the environment has caused considerable concern. BPA is frequently detected in the environment because of improper disposal practices [6,11]. It can be found in various environmental compartments, including soil, water and even air [11,44]. The prevalent occurrence of BPA in the environment is predominantly linked to the widespread utilisation of polycarbonate plastics and epoxy resins [6,38]. These compounds are extensively used in human activities, particularly in packaging materials, piping and numerous household items [6,38]. The improper disposal of items containing BPA derivatives primarily impacts the soil environment, and the presence of BPA in aqueous systems can stem from its release from soil or sediment matrices [7]. BPA's high octanol–water partition coefficient indicates that it is usually absorbed by soil or sediment matrices rather than dissolved in water [45]. Changes in environmental conditions and the presence of soil microbiomes play a pivotal role in the transfer of BPA from soil to aquatic environments [1,18]. Recent studies documenting the occurrence of BPA in the environment are summarised in Table 1.

Table 1. Recent reports about the occurrence of BPA in the environment.

No	Contaminated Medium/Organism	Location	Summary	Source
1	Air	Argentina	Although the transfer of BPA into air phase is considered to be low, it can still be detectable in the airborne. BPA concentration was associated with particulate matter in the air. A maximum concentration of 2454 pg/m^3 was found in the air during spring season. Potential hazard from dermal exposure or inhalation of BPA has not been widely studied yet.	Graziani et al. [44]
2	Food commodity	China	BPA was found in consumable goods in local Chinese market. Among 151 canned food samples, >92% of it were contaminated with BPA. Canned congee was the major contributor of BPA in canned food sample.	Cao et al. [46]
3	Food commodity	Nigeria	Exposure of BPA to humans was highlighted after results found that BPA concentrations in food commodities were detected. Results showed that vegetable oil contains the highest BPA of 28.4 ng/g, followed by canned fish and beef with 26.3 ng/g and 21.3 ng/g, respectively. Canned food is considered to be major source of BPA exposure to humans, since it is used as a metal coating compound.	Adeyi and Babalola [14]
4	Human	Belgium	BPA was found in the human body, assessed via a urine test in adolescents. More than 80% of the tested participant showed positive of BPA in their urine sample. The observed BPA concentration was still below the allowable limit. Socio-economic status and food consumption were highly related to BPA concentration among the tested participants.	Gys et al. [16]

Table 1. *Cont.*

No	Contaminated Medium/Organism	Location	Summary	Source
5	Soil and surface water	Canada	BPA was found in the Canadian environment, including soil and surface water. It was thought to originate from wastewater, biosolid waste, and leachate percolation. BPA concentrations in agricultural soil sample showed the potential harm of BPA exposure in field commodities. The surface water concentration of BPA was considered to increase with time, reaching up to 6.37 μg/L, with future increments needing to be monitored.	Gewurtz et al. [10]
6	Surface sediment and bivalves	Iran	High concentrations of BPA (787.01 ng/g) were found in surface sediments received from municipal wastewater disposal. BPA was also observed in bivalves nearby the sampling location, with concentrations reaching up to 340.16 ng/g. It was proven that anthropogenic activity contributed to the occurrence of BPA in the environment, especially the aquatic ecosystem.	Jahromi et al. [45]
7	Surface water, soil, and aquatic animal	China	A high concentration of BPA was observed surrounding the plastic industry in Southeast China. The observed concentrations were 240 ng–5.68 μg/L in surface water, 38.7 ng–2.96 μg/g in soil, and 116.1–477.4 ng/g in aquatic animals. These results found that internal industrial wastewater treatment plant still releases a considerable amount of BPA into the surrounding environment.	Lin et al. [11]

3. Endocrine and Toxicological Effects of BPA

Numerous reports concerning the toxic effects of BPA on human and animal health have emerged owing to the extensive application of BPA and its prevalent presence in the environment. BPA is classified as an endocrine-disrupting chemical (EDC) because of its acute toxicity to aquatic organisms, with exposure concentrations ranging from 1000 μg/L to 10,000 μg/L [47]. EDCs, including BPA, can disrupt the endocrine system by interfering with or blocking natural hormones, leading to hormonal imbalance [48]. BPA's oestrogenic effects have been observed even at concentrations lower than 1 $\mu g/m^3$ [41]. Globally, widespread BPA exposure has been confirmed through studies conducted in various countries; BPA is present in the urine samples of over 90% of their study populations [49]. Moreover, BPA can induce oxidative stress and damage hepatocytes while potentially manipulating immune activity, contributing to obesity development and exhibiting mutagenic activity in eukaryotic cells [50]. Early-life exposure to BPA is associated with increased risk of mammary and prostate cancers. Moreover, BPA-induced alterations in centrosomes and microtubule organisation have been linked to euploidy in cells and tissues and contribute to cancer progression [51]. BPA exposure poses risks to the health of fetuses, infants and young children because they have low levels of regulated activity, synthesis and hormone elimination [52]. Notably, childhood exposure to BPA has been linked to inattention, anxiety, hyperactivity, depression and conduct problems [53]. For a more comprehensive understanding of BPA's toxic effects on vertebrates, additional information can be found in other review articles [38,50,54].

4. Treatment Technologies Available for BPA Removal

4.1. Physicochemical Treatments

Coagulation or flocculation, a physicochemical treatment, is employed to remove BPA that sediments onto sludge during the primary treatment phase in wastewater treatment [55]. However, the effectiveness of this method is limited, and its highest recorded BPA removal rate is 1% [56]. In the secondary treatment stage, BPA is subjected to advanced processes, including adsorption, oxidation, advanced oxidation and membrane technologies, which have high removal efficiency [57]. These processes will be further explored in the subsequent section.

4.1.1. Adsorption Processes

Various types of adsorbents for BPA removal technologies have been explored, and adsorption is widely recognised as a cost-effective method [58]. The impressive efficacy of adsorbents has garnered significant interest because of its potential economic feasibility. The success of the adsorption is intricately tied to its adsorption capacity [57], and adsorbents can be broadly categorised into several types [59]: natural adsorbents (e.g., chitosan and clays), carbon and graphene-based materials, nanomaterials, composite materials, molecularly imprinted polymers, agricultural waste and miscellaneous adsorbents. Various adsorbents, such as activated carbon, chitosan, graphene and zeolites, have been investigated for BPA removal from diverse aqueous effluents, but their application in industrial wastewater settings requires further study [60]. Carbon-based adsorbents, including activated carbon, carbon nanotubes and graphene, are widely used because of their stability, exceptional mechanical properties and substantial surface areas [61]. Activated carbon stands out for its abundant functional groups, high-temperature resistance, good porosity, chemical stability and substantial surface area [62].

The mechanisms underlying BPA removal using these adsorbents involve the interaction between BPA molecules and adsorbent surfaces. Various factors, such as functional groups on adsorbents' surfaces, facilitate the chemical bonding or physical adsorption of BPA molecules [63]. Additionally, adsorption onto carbonaceous materials depends on various factors, including the types of raw materials, technique used for adsorbent synthesis and modifications to the adsorbents' surfaces and surface areas [64]. For instance, surface area and porosity are crucial factors in creating adsorption sites for BPA on carbon-based adsorbents. Activated carbon, known for its high surface area and numerous functional groups, provides favourable conditions for BPA adsorption. Surface modifications, including impregnation with substances, including $AlCl_3$, Fe_3O_4, $MgSiO_3$ and $ZnCl_2$, enhance adsorption capacity [17]. Moreover, Dong et al. [63] highlighted the efficacy of nitrogen-doped organic porous azo-linked polymer (ALP-p) adsorbents in BPA removal. ALP-p provides abundant surface sites for BPA adsorption through chemical bonding, physical adsorption and interactions, such as π–π and hydrogen bonding, showing promise for BPA removal.

Adsorbents employed for BPA removal in recent years are summarised in Table 2. Carbon nanotubes exhibit notably high BPA removal rates, and polydopamine-carbon (PDA-C) composite demonstrated a significant adsorption capacity for BPA. The use of carbonaceous materials for BPA removal has demonstrated high efficiency in treating BPA-contaminated pure water. However, evaluating their performance in treating drinking water is vital due to the significant impact of solution pH and adsorbent ionic strength [57,65].

Table 2. BPA removal by different materials of adsorbents.

No	Adsorbent Materials	Initial BPA Concentration	Dosage	Adsorption Capacity (q_m)	Summary	References
1	nZVI-chitosan	6 mg/L	1.5 g/L	65.16 mg/g	The adsorption process achieved 93.8% BPA removal from real pharmaceutical wastewater, 95% removal from synthetic wastewater, with a short 1 h adsorption time, and the adsorbent could be reused for up to three cycles.	Dehghani et al. [66]
2	Phosphonated Halomonas Levan (PhHL)	10 mg/L	0.5 g/L	126.6 mg/g	The adsorption process reached equilibrium after 360 min, and the adsorbent could be reused for three cycles, with a 28.6% decrease in adsorption percentage after the third cycle.	Hacıosmanoğlu et al. [67]

Table 2. *Cont.*

No	Adsorbent Materials	Initial BPA Concentration	Dosage	Adsorption Capacity (q_m)	Summary	References
3	Sulfonic acid functionalized carbonaceous adsorbent (TW-SO3H) from tea leaves	100–400 ppm	5–20 mg/20 mL	236.80 mg/g	The adsorbent can be used for three cycles, and increasing the adsorbent dosage enhances BPA removal until agglomeration occurs.	Ahsan et al. [68]
4	Polydopamine-carbon, PDA-C	50 mg/L	5 mg	1351 mg/g	The adsorption capacity was 1.5 times higher than conventional carbon, and the process was completed in less than 5 min.	Sun et al. [64]
5	Modification of multi-walled carbon nanotube with iron oxide and manganese dioxide (MWCNTs-Fe3O4−MnO2)	22.8 ng/mL	50 mg	132.9 mg/g	The adsorption process took 150 min, and the adsorbent could be reused at least six times, resulting in up to 99% BPA removal.	Guo et al. [69]
6	Calcium alginate/activated carbon (A-AC)	30–300 mg/L	1g/L	368.3 mg/g	The adsorbent could be used for at least six cycles without reduced adsorption, and it took 50 h to reach adsorption equilibrium.	Noufel et al. [70]
7	Xerogel (RFX), a chemical-activated carbon from Kraft lignin (KLP), commercial activated carbon (F400)	100 mg/L	0.36 g/L	F400 = 407 mg/g KLP = 220 mg/g xerogel = 78 mg/g	The adsorption process reached equilibrium in 24 h, with KLP and RFX exhibiting higher kinetic adsorption compared to F400, while F400 and KLP showed the highest BPA recovery.	Hernández-Abreu et al. [60]
8	Biomass activated carbon (*Tithonia diversifolia*)	40 mg/L	0.2 g/L	15.69 mg/g	98.2% BPA removal was achieved in 80 min.	Supong et al. [62]
9	Cu-BDC MOFs Cu-BDC@GrO (graphene oxide)	20 mg	20 mL of 100 ppm	182 mg/g	Maximum BPA removal occurred in 30 min with increased adsorbent dosage, and the adsorbent could be reused for up to five cycles with minimal efficiency loss.	Ahsan et al. [71]
11	Cellulose acetate (cigarettes butt) activated carbon	60 mg/L	0.2 g	364.21 mg/g	After seven cycles of use, the adsorption capacity remained at 94.21%, and maximum adsorption was achieved with a 150 min contact time.	Alhokbany et al. [61]
12	Calcite sludge-aluminum hydroxide (CAl)	200 mg/L	-	83.53 mg/g	The adsorbent was recycled five times and ethanol was used as a desorbing agent.	Choong et al. [17]
13	Magnetic vermiculite-modified (MV) -poly(trimesoyl chloride-melamine) (MP)	10 mg/L	200 mg	273.67 mg/g	The adsorbent demonstrated satisfactory adsorption–desorption ability over five cycles, with a 66% reduction in BPA after the seventh cycle of adsorption/desorption.	Saleh et al. [72]
15	Nitrogen-containing covalent organic framework (PyTTA-Dva-COF)	100 mg/L	10 mg	285 mg/g	The regeneration study showed excellent performance up to the seventh cycle, with BPA sorption maintained at 39 mg/g.	Hao et al. [73]

4.1.2. Membrane Technologies

Membrane technologies offer distinct advantages to water treatment owing to their remarkable ability to achieve a low molecular weight cutoff (MWCO) and yield high-quality effluents. Traditional membrane filtration typically features MWCO values exceeding the molecular weights of contaminants, decreasing effectiveness in removing organic pollutants [74]. Moreover, these technologies can remove microorganisms without chemical disinfection. From various membrane operation modes, ultrafiltration (UF) stands out because of its low-pressure operational requirement, which ensures energy saving. Previous studies commonly employed microfiltration (MF; 0.1–10 µm), NF, UF (10–150 nm) and reverse osmosis (RO) membranes as part of low-pressure membrane technologies. Furthermore, the efficacy of membrane filtration methods hinges on the selection of appropriate membrane materials for targeting specific compounds. Membrane retention efficiency is influenced by factors, such as adsorption, charge repulsion and size exclusion [75].

Membrane treatment can be classified into two distinct mechanisms: sieving and adsorption. NF and RO membranes exemplify the sieving mechanism, exhibiting impressive BPA removal capabilities [23,76,77]. The application of membrane filtration faces significant challenges because of unsuitable pore size, high synthesis cost, membrane fouling and hydrophobicity, necessitating high operating pressure and suffering from reduced permeability [78,79]. The other category of membrane treatment relies on an adsorption mechanism, exemplified by affinity membranes, including UF membranes. In NF membranes, the interaction between charge behaviour and pore size significantly influences BPA removal. Despite demonstrating excellent permeability, affinity membranes still fall short in achieving satisfactory adsorption capacity. Prior research has underscored challenges in simultaneously achieving high permeability and adsorption capacity for effective BPA removal [78,80].

Various types of membranes employed in BPA removal are in Table 3. A comprehensive overview suggests that the most substantial BPA removal can be attained through the synergistic employment of membranes with catalysts and oxidants. The retention of BPA during membrane treatment is primarily influenced by charge repulsion, adsorption and size exclusion mechanisms. Notably, the retention capacity of BPA tends to decrease in single-membrane operations often because of membrane saturation. Additionally, under alkaline conditions, the deprotonation process becomes challenging.

Table 3. Membrane technologies and its efficiencies.

No	Membrane	Type	Removal Efficiency	BPA Removal Process	Reference
1	Layer-by-layer (LBL) biocatalytic nanofiltration membrane	Nanofiltration	92.5%	• This research involved a layer-by-layer membrane with laccase immobilized on each layer. • Various membranes were fabricated using three different methods. The LBL NF membrane fabricated through the post-immobilization laccase method showed the highest BPA removal. • Adsorption and membrane rejection were followed by laccase oxidation. More than 80% removal of BPA could be achieved in 14 days (six cycles) of reusability.	X. Li et al. [81]
2	Electrochemical filtration carbon membrane (ECM)	-	97.73%	• Organic pollutants underwent electrochemical oxidation directly and indirectly. • The ECM permeability was high, at 393.17 L/(m^2 h bar).	Pan et al. [82]

Table 3. *Cont.*

No	Membrane	Type	Removal Efficiency	BPA Removal Process	Reference
3	Polyamide nanofiltration membrane	Nanofiltration	88.5%	• A coagulation process was used before the membrane filtration process for enhanced removal efficiency. • The membrane was deposited with hydrolyzed aluminum nanoparticles. • The removal efficiency of BPA was increased compared to single nanofiltration (60.7%). • The removal of BPA occurred via a electrostatic repelling interaction on the membrane.	P. Wang et al. [83]
4	Dynamic electrodeposited CuO/carbon membrane (DECuO/CM)	Microfiltration	98.04%	• This work combined electrocatalytic oxidation with microfiltration for BPA removal. • The membrane was fabricated by depositing CuO on the carbon membrane. The DECuO/CM had a permeability of 823.03 L/(m^2 h bar). • The authors claimed that after the fourth cycle of usage, the removal ability still achieved 99.8% efficiency.	C. Li et al. [84]
5	Catalytic ceramic membrane (CCMs)	-	80% (C_o = 3 mg/L)	• In this study, the research was carried out by combining catalytic ozonation and membrane filtration. • The membrane was prepared through citrate sol-gel with the aid of wet impregnation.	Lee et al. [85]
6	Catalyst immobilized ceramic membrane (CIM)	-	95% (C_o = 10 mg/L)	• This study coupled a peroxymonosulfate (PMS) oxidation process and CuO immobilized membrane filtration technology. • The CIM system was observed to be little affected by the PMS dose, BPA concentration and CuO amount, compared to the catalyst dispersal in the feed water (CDF) process.	S. Wang et al. [86]
7	PVDF$_{MW}$ catalytic-membrane	Microfiltration	40% Co = 50 µm	• This work utilized a microwave method to fabricate the in situ membrane of polyacrylic acid (PAA) polymerization on polyvinylidene fluoride (PVDF). • nZVI was loaded on the PDVF$_{MW}$ membrane for the degradation of BPA.	Silva et al. [87]
8	PVC membrane	Ultrafiltration	60% C_o = 25–50 mg/L	• The initial concentration and ionic strength were found to have a lesser effect on BPA retention. • Low pressure was preferred in the operation studied.	Wu et al. [75]
9	Forward osmosis membrane	Forward Osmosis	40% C_o = 10 µg/L	• A fouling layer helped to elevate the hydrophilicity of the membrane.	Linares et al. [88]

4.1.3. Conventional Oxidation Processes

At low BPA concentrations, conventional physical processes, such as coagulation, sedimentation and filtration, are insufficient for the removal of these emerging pollutants [89]. By contrast, oxidation processes have gained significant traction in water treatment because of their cost-effectiveness. Traditionally, chemical oxidants, including chlorine, chlorine oxide, ferrate, ozone and permanganate, have been widely employed to eliminate emerging pollutants [57,90]. However, the application of these techniques often falls short in achieving complete BPA removal, necessitating the adoption of advanced treatment methods. Furthermore, common oxidation processes are burdened with drawbacks, including the generation of potentially harmful by-products and relatively low oxidation activity [91].

Permanganate is a potent oxidising agent known for its robust capacity to initiate oxidation. Kinetic studies have demonstrated its active oxidant properties [92], and permanganate enhances the coagulation of micropollutants in drinking water and contaminated groundwater. Permanganate exhibits rapid reactivity with electron-rich organic moieties, such as olefins and phenols, leading to instantaneous reactions [93]. Importantly, the application of permanganate in water treatment is advantageous as it does not generate harmful by-products [94]. However, it is worth noting that the oxidation efficiency of permanganate falls short when compared to oxidants like ferrate and ozone, resulting in longer treatment periods for the elimination of oestrogen activity [57].

The presence of humic acid (HA) even in minute quantities (e.g., 0.15 mg/L) enhances the oxidation of triclosan and phenols [57,95]. Ecologically relevant concentrations of HA, HCO_3^-, Fe^{2+} and Fe^{3+} improve BPA removal, with the following order of effectiveness: HA > HCO_3^- > Fe^{2+} > Fe^{3+}. Moreover, in real water matrices, BPA is oxidated by permanganate e over a broad pH range (5–9) in the presence of ligands, such as EDTA, phosphate and pyrophosphate [96,97]. However, a previous study revealed that over 99% of BPA degradation was achieved within 15 min at pH 7 [95]. Notably, the rate constants for BPA and permanganate reactions are significantly influenced by temperature, as highlighted by Yang et al. [98], who found the kinetic behaviour of BPA oxidation to conform to a second-order rate law. In recent investigations, epigallocatechin gallate (EGCG) extracted from green tea was found to enhance the oxidation activity of BPA by permanganate) [91]. EGCG exhibited superior performance in BPA oxidation, achieving a 90% degradation within 30 min, surpassing the capabilities of EDTA, hydroxylamine, citrate and sulphite. The optimal molar ratio of permanganate to EGCG was determined to be 1:0.1 within a pH range of 5–8. Furthermore, this reagent exhibited the ability to simultaneously reduce and chelate contaminants, including chromium and emerging pollutants [99,100]. However, it's worth noting that the PM/EGCG system's performance may be diminished in the presence of HCO_3^- and oxygen.

Chlorine stands as the ubiquitous oxidant used globally in both domestic wastewater treatment and potable water disinfection. Free chlorine has been identified as an agent capable of degrading a wide array of organic compounds, including phenolic compounds [101–103]. Under neutral conditions, BPA degradation by chlorine exhibits significant kinetics, conforming to a second-order rate constant (58 M^{-1} s^{-1}), with the formation of chlorinated BPA through stepwise electrophilic substitution [101]. Previous studies investigating the chlorination (0.5–1 mg/L) of synthetic water spiked with BPA have shown that BPA degradation occurs within a four-hour timeframe, while the resultant BPA constituents are generated instantly and persist within the water matrix for over 10 h [57,101]. Lane et al. [104] noted that in the presence of 1 mg/L of free chlorine, the half-lives of BPA and BPS range from three minutes to 35 min, spanning a pH range of 6 to 11 and temperatures of 10–25 °C. In contrast, when exposed to 3.5 mg/L of monochloroamine (MCA, NH_2Cl), the half-lives of BPA and BPS extend to 1 to 10 days, with prolongation linked to higher pH values and lower temperatures.

The presence of HA has been found to impede the degradation of BPA due to its competition for chlorine consumption, as well as its role in the reduction process of phenoxy radicals back to parent phenols [102]. It is believed that oxygen-functional groups within the HA structure react with free chlorine, creating competition with BPA for reactive sites [103]. The chlorination of BPA leads to the formation of various disinfection by-products (DBPs). In oxidation tests, the mono-, di-, tri- and tetra-chloro-BPA by-products were identified in solution following the chlorination of BPA. These by-products exhibit heightened cytotoxicity, genotoxicity and potential harm to human oestrogenic activity [104]. Furthermore, J. Y. Hu et al. [105] observed insignificant reactions between BPA by-products and chlorine after one-hour BPA chlorination, resulting in the accumulation of these by-products in the solution. Given these findings, this technique should not be used in water treatment processes.

Ferrate is renowned for its remarkable oxidising capacity, with a reduction potential of 2.2 V under acidic conditions, which decreases to 0.7 V under basic conditions [106,107]. This elevated redox potential affords ferrate enhanced efficacy as a disinfectant when compared to ozone (2.0 V) and chlorine [108]. Notably, ferrate oxidation deactivate up to 99.9%

of indigenous microbial communities [106,109], and promotes the formation of insoluble ferric hydroxide particles. These ferric hydroxide particles are versatile, serving as coagulants and precipitants and facilitating the removal of organic matter, metal ions, hazardous ions, nutrients and suspended particles through adsorption mechanisms [57,106,107].

However, ferrate is recognised for its selectivity towards electron-rich moieties, such as amines, anilines, olefins and phenols [110]. In the study conducted by Han et al. [106], a substantial removal rate of 97.5% for BPA was achieved within 10 min at pH 7, and the ferrate-to-BPA molar ratio was 8 at 298 K. However, the initial degradation of BPA results in the generation of intermediate products, which are highly toxic in the first five minutes because of the hysteric effect arising from aromatic intermediates. The proposed pathway for BPA degradation by ferrate involves a sequence of steps encompassing dehydroxylation, cleavage of C–C bonds, addition of OH groups and oxidation. Kinetic studies on BPA degradation by ferrate align well with a pseudo second-order reaction law. Notably, the rate constant for BPA degradation by ferrate was 640/ms under neutral conditions [110].

The molar ratio of ferrate to BPA exerts a significant influence on the efficacy of chemical oxidation process using ferrate. For instance, at a molar ratio of 5 (ferrate:BPA), a notably high oxidation reaction rate (90% BPA degradation) was observed over distinct time intervals, and 30% of dissolved organic carbon (DOC) was detected in a molar ratio of 4 [111,112]. In another study, BPA oxidation was completed within 30 min in a ferrate-to-BPA molar ratio of 3 at an initial BPA concentration of 1.5 mg/L [95]. The investigations revealed that the concentrations of BPA intermediates and end products (DOC and phenyl rings) in the solution decrease with increasing ferrate dosage and oxidation time. Furthermore, the effectiveness of BPA removal exhibits high performance over a wide pH range (5–9.5), and removal rates are notably heightened at pH levels of 5–6. HCO_3^- promotes BPA removal. Conversely, constituents, such as HA and SiO_2^- or SiO_3^-, hinder BPA removal by ferrate, and tert-butanol causes marginal reduction in BPA removal rate in contrast to ferrate from permanganate and chlorine. However, this method may introduce toxicity concerns because of the formation of transformation products, particularly at low molar ratios [107]. In summary, ferrate displays significant potential as an environmentally friendly oxidant and does not generate harmful by-products. Its multifaceted nature as a coagulant, oxidant and disinfectant for abating various pollutants (biological and chemical species) underscores its benefits that foster sustainable water and wastewater treatment practices [112].

Ozone is widely used in disinfection treatments, prized for its potent oxidising properties and rapid degradation within water [113–115]. When ozone is introduced to water, it generates an array of oxidative species, including hydroxyl radicals, which are notably more robust than the original ozone molecule. The presence of hydroxyl radicals is widely regarded as the primary driver of ozonation. This reaction, which is an indirect reaction, can be attenuated by hydroxyl group scavengers, such as bicarbonate, carbonate, humic substances, p-chlorobenzoate and tert-butanol [115,116]. Moreover, high concentrations of hydrogen peroxide (H_2O_2) can accelerate mineralisation by enhancing contaminant degradation [117]. Highlighting the significance of selecting an optimal H_2O_2 concentration that balances treatment efficiency and environmental responsibility, this study underscores the necessity of achieving effective pollutant removal while minimising the ecological consequences of excessive reagent use in BPA wastewater treatment.

Ozone exhibits a predilection for targeting double bonds, particularly C bonds, within organic molecules, including aromatics and olefins [115,118]. This characteristic underscores ozone's effectiveness in degrading substances, such as BPA [119]. An indirect reaction involving hydroxyl radicals is characterised by its non-selective nature [115]. According to Kanakaraju et al. [120], parameters, such as pH, temperature and ozone dosage, significantly influence the removal and mineralisation of contaminants through ozonation. Furthermore, the presence of diverse functional groups—aryl groups, aliphatic hydroxyls and carboxyls—results in varying degradation rate constants during ozonation [121].

Kusvuran and Yildirim [122] demonstrated the complete degradation of BPA with an initial concentration of 0.509 mM within 25 min at a pH of 3; the stoichiometric ratio of ozone to BPA was 10.30; notably, when the initial BPA concentration was increased (from 0.051 mM to 0.509 mM), the degradation rate constant of the pseudo first-order reaction exhibited a decreasing trend (from 19.3 s^{-1} to 13.3 s^{-1}). Furthermore, a 5.5% increment in Henry's constant, attributed to the strengthening of the BPA ionic solution, contributed to a reduction in ozone decomposition. This phenomenon aligns with the observations of Gultekin et al. [123] regarding the degradation of BPA by ozone, where a pseudo first-order rate acceleration was noted when BPA initial concentration decreased and ozone was added. After 25 min of ozonation, a 30% ozone mineralisation rate was achieved.

In a study of Ahmad et al. [113], the degradation of BPA in Skudai River water through ozone-based batch experiments was investigated; the results demonstrated that complete BPA removal was attained within a remarkably short period of 30 s, employing an initial BPA concentration of 0.5 mg/L at a pH of 7 and temperature of 21 °C. However, the efficiency of BPA removal exhibited a reduction of 55% as the initial BPA concentration was elevated to 5 mg/L. The presence of a maximum DOC concentration of 9.17 mg/L in the river water had an influential effect, leading to the rapid diminution of dissolved ozone concentration. As a result, the decomposition of ozone in the river water ranged from 87% to 99% within 120 s.

However, a potential concern regarding the presence of bromide (50 µg/L) in water solutions during the ozonation process should be highlighted. This compound can lead to the formation of bromate, a known carcinogen for humans. The generation of harmful by-products is generally not associated with ozonation, and the production of ozonation by-products in drinking water, such as ketones, carboxylic acids and aldehydes, has not been extensively studied in relation to public health protection [118]. Additionally, ozone's reactivity varies by functional group, and this variation potentially reduces its efficiency, especially under acidic pH conditions and during the treatment of compounds, such as BPA [124]. In practical applications, ozonation may incur high costs and may not be considered energy efficient because of the short lifespan of ozone. Furthermore, the scope of toxicity studies related to ozonation is limited, necessitating careful consideration before its widespread implementation [120].

In summary, the degradation by-products produced through the use of traditional oxidants vary. Permanganate and ozone have been recommended for the removal of BPA from drinking water because they have lower levels of toxicity than the by-products generated by other oxidants [57]. Chemical oxidation treatment has been predominantly employed to effectively treat emerging contaminants (ECs) and refine water quality.

4.1.4. Advanced Oxidation Processes (AOPs)

In wastewater and water treatment, advanced oxidation processes (AOPs) have garnered significant interest because of their potential benefits. AOPs have superior removal efficiency compared with conventional oxidation methods and are thus valuable for water purification. The generation of reactive radicals, such as hydroxyl radicals and sulphate radicals, are central to advanced oxidation process and play a crucial role in breaking down stubborn pollutants [118]. These free radicals interact with pollutants, leading to the formation of by-products or intermediates with low molecular weights before complete mineralisation [125]. Various AOPs are available (Table 4), including electrochemical oxidation, Fenton processes, Fenton-related treatments, photocatalysis, microwave radiation, ozonation and ultrasonic radiation [121]. These methods offer diverse mechanisms for promoting pollutant degradation and facilitating the purification of water and wastewater.

Table 4. AOPs and their efficiency.

Treatment	BPA Removal Efficiency	Summary	References
Photocatalysis	91%	• TiO_2-x/rGO nanocomposite • The optimum dosage of catalyst is 1 g/L • Initial BPA concentration of 2.5 mg/L • The light intensity of 2000 ± 10 w/m^2	Xu et al. [126]
	99.4%	• TiO_2@MIL-101(Cr) nanocomposite • Initial BPA conc. of 10 mg/L • The BPA degradation was possessed by great superoxide radical	Tang et al. [127]
	100%	• LiCl–CN nanotubes (ceramic films) • 0.3g/L catalyst dosage • The degradation of BPA dominated by superoxide radicals (·O_2^-) and photogenerated holes (h^+).	Huang et al. [128]
	91.9%	• Ag/p-Ag_2O/n-$BiVO_4$ plasmonic • 20 mg/L of initial BPA conc • Simultaneous chromium and BPA removal • Dosage = 0.02 mg/50 mL	Zhao et al. [129]
	93.2%	• TiO_2/WO_3/GO nanocomposite • Initial BPA conc. of 10 mg/L • Dosage 2 mg/L • High photocatalytic activity under light radiation and sunlight	Hao et al. [130]
Photochemical oxidation	98.98% (SPS) 95.43% (H_2O_2)	• Initial BPA conc. = 0.04 mM • SPS showed slightly higher BPA oxidation compared to hydrogen peroxide • Dosage SPS = 11.76 mM • Dosage H_2O_2 = 1.26 mM	Sharma et al. [131]
	>80%	• UV/O_3 and UV/O_3/H_2O_2 • O_3 dosage = 1 mg/L • H_2O_2 dosage = 500 µM	Wardenier et al. [132]
	56% (H_2O_2) >95% (O_3)	• UVC/H_2O_2 and UVA/ozone • H_2O_2 dosage = 0.042 M	Mehrabani-Zeinabad et al. [133]
	100%	• UVC/H_2O_2 and UVC/$S_2O_8^-$ • The mineralization of both treatments is in the range of 70–85%	Olmez-Hanci et al. [134]
	100%	• UV/H_2O_2, UV/$K_2S_2O_8$, UV/Na_2CO_3 • $[BPA]_0 = 10$ mg/L, • $[H_2O_2]_0 = [K_2S_2O_8]_0 = [Na_2CO_3]_0 = 500\ \mu M$. • The efficiency of BPA degradation is in the following order: UV/$K_2S_2O_8$ > UV/H_2O_2 > UV/Na_2CO_3	Sánchez-Polo et al. [135]
Fenton-based process	100%	• $[BPA]_0 = 50$ mg/L • 0.10 mM Fe^{3+}; 5.0 mM of H_2O_2; UV-A light irradiation; pH = 3	Molkenthin et al. [136]
	92.5%	• $Cu_{0.5}Mn_{0.5}Fe_2O_4$ = 0.08 g/L • $[BPA]_0 = 10$ mg/L • [H2O2] = 10 mM, pH = 4.2	J. Yang et al. [137]
	99.2%	• $CuFeO_2$ = 1 g/L • $[BPA]_0 = 0.1$ mmol/L • $[H_2O_2]$ = 20 mmol/L, pH = 5	X. Zhang et al. [138]
Ultrasonic cavitation	100%	• $[BPA]_0 = 118$ µmol/L • Ultrasonic frequency = 300 kHz, 80 W, 90 min • Saturating gas = oxygen	Torres et al. [139]
	70%	• Ultrasonic frequency = 20 kHz, 120 min, pH = 6.5 • $[BPA]_0 = 100$ g/L; $[CCl_4]_0 = 25$ µg/L	Guo and Feng [140]
	47%	• $[BPA]_0 = 0.044$ mM, $[H_2O_2]$ = 20 mM • Ultrasonic frequency = 35 kHz, 40 W, 60 min	Lim et al. [141]

Photocatalysis

In photocatalysis, a catalyst is utilised to facilitate chemical conversions in the presence of light [142]. Photocatalysis offsets the shortcomings of photolysis treatment, which has a poor degradation rate. Photocatalytic treatments for BPA using catalysts, such as TiO_2, Ag_3PO_4/rGH, Bi_2WO_6 and co-doped BiOCl [143–146], and the use of titanium dioxide (TiO_2) in photooxidation has garnered attention because of its stability, ease of preparation, low-cost catalyst requirement and environmentally friendliness [126,147].

A drawback of TiO_2 powders is difficulty in separating TiO_2 from treated water. The synthesis of TiO_2 with materials, such as carbon, zeolite and ceramic, and its binding to supports and films, including glass materials, clay, activated carbon and plastic mesh sheets, have been explored to enhance mass transfer between contaminants and catalysts' surfaces [57,148,149]. Moreover, the efficiency of photocatalytic conversion can be reduced by insufficient electron transfer caused by the recombination of holes and electrons. To mitigate this issue, several modifications have been investigated, including the deposition of transition and noble metals [150,151], incorporation of graphene [152] and semiconductor restructuring [153], to improve electron transfer and minimise recombination effects.

Hunge et al. [154] synthesised TiO_2@ND composite photocatalysts by using a water-based method and studied the impact of ND loading on TiO_2 properties; they then confirmed composite formation and investigated factors affecting photocatalytic BPA degradation; their research revealed that neutral and acidic conditions enhanced BPA degradation and complete removal was achieved with 8 mg of TiO_2-3@ND composite at pH 5.1 under UV light. Enhanced light absorption, efficient charge separation and reduced charge recombination in the composites accounted for these improvements. The reaction of free hydroxyl radicals with BPA generates 4-isopropanolphenol, which subsequently undergoes cleavage to form 4-hydroxybenzaldehyde and hydroquinone as intermediates. The main intermediate, 4-hydroxybenzaldehyde, further undergoes mineralisation through reaction with $O_2{}^-$ to produce water and carbon dioxide [127].

Photooxidation with UV Radiation

In photooxidation, hydroxyl and sulphate radicals can be generated through the activation of chemical oxidants with UV or solar radiation, thermal processes or their combinations. Various chemical oxidants have been used, including chlorine dioxide, hydrogen peroxide, persulphate, permanganates, hypochlorite and peroxymonosulphate [21,111,155,156].

Sharma et al. [131] stated that hydrogen peroxide (H_2O_2) and sodium persulphate (SPS) are extensively used for water treatment as oxidants because of their high redox potential. Irradiation with UV light at a power of 40 W and wavelength of 254 nm for 240 min activates H_2O_2 and SPS, resulting in the formation of two hydroxyl radicals (2OH•) and two sulphate radicals ($2SO4\bullet^-$). In the oxidation of BPA, sulphate radicals are more efficient than hydroxyl radicals. Additionally, Chen et al. [155] revealed that UV does not degrade BPA in the absence of H_2O_2. The combination of H_2O_2 and UV is effective in removing BPA parent compounds. Studies on the degradation of BPA with H_2O_2/UVC and $S_2O_8{}^{2-}$/UVC produced degradation intermediates, such as fumaric, oxalic, succinic acids, 3-methylbenzoic, and 4-sulphobenzoic acids [134].

The comparative study of HO•, $SO_4\bullet^-$ and $CO_3\bullet^-/HCO_3\bullet$ radicals in BPA photodegradation was conducted by Sánchez-Polo et al. [135]. The degradation of BPA was strongly influenced by pH conditions. Low degradation was observed at acidic or basic pH because of hydroxyl scavengers ($PO_4{}^{3-}$, $HPO_4{}^{2-}$, H_2PO_4-) in the solution. Under acidic conditions, H^+ acts as a hydroxyl scavenger, and under basic conditions, hydrogen peroxide transforms into water and oxygen instead of hydroxyl radicals [157]. In the study, UV/$K_2S_2O_8$ is more effective than UV/H_2O_2 and UV/Na_2CO_3, showing high BPA and TOC removal rates within a short time [158]. This result was attributed to the formation of HO• and $SO_4\bullet^-$ radicals during the treatment. The rate of reduction in toxicity was higher than that in other methods. The second-order rate constant of sulphate radicals reacting with BPA ($k_{SO4\bullet^-BPA}$) was $1.37 \pm 0.15 \times 10^9\ M^{-1}\ s^{-1}$. Only 1% of BPA degradation was recorded with single treatment of UV radiation [133,135]. In the findings of Irmak et al. [159], a comparison between ozone treatment and UV/O_3 revealed that the difference in degrading BPA between the techniques was insignificant. According to Rivas et al. [160], BPA degradation via photolysis and ozonation is effective, except in complete mineralisation. However, the mineralisation of BPA can be improved by adding O_3/UV/TiO_2 and activated carbon.

Fenton-Related Processes

Fenton oxidation involves the generation of hydroxyl radicals through the reaction of hydrogen peroxide with iron [57]. Fenton's capability as a strong oxidising reagent, along with its potential for stable analysis, has attracted interest, particularly in the degradation of organic pollutants. According to M. Wang et al. [161], the optimal degradation of BPA via the Fenton technique can be achieved at a pH of 3.5, a ratio of 10 for C (H_2O_2) to C (Fe^{2+}) and an increase in temperature, which proportionally increases BPA degradation. The findings suggest that the generation of isopropyl phenol, phenol, p-diphenol and other intermediates results from the chemical bond breakage between BPA and isopropyl group facilitated by the Fenton technique. However, the traditional Fenton process requires iron post-treatment on the produced sludge [162]. Additionally, the need for specific dosage levels of catalysts and peroxymonosulphate constrained the efficient decomposition of BPA in water through Fenton-like reactions dominated by single-Fe atom catalysts [163].

Heterogeneous Fenton oxidation has been employed as an improvement over the traditional Fenton process by immobilising iron catalysts onto solid supports, such as carbon nanotubes, clays, activated carbon and zeolite for H_2O_2 activation [138]. However, iron-based catalysts are less effective in activating hydrogen peroxide and slower in degrading organic pollutants [164,165].

The interaction between Fenton reagent and UV light radiation is referred to as photo-Fenton. The purpose of using UV light is to enhance the effectiveness of the Fenton process. The generation of hydroxyl radicals occurs through the decomposition of hydrogen peroxide catalysed by iron [125,166]. The effectiveness of the photo-Fenton technique is maximised under acidic to near neutral pH conditions. Under acidic conditions, the formation of hydroxyl radicals (OH•) and Fe^{2+} is facilitated by the photoreduction of $Fe(OH)^{2+}$ and $Fe(OH)_2{}^{4+}$ under UV light radiation. On the other hand, coagulation occurs at neutral pH because of the precipitation of amorphous ferric oxyhydroxides in the absence of any ion. According to Molkenthin et al. [136], the degradation of BPA decreased from 100% (at pH 3–7) to 34% at pH 7 when sodium carbonate was added. The study reported that the presence of UV light reduced the time needed for BPA degradation from four minutes without UV light to two minutes with UV light. The optimal BPA degradation was observed at a pH of 3.

The utilisation of bimetallic oxides in the photo-Fenton process has garnered significant attention because of their high catalytic activity. The use of a transition metal-based catalyst, such as $Cu_{0.5}Mn_{0.5}Fe_2O_4$, for activating H_2O_2 in photo-Fenton was studied by J. Yang et al. [137]. The catalysts remained stable even after eight successive runs, resulting in a remarkable 92.5% degradation of BPA. Similarly, X. Zhang et al. [138] reported that $CuFeO_2$ exhibited a H_2O_2 utilisation efficiency of 57.8% and achieved a BPA removal rate of 99.2% after 120 min of contact time. The enhanced catalytic activity was attributed to the synergistic effects of redox pairs involving Cu(I)/Cu(II) and Fe(II)/Fe(III).

Ultrasound Treatment

The utilisation of acoustic cavitation to generate hydroxyl radicals has proven to be an effective method for BPA decomposition. Acoustic cavitation involves cyclic formation, growth and collapse of microbubbles. Research into ultrasonic treatment for BPA degradation has shown excellent results at an ultrasonic frequency of 300 kHz and under oxygen-saturated conditions [139]. However, despite its efficiency, approximately 80% of TOC (total organic carbon) and more than 50% of COD (chemical oxygen demand) were still present in the solution following treatment. The degradation pathway of BPA was found to be influenced by hydroxyl radicals, as indicated by the presence of hydroxylated aromatic compounds after ultrasonic treatment. These hydroxylated aromatic compounds further transformed into biodegradable aliphatic acids over a two-hour period. Some of the identified intermediate products included monohydroxylated BPA, 4-isopropenylphenol, quinone of monohydroxylated BPA, dihydroxylated BPA, quinone of dihydroxylated BPA, monohydroxylated 4-isopropenylphenol and 4-hydroxyacetophenone.

Torres et al. [167] introduced a combination of ultrasound, UV and Fe^{2+} to enhance COD and TOC removal; their results indicated that after four hours of treatment, 70% of TOC was removed by the combined methods and photo-Fenton and ultrasound alone achieved 29% and 11% TOC removal, respectively. The impressive outcomes were attributed to the complete degradation of BPA compounds by ultrasound and the complete mineralisation of by-products through the photo-Fenton process. BPA degradation was accelerated during treatment with air because of the generation of excess radicals and acids; however, the degradation slowed down when air was replaced with argon and oxygen. The presence of hydroxyl scavengers, such as t-butanol and carbonate, results in low degradation rates [168]. Z. Guo and Feng [140] investigated the BPA treatment using ultrasonic frequencies (20 kHz) and chlorinated drinking water. The addition of CCl_4 enhanced BPA degradation. Additionally, Lim et al. [141] noted that a treatment using ultrasound and hydrogen peroxide improves BPA degradation but TOC removal is limited because it cannot degrade intermediates during sonochemical reactions.

Table 4 provides a summary of various AOP treatments with different levels of efficiency. While AOPs offer the potential for excellent removal of BPA, it's important to consider several factors before their commercialisation, including the cost of operation, maintenance, power consumption and the potential generation of harmful by-products.

Sonocatalytic Treatment

Notably, studies have demonstrated that increasing ultrasound intensity enhances the degradation rate of BPA by boosting the quantity of radicals present in the BPA solution. However, the limitation of ultrasound should be acknowledged: it decomposes non-volatile organic compounds through reactions involving •H and •OH radicals [140,169,170]. To overcome this limitation and further improve the efficiency of sonodegradation for organic pollutant removal, hybrid processes like sonocatalytic oxidation with specific catalysts are often employed. Various sonocatalysts, including TiO_2 [171], magnetic mesoporous TiO_2 [172], stainless steel wire mesh [173] and $LaFeO_3$ perovskite oxide [174], boost cavitation bubble formation in ultrasound processes. When droplets reach a critical size, asymmetric bubble implosion generates high-speed microjets and high-pressure shock waves under ultrasound irradiation, elevating local temperature and pressure (e.g., up to 15,000 K and 1000 atm). These conditions enhance water pyrolysis, leading to the formation of •OH radicals and further accelerating BPA degradation [175,176].

Plasma Treatment

Plasma treatment, exemplified by dielectric barrier discharge plasma (DBDP), effectively removes non-biodegradable organic pollutants, such as BPA from water [177]. These processes generate a wide range of highly reactive species, including hydroxyl radicals (•OH), hydroperoxyl radicals, hydrogen and oxygen, and physical effects, such as shock waves and UV light, all of which work synergistically to efficiently degrade a variety of organic compounds [178]. For example, a study conducted by Yang et al. [177] employed DBDP to eliminate BPA and achieved a remarkable 96.8% COD removal in wastewater from a pharmaceutical factory. Furthermore, radical quenching experiments and electron paramagnetic resonance tests confirmed that •OH was the primary reactive oxygen species responsible for BPA degradation. The study identified eight major BPA degradation intermediates using UPLC-MS, contributing to a potential degradation pathway for BPA. Despite facing challenges in energy efficiency, current research aims to enhance the effectiveness of plasma treatment processes by combining them with other treatment methods, making them a critical area of study for the removal of BPA and other persistent organic pollutants from water [179,180].

4.2. Biological Treatments

In biological treatments, the removal of ECs is driven by biodegradation mechanisms. Microorganisms such as bacteria, algae and fungi play a crucial role in degrading ECs, breaking them down from large molecular weights to smaller molecules and eventually mineralising them into inorganic compounds, including carbon dioxide and water [181]. Traditional biological treatment methods have been widely employed in wastewater treatment for removing ECs. Biological treatment can be broadly categorised into aerobic and anaerobic processes. Aerobic processes include techniques like activated sludge, sequence batch reactor (SBR) and membrane reactor (MBR). On the other hand, anaerobic processes encompass anaerobic film reactors and anaerobic sludge reactors. Various biological treatment technologies have been employed for BPA treatment. Their efficiency in removing BPA is summarised in Table 5. Many of these treatment methods have shown excellent BPA removal rates. According to Ahmed et al. [182], the hierarchy of effectiveness for biological treatment of ECs is as follows: MBR > activated sludge > aerobic > constructed wetland > microalgae > biological activated carbon > anaerobic processes. Biodegradation and sorption processes are the primary mechanisms governing BPA removal, with their relative contributions varying among different wastewater treatment plants (WWTPs) and operational conditions. In WWTPs utilising bioreactors, such as activated sludge systems, biodegradation plays a substantial role, owing to BPA's biodegradable nature and low vapor pressure [56].

Table 5. Removal of BPA efficiencies by biological technologies.

Treatment System	Influent Concentration	BPA Removal Efficiency	Type of Wastewater	Reference
Activated Sludge	100 µg/L	79.3%	Synthetic wastewater	Huang et al. [119]
Activated Sludge	90 ng/L	52%	Wastewater	Xue and Kannan [183]
Activated Sludge	1 mg/L	80.7%	Domestic Wastewater	Sun et al. [184]
Activated Sludge	-	Approx. 100%	Municipal Wastewater	Y. Qian et al. [185]
BAF	400 ng/L	95%	Wastewater	Guerra et al. [56]
MBR	1–15 mg/L	98%	Synthetic WW	Seyhi et al. [186]
GSBR	0–12 mg/L	97%	Synthetic WW	Cydzik-Kwiatkowska et al. [187]

4.2.1. Activated Sludge System

This system involves the generation of biomass through the growth of microorganisms in aeration tanks where dissolved oxygen is present [188]. Microorganisms in sludge are responsible for breaking down organic matter into water, carbon dioxide and inorganic compounds. The activated sludge system offers lower operational costs than advanced oxidation processes (AOPs) and is more environmentally friendly compared with chlorination [189,190]. Previous studies have indicated that BPA removal in an activated sludge system is effective when compared to other treatment technologies, such as lagoon treatment [191] and biological trickling filters [55,192]. The activated sludge system involves adsorption and biodegradation (Sun et al., 2017).

A previous study determined the efficient removal of phenolic compounds, including BPA, by forming complexes with divalent metal cations in the sludge [193]. The microbial community in the sludge is believed to be the main contributor to the removal of pollutants [194]. BPA degradation occurs through the activity of ammonia-oxidising bacteria via co-metabolism [195]. Metabolism and co-metabolism are the two pathways of EC biodegradation. In the co-metabolic pathway, microorganisms utilise carbon as the primary source, and the synthesis of enzymes is used for the degradation of ECs. In the metabolic pathway, microorganisms use ECs as a substrate for cell generation and synthesise enzymes for their metabolic activities [113].

Yan et al. [196] studied the role of extracellular polymeric substances (EPS) in sludge regarding the removal of BPA. The study revealed that BPA automatically binds to EPSs, especially to proteins within EPSs, through hydrophobic interactions. This binding between BPA and EPSs is enhanced by high ionic strength, elevated temperature and a pH of 7, which helps to stabilise BPA in the sludge. The oxidation of BPA generates main intermediates, such as 4-hydroxyacetophenone, 4-hydroxybenzaldehyde and 4-hydroxybenzoic acid, but not all of them are fully oxidised to carbon dioxide [197]. A 12-h biodegradation of BPA showed that sludge toxicity persisted until the first eight hours [198].

According to Y. Qian et al. [185], the removal of BPA is influenced by its binding with EPSs. The effect of hydraulic retention time (HRT) on BPA removal was investigated by Boonnorat et al. [199]. They found that the removal of BPA remained consistent at approximately 87–93% for 18- and 24-h HRTs. However, a slight decrease in BPA removal, ranging from 71% to 93%, was observed at a 12-h HRT. The researchers suggested that an 18-h HRT is the optimal choice for the activated sludge system when treating low-micropollutants wastewater. Nevertheless, this system does face challenges such as the generation of large amounts of sludge and the potential toxicity of the sludge due to BPA degradation, which can lead to secondary pollution. To enhance the efficiency of the activated sludge process, upgrading to granular sludge, which contains numerous functional bacteria and inorganic compounds, has been proposed as a solution [55].

4.2.2. Biological Aerated Filter (BAF)

The biological aerated filter (BAF) system is a bioreactor that involves the attachment of biomass to a suspended medium [56]. BAF has been shown to achieve a high removal efficiency of 95% for BPA, surpassing the 68% BPA removal rate achieved by the activated sludge process in WWTPs [56]. However, Dong et al. [200] noted that porous biofilter materials in the BAF system can impact water purification effectiveness, requiring careful selection and maintenance. According to H. Wang et al. [201], the activated sludge system was found to be more efficient in removing BPA in municipal WWTPs compared to the BAF and lagoon systems. In a continuous flow bioreactor with nitrifying sludge, BPA was found to degrade to dinitro- and nitro-BPA compounds [202].

4.2.3. Membrane Bioreactor (MBR)

The membrane bioreactor (MBR) is a comprehensive approach that integrates adsorption, membrane filtration and biodegradation processes to effectively remove ECs, such as BPA, from wastewater. BPA removal in the MBR system primarily involves adsorption onto MBR sludge and subsequent biodegradation by specific microorganisms [185]. Adsorption reaches equilibrium rapidly, especially at low BPA concentrations. Seyhi et al. [203] found that BPA adsorption onto the sludge is exothermic ($\Delta_{ad}H^0 = -82.121$ kJ/mol) and hydrophobic. Interactions, including Van der Waals or electrostatic strengths occur during adsorption. The mass balance analysis revealed that 14% of the initial BPA loading adsorbs on the membrane, whereas 85% undergoes biological oxidation. Only 0.7% of BPA remains in treated water, with a minimal retention of 0.3% in the sludge liquor, where microorganisms subsequently oxidise it. The biodegradation of BPA yields primary metabolites, such as 4-hydroxyacetephenone and 4-hydroxybenzoic acid, confirming this process. The small floc size, unique microorganisms and diffusive mass transfer limitations in MBR differentiate it from conventional activated sludge, impacting its efficiency in BPA removal [203]. Contaminants larger than the membrane's molecular weight cutoff are retained during membrane filtration, where biodegradation by BPA-degrading microorganisms takes place. Effective adsorption typically occurs when the partition coefficient (log Kow) is greater than 3.2, and successful biodegradation relies on extended retention times and a significant population of microorganisms capable of breaking down BPA [55,182].

The removal efficiency of BPA in MBR is influenced by various factors, including pH, temperature, sludge age, wastewater composition, the presence of anoxic and anaerobic zones and conductivity [189]. Comparatively high BPA removal rates of around 95% have been achieved with membrane reactors, showing minimal differences compared to SBR [204]. In a study by Seyhi et al. [186], MBR exhibited BPA removal exceeding 98%. However, a toxicity threshold of 21.6 g BPA/m^3/d was identified, indicating toxicity to the bacteria within the bioreactor, which was higher than that observed in conventional activated sludge systems (2.5 g BPA/m^3/d). This study also noted simultaneous removal of ammonia nitrogen (>99%) and phosphate (61%). At low BPA concentrations (<1 mg/L), no degradation occurs and BPA accumulates on the sludge. An impressive 99% removal efficiency is achieved when the initial BPA concentration is increased to 16 mg/L [205].

One major challenge in MBR technology is effectively managing membrane fouling, which, despite extensive research, still lacks comprehensive understanding [206]. Overall, MBR demonstrates slightly better BPA removal efficiency than activated sludge processes. However, limited studies have addressed factors related to membrane fouling and clogging. Recent investigations have explored combining the moving bed biofilm reactor (MBBR) with the MBR system to mitigate membrane fouling issues [207]. Implementing MBBR as a pre-treatment step has shown potential to reduce membrane fouling and enhance MBR performance, resulting in a 90% BPA removal rate within the MBBR–MBR system.

4.2.4. Granular Sequencing Batch Reactor (GSBR)

Aerobic granules were employed within granular sequencing batch reactors. The specialty of these aerobic granules lies in their layered structures, which accommodates multiple microbial species capable of simultaneously removing micropollutants and nutrients [208]. The age of aerobic granules and the substantial amount of EPSs on these granules significantly contribute to the enhanced activity of microorganisms within granules [209]. The implementation of an aerobic granular sludge system is advantageous in terms of requiring a small footprint and offering potential cost savings in capital and operational expenses [210]. However, a challenge associated with aerobic granular sludge systems is their sensitivity to high influent concentrations of BPA, which can result in reduced degradation rates and increased production of extracellular substances, potentially affecting treatment efficiency [211]. Cydzik-Kwiatkowska et al. [187] demonstrated that a removal efficiency of more than 97% for BPA during an eight-hour operational period. Additionally, the removal of ammonia commenced as the BPA concentration decreased to 2 mg/L. This result underscored the potential of aerobic granular sludge systems for effectively removing BPA and other contaminants from wastewater while optimising space usage and operational costs. The biodegradation of BPA in aerobic granules involves a complex metabolic pathway, resulting in the formation of 3-(benzyloxy)benzoic acid among other metabolites. Certain microorganisms, like *Sphingomonas* sp., play a key role in metabolising BPA [187]. Monitoring for hazardous BPA degradation by-products, such as 3-(benzyloxy)benzoic acid, is essential, especially in BPA-rich wastewater, despite successful removal within an eight-hour cycle in aerobic GSBRs [208].

4.3. Emergence of Hybrid/Integrated Systems for BPA Removal

In general, a hybrid treatment system can be defined as the hybridisation of several treatment functions in one unit of treatment system (such as MBR in Figure 1), while the integrated treatment system was the integration of several treatment processes in one unit of treatment train (such as the one shown in Figure 2). Nowadays, the integration or hybridisation of conventional treatment technology with advanced and novel technologies started to gain interest among researchers. The purpose of having integrated or hybrid system was to meet the latest requirements, such as law enforcement, removal of hazardous contaminants and the production of clean water that has potential for water reuse. Other advantages of integrated or hybrid system was the weaknesses in certain processes can be overcome by other processes in hybrid or integrated systems. In the context of BPA removal in wastewater, several integrated or hybrid technologies, namely, membrane filtration, AOP and biological treatment [125]. Different combinations in hybrid or integrated systems for BPA removal have been described in detail in the next section.

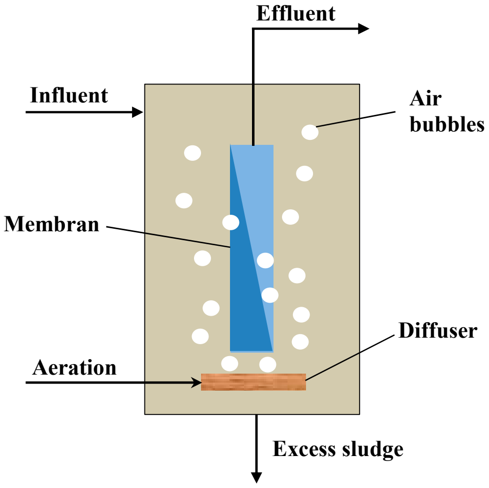

Figure 1. Typical configuration of MBR.

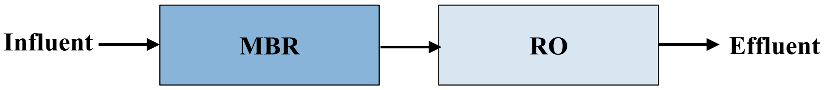

Figure 2. Configuration of integrated MBR–RO treatment train.

4.3.1. Technologies Combining Biological Treatments and Membrane Filtration

Nowadays, the combination of biological treatments with membrane filtration techniques, particularly in the context of MBR applications, has gained prominence for BPA removal from wastewater. MBRs have demonstrated not only efficient BPA removal capabilities but also effectiveness in removing other EDCs. Additionally, membrane filtration processes, such as RO and NF have exhibited substantial removal performance for EDCs such as BPA when applied individually [212]. Consequently, the potential of these two technologies has drawn the interest of researchers to explore their combined effectiveness in enhancing BPA removal from wastewater [213–215].

Given that BPA is characterised as a hydrophobic organic compound, its removal mechanisms in the MBR system are primarily attributed to adsorption onto activated sludge flocs and subsequent biodegradation. Volatilisation and abiotic hydrolysis are believed to be negligible, as suggested by other researchers. Fudala-Ksiazek et al. [213] reported on an integrated MBR–UF system that exhibited remarkable efficiency in BPA removal (100%). The authors highlighted that the gradual reduction in BPA concentration underscores the significance of the adsorption mechanism facilitated by activated sludge within the MBR. This phenomenon is particularly prominent during the acclimatisation phase of activated sludge, during which microorganisms require time to adapt and effectively degrade BPA. The findings from this study align with the conclusions drawn by Chen et al. [216], who noted a minor contribution of sludge adsorption to BPA removal, emphasising biodegradation as the primary driving factor. Zhu and Li [215] conducted a comparative analysis between conventional MBR systems and integrated MBR–OF systems, focusing on BPA removal from synthetic municipal wastewater. Their results indicated that biodegradation predominantly influenced total BPA removal. MBR and MBR–OF systems demonstrated removal efficiencies of 93.9% and 98%, respectively. Sahar et al. [214] also conducted a comparative study, evaluating the performance of CAS–UF/RO and MBR–RO systems in treating raw sewage from the Tel-Aviv WWTP on a pilot plant scale. The MBR–RO system exhibited high BPA removal rates (>99%) after the RO stage. In another investigation by Lee et al. [217], various plant-scale wastewater treatment processes utilising the MBR system integrated with NF and RO stages were examined for BPA removal. At an influent concentration of 0.09 μg/L, the BPA concentration was lowered to 0.006 μg/L following MBR treatment. Further polishing through NF and RO stages reduced BPA concentrations to 0.004 and 0.003 μg/L, respectively.

Table 6 provides a comprehensive overview of the performance achieved by integrated or hybrid treatment systems in terms of BPA removal. The results distinctly demonstrate that the combination of UF/OF/RO/NF with MBR processes serves as an exceptional complementary treatment because BPA is either entirely degraded or its concentrations dropped below detection limits, resulting in outstanding removal efficiencies. Among all the integrated MBR–UF/OF/RO/NF systems, BPA removal proved highly effective, with overall efficiency exceeding 95%. Remarkably, integrated MBR–UF exhibited successful BPA removal even at high influent concentrations, such as 606 μg/L. In conclusion, the integration of biological treatments with membrane filtration, such as UF, OF, RO and NF, exhibits a remarkable capacity for achieving high removal efficiency across a wide spectrum of BPA concentrations. However, certain limitations should be considered, including energy demands and potential issues related to membrane fouling, when designing and implementing integrated or hybrid treatment systems [218].

Table 6. Hybrid/integrated treatment systems for BPA removal.

Treatment Processes	**Hybrid/Integrated Systems**	**BPA Source**	**Influent (μg/L)**	**Removal (%)**	**Reference**
Biological treatments + membrane filtrations	MBR + UF	Municipal solid waste	606	100	Fudala-Ksiazek et al. [213]
	MBR + OF	Synthetic municipal wastewater	-	98	Zhu and Li [215]
	MBR + RO	Municipal wastewater	3.7	99	Sahar et al. [214]
	MBR + NF/RO	Sewage water	0.09	95 (NF) 96 (RO)	Lee et al. [170]
Adsorption + AOPs	Adsorption + catalytic ozonation	Synthetic wastewater	50 mg/L	98	Huang et al. [219]
	Adsorption + PEC	Synthetic wastewater	20 mg/L	100	Zhang et al. [220]
	Adsorption + PC	Synthetic wastewater	50 mg/L	98	Mohanta and Ahmaruzzaman [221]
	Adsorption + PC	Synthetic wastewater	50 mg/L	85	Chatterjee et al. [222]
	Adsorption + Fenton	Synthetic wastewater	50 mg/L	87	Xu et al. [223]
AOPs + membrane filtrations	Fenton + NF	Synthetic wastewater	300 mg/L	100	Escalona et al. [224]
	β-MnO_2 nanowires + MF	Synthetic wastewater	10 mg/L	99	Zhang et al. [225]
	Catalytic ozonation + CM	Synthetic wastewater	3 mg/L	80	Lee et al. [85]

4.3.2. Technologies Combining Adsorption and AOPs

Recent experimental studies have highlighted the remarkable potential of technologies that combine adsorption with AOPs for effective BPA treatment [219–221]. These studies have leveraged distinct AOPs, such as ozonation, photocatalytic (PC), Fenton and other processes, to enhance the efficiency of diverse adsorption treatment methods through the development of hybrid or integrated systems. The compilation of technologies that capitalise on the synergy between adsorption and AOPs is provided in Table 6.

In the realm of various hybrid or integrated systems for BPA removal from water, adsorption processes have garnered considerable interest. Among the most commonly employed adsorbents are carbonaceous materials, including graphene [220], carbon nanotubes [219], carbon nanoflakes [221] and activated carbon [226]. These materials have attracted attention due to their expansive surface area and porous structure [221]. However, it is essential to note that the regenerative capacity of these adsorption processes is somewhat constrained. Consequently, the potential for secondary pollution arises as these methods can merely transfer pollutants to another phase.

Acknowledging the limitations of adsorption technologies, advanced oxidation processes (AOPs) emerged as highly promising methods capable of achieving complete degradation of organic pollutants [227]. These AOPs encompass various technologies including ozonation [156], photocatalysis [228] and Fenton's reagent [229]. However, each of these technologies does have its own shortcomings, such as the generation of precipitates and energy consumption, among others. To address these drawbacks, the combination of adsorption and AOPs technologies offers an effective approach for removing organic pollutants, such as BPA, from wastewater through comprehensive degradation and mineralisation.

Recently, a novel hybrid system involving the simultaneous processes of adsorption-catalytic ozonation using synthesised MWCNT/Fe_3O_4 composites has been investigated for the removal of BPA from aqueous solutions [219]. This hybrid approach achieved a remarkable removal efficiency of 98% for BPA (Table 6). The primary mechanism driving this high removal rate was identified as catalytic ozonation. The study explored the effects of various factors, such as catalyst dosage, pH value and HA concentration on the removal process. Notably, the hybrid system exhibited excellent removal capabilities, particularly in the presence of HA, which acted to enhance the degradation of BPA. Interestingly, the adsorption mechanism did not appear to be the pivotal factor contributing to the improved removal efficiency of BPA when HA was present. In conclusion, the hybrid adsorption-catalytic ozonation process demonstrates significant potential for efficiently removing BPA from aqueous solutions.

A recent innovative approach for the removal of BPA involved the combination of adsorption and photoelectrocatalytic (PEC) processes, as explored by Zhang et al. [219]. PEC technology is a catalytic oxidation method that leverages photoelectric synergy [230]. In this context, Zhang et al. [220] reported on a novel hybrid system where the unique adsorption properties of 3D graphene hydrogel (rGH) were combined with the effective photoelectrocatalytic capabilities of TiO_2, resulting in a TiO_2–rGH composite with a 3D network structure. The utilisation of this hybrid material led to a remarkable 100% degradation of low-concentration BPA (20 mg/L) within a short timeframe of five hours (Table 6). This outcome highlights the favourable adsorption–PEC synergistic effect achieved by TiO_2–rGH. In conclusion, the TiO_2–rGH composite exhibits promising potential for application in wastewater treatment processes.

As summarised in Table 6, all technologies that combine adsorption and AOPs have demonstrated effective removal efficiency, particularly at high BPA concentrations ranging from 20 mg/L to 50 mg/L. Notably, the adsorption–catalytic ozonation process achieved a removal efficiency of 98%, and adsorption–PEC and adsorption–PC achieved complete removal with efficiency of 100% and 98%, respectively. In essence, the integration of adsorption and AOP technologies has shown remarkable removal efficacy even when the influent concentrations of BPA are elevated. However, certain constraints, such as operating costs associated with adsorbents, should be considered during the design of integrated or hybrid treatment systems [59].

4.3.3. Technologies Combining AOPs and Membrane Filtrations

The combination of AOPs with membrane filtration presents a viable technology for effectively removing BPA from wastewater. Numerous studies have been conducted to enhance the oxidation process in tandem with membrane separation. Membranes offer the advantage of purely physical separation, and their modular design makes them an appealing alternative for water treatment [224]. However, the potential of membrane filtration for wastewater purification can be limited by membrane clogging caused by pollutants [231], resulting in decreased filtration cycles and shortened membrane lifespan. This limitation can lead to reduced BPA removal efficiency. To overcome this challenge and optimise membrane retention for BPA removal while extending the lifespan of the membranes, different aspects of AOPs, such as Fenton's reagent, can be integrated with membrane processes. This integration has the potential to enhance the overall treatment efficiency, making the technology more robust and effective in addressing BPA contamination in wastewater.

In a study by Escalona et al. [224], the integration of Fenton treatment with NF for BPA removal was investigated. Results regarding Fenton–NF system's performance for BPA removal are summarised in Table 6. Under optimal conditions (pH 3, H_2O_2/BPA ratio of 0.20, Fe(II)/BPA ratio of 0.012), the combined Fenton and NF processes achieved complete removal of BPA at concentrations of up to 300 mg/L in less than two minutes. However, significant membrane fouling occurred in the NF effluent even after Fenton oxidation. This finding highlights the importance of addressing membrane fouling issues when integrating AOPs with membrane processes for BPA removal in wastewater treatment.

The capability of a novel process combining β-MnO_2 nanowires oxidation and MF for the removal of BPA was reported by Zhang et al. [225]. The integrated process proved that β-MnO_2 nanowires can effectively degrade BPA. The effective removal by β-MnO_2 nanowires was influenced by factors such as pH, HA and coexisting metal ions, such as Ca(II), Mg(II) and Mn(II), which induced suppressive effects. After the oxidation process, β-MnO_2 nanowires can be easily and entirely separated by MF, as the turbidity of the effluent after MF was almost zero.

Lee et al. [85] investigated the degradation of BPA using a novel hybrid catalytic ozonation–membrane filtration process. In their study, they fabricated nanocatalyst-functionalised catalytic ceramic membranes (CCMs) through a citrate sol-gel assisted wet impregnation method and applied them in the hybrid process. The results indicated that the CeOx-impregnated CCM (Ce-CCM) in the hybrid process exhibited superior BPA mineralisation capability and more efficient ozone utilisation compared to the MnOx-impregnated CCM, original ceramic membrane (CM) and sole ozonation. The catalytic ozone decomposition by Ce–CCM resulted in higher generation of reactive oxygen species, promoting effective BPA mineralisation within the membrane micropores. This enhanced mineralisation ability of the Ce–CCM was attributed to the presence of highly dispersed surface-active sites throughout the CCM pores and the involvement of a Ce(III/IV) redox pair in facilitating electron transfer.

Based on the removal data presented in Table 6, this study provides support for the effectiveness of the proposed integrated or hybrid AOP–membrane filtration process for BPA degradation. AOPs have the potential to address membrane biofouling concerns, carefully considering the compatibility of AOPs with the membrane unit when designing integrated or hybrid systems. For instance, previous research has highlighted various issues stemming from the combination of ozone as a strong oxidant with membrane filtration units. Ozone application has been shown to (1) degrade membrane performance by breaking down amide functional groups in polyamide membranes [232], (2) compromise membrane surfaces because of the formation of carcinogenic bromine compounds [233] and (3) exacerbate biofouling by breaking down organic matter with large molecular weight and promote microbial growth [234]. To address these challenges, further studies are warranted to explore novel treatment strategies aimed at mitigating biofouling issues, particularly in BPA degradation.

Other issues related to the integrated/hybrid AOP–membrane filtration process include the associated costs, which are crucial for determining the economic and environmental feasibility of this approach. However, data related to the cost of integrated or hybrid AOP–membrane filtration process is scarce, as the concept of integrated or hybrid processes is relatively newer than standalone AOPs or membrane processes. Consequently, asserting that integrated or hybrid processes are more profitable than standalone AOPs or membrane processes is challenging. Further studies involving cost analysis for the hybrid or integrated AOP–membrane filtration process need to be conducted to gain a comprehensive understanding of the potential of this approach.

5. Discussion on Comparative Performance of BPA Removal

Focusing on the removal of BPA from wastewater, various treatment methods have shown different levels of efficiency. Filtration methods have exhibited removal efficiency ranging from 40% to 98%, AOP methods have achieved removal percentages ranging from 47% to 100% and biological methods have demonstrated removal efficiency ranging from 52% to 100%. The efficacy of BPA removal is influenced by treatment method and the characteristics of wastewater being treated. Additionally, operational and environmental conditions play a significant role in affecting BPA removal outcomes [235,236]. Each treatment technology has advantages and disadvantages. In membrane filtration, concerns arise regarding the maintenance of filters and the energy requirements for maintaining pressure flow in real-scale applications, despite its good removal efficiency [46,237]. Similarly, in AOPs, energy requirements are a central concern [132]. Biological treatments offer an alternative by reducing energy consumption, but the proper maintenance of bacteria in the reactor and effective biomass handling remain important considerations [238,239].

The hybrid method has demonstrated better overall BPA removal efficiency, typically ranging from 80% to 100%. This approach involves treating the effluent from the first technique with a second technique [240,241]. By combining two different methods in a simultaneous treatment, the hybrid approach leverages the strengths of both technologies. This setup allows the effluent from the first unit to undergo further treatment in the second unit, effectively improving the treatment process. In this hybrid configuration, the effluent from the first unit does not need to meet the effluent standards directly, as the second unit will provide additional treatment. Through this combination, capital and operational costs can be optimised. An inexpensive technology can be selected as the first stage, and a more expensive technology can be used in the second stage to polish the effluent. Given the relatively high energy consumption and maintenance requirements, AOP and membrane filtration are often positioned as the second stage in hybrid treatments, thus receiving a lower load. Biological treatment and adsorption are recommended for wastewater with BPA concentrations higher than 1 mg/L. The application of AOP and membrane filtration may be more suitable for concentrations lower than 1 mg/L, allowing for load reduction and subsequently reducing operational and maintenance costs.

6. Future Directions

BPA and its derivative compounds continue to persist in the environment due to their widespread use in modern society, leading to ongoing environmental concerns [3,38]. A clear understanding of the fate of BPA and its derivatives is crucial to the resolution of these concerns [5,18,242]. Research into this area should focus on factors, such as persistence characteristics [243] and the transport of these compounds between different environmental phases [3]. Effective degradation of BPA is attainable through both physicochemical and biological methods [19,236,244]. Many physicochemical treatments aim to prevent the release of BPA and its derivatives into the environment, research into the degradation, detoxification and removal of these compounds from already contaminated environments may be challenging because of potential chemical residues that could cause further harm. On the other hand, biological treatment shows promise for in situ remediation, thanks to its environmentally friendly nature and potential effectiveness.

The potential for BPA degradation is promising, and the specific pathways and mechanisms involved in its degradation remain unclear. In-depth research into the degradation pathways, mechanisms, enzymes, genes and identification of potential organisms (plants and microbes) is essential. This information can be highly valuable for designing effective treatment reactors [1,6,245]. Notably, a significant portion of BPA removal studies has been conducted under laboratory conditions [1,38], and understanding of its natural attenuation in situ is limited. A comprehensive study of various factors in real contaminated environments can greatly enhance knowledge in this field. This research can uncover potential transport routes, risks to various organisms and potential impacts on human health. In-depth investigations into these aspects can significantly contribute to BPA removal, especially when hybrid treatment reactors are used. Such studies can provide insights into the synergistic effects of various species under specific environmental conditions, leading to optimal treatment performance.

Future developments and emerging trends in BPA wastewater treatment are promising and aim to enhance efficiency, sustainability and scalability. These include advanced treatment technologies, such as membrane-based processes (RO and NF), which aim to reduce energy consumption and operational costs while exploring hybrid treatment systems [212]. Genetic engineering of microorganisms shows potential as approaches that accelerate BPA degradation and increase its efficiency, and resource recovery efforts focus on extracting valuable compounds and energy sources during treatment [246]. Advances in sensor technology enable precise treatment process control, minimising energy consumption [247]. Efforts have been devoted to reducing the overall costs of BPA removal technologies through operational optimisation and innovative materials [248]. Comprehensive environmental impact assessments are crucial to understanding the ecological and human health implications of BPA removal processes [249]. Collaborative efforts among researchers, environmental agencies and industries are essential to the advancement of BPA wastewater treatment through knowledge sharing and open-access data. In summary, the BPA wastewater treatment field is advancing rapidly, emphasising innovation, interdisciplinary collaboration and sustainable practices to address ongoing environmental concerns related to BPA contamination.

7. Conclusions

Several physicochemical and biological treatment technologies have been developed for BPA removal. Physicochemical processes, such as filtration and AOP methods, have proven effective in BPA removal, with efficiency ranging from 40% to 98% and 47% to 100%, respectively. Various biological treatments, including conventional activated sludge processes and MBR, show promise for BPA degradation (52–100%). However, these available treatments come with limitations and drawbacks. Biological treatments involve challenges like bacteria maintenance in reactors and biomass handling. Membrane filtrations require maintenance of filters and energy for pressure flow, while AOPs demand significant energy consumption. Fortunately, most hybrid/integrated systems demonstrate better overall BPA removal rates (80–100%). The simultaneous treatment using two different methods can leverage the advantages of both technologies when successfully implemented in a hybrid or integrated approach. For instance, effluent from the first unit does not need to meet the effluent standard directly because the second unit can further treat it. This combination reduces capital and operational costs by selecting a cost-effective technology as the first stage, followed by a second high-cost technology for further polishing with a lower load. Owing to their high energy consumption and maintenance requirements, AOP and membrane filtration should be placed as the second unit in hybrid treatment, thereby receiving a low load. Biological treatment and adsorption are recommended for wastewater with BPA concentrations higher than 1 mg/L. The application of AOP and membrane filtration can be suitable for concentrations lower than 1 mg/L to reduce the load, potentially leading to lower operational and maintenance costs.

Author Contributions: Conceptualization, H.A.H., M.H.M., S.B.K. and J.B.; methodology, M.H.M., S.B.K., J.B. and O.H.A.; investigation, M.H.M., S.B.K., J.B. and O.H.A.; writing—original draft preparation, M.H.M., S.B.K., J.B. and O.H.A.; writing—review and editing, H.A.H. and M.H.M.; visualization, H.A.H. and M.H.M.; supervision, H.A.H.; project administration, H.A.H.; funding acquisition, H.A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the Ministry of Higher Education (MOHE), Malaysia through the Transdisciplinary Research Grant Scheme (TRGS).

Data Availability Statement: All data are presented in the article.

Acknowledgments: The authors would like to acknowledge the Ministry of Higher Education, Malaysia for funding this research programme through the Transdisciplinary Research Grand Scheme (TRGS) with grant title Resilience and Security of Water through Sustainable Localised Domestic Wastewater Reclamation for Landscaping and Toilet Use (Grant no.: TRGS/1/2022/UKM/02/3), Project No. 1: Immobilized Microalgae-Photocatalytic Membrane Technology for the Elimination of Emerging Contaminants and Viruses for High Quality Reclaimed Domestic Wastewater (Grant no.: TRGS/1/2022/UKM/02/3/1).

Conflicts of Interest: The authors declare no conflict of interest.

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