Bacterial degradation of bisphenol A and its analogues: An overview

Julia de Morais Farias
Federal University of the State of Rio de Janeiro: Universidade Federal do Estado do Rio de Janeiro
Natascha Krepsky (natascha@unirio.br)
Universidade Federal do Estado do Rio de Janeiro https://orcid.org/0000-0003-2314-5563

Research Article

Keywords: Emerging contaminants, endocrine disruptor, xenobiotic, consortium, mixtures, bacterial community

Posted Date: June 9th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1631241/v1

Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on September 27th, 2022. See the published version at https://doi.org/10.1007/s11356-022-23035-3.

Abstract

Bisphenol A (BPA) is one of the most produced synthetic monomers in the world and is widespread in the environment. Due to its adverse effects on life, BPA was replaced by bisphenol analogues (BP). Bacteria can degrade BPA and other bisphenol analogues (BP) diminishing their concentrations in the environment. To summarize the knowledge and contribute to future studies, in this review we surveyed papers on bacterial degradation of twelve different bisphenol analogues published until 2020. A total of 84 original papers from PubMed and Google Scholar were selected for this review. Most of the studies (95.2%, $n = 80$) on bacterial degradation of bisphenol analogues (BP) focused on bisphenol A (BPA), and then on BPF, and BPS. The number of studies on bacterial degradation of bisphenol analogues increased almost six times from 2000 ($n = 2$) to 2020 ($n = 11$). Indigenous microorganisms and the genera *Sphingobium* and *Cupriavidus* could degrade several BP. However, few studies focused on *Cupriavidus*. Biodegradation of BPA does not imply the degradation of other analogues. The acknowledgement of various aspects of BP bacterial biodegradation is vital for choosing the most suitable microorganisms for the bioremediation of a single BP or a mixture of BP.

1. Introduction

Bisphenol A (BPA; 4-[2-(4-hydroxyphenyl)propan-2-yl]phenol) is one of the synthetic monomers most produced and used in the world (Michałowicz 2014). The wide use of BPA resulted in an estimated annual production of 8 million tons in 2016. It is estimated that BPA production will reach 10.6 million tons by 2022 (Bisphenol 2016). The Russian A. P. Dianin was the first to synthesize this compound in 1891. BPA was synthesized by the reaction of two molecules of phenol with acid-catalyzed acetone (Alexander and Dill 1998; Rubin and Soto 2009). In 1930, BPA was a potential candidate for synthetic estrogen due to its estrogenic activity. However, the industry chose diethylstilbestrol (DES) instead of BPA (Dodds and Lawson 1936; Rubin and Soto 2009). In the 1940s and 1950s, BPA was introduced in the plastic industry (Rubin and Soto 2009). Nowadays, this compound can be used to manufacture polycarbonates, epoxy resins, flame retardants, and paper thermal, among other uses (Geens et al. 2011).

Due to its widespread production, BPA is continuously released into the environment. It was detected in all environmental compartments, including soil, air, sediment, and water (Corrales et al. 2015; Crain et al. 2007; Flint et al. 2012; Michałowicz 2014). However, BPA is a xenobiotic and endocrine disruptor. This means BPA is a synthetic substance foreign to the natural environment (Gaylarde et al. 2005) and an exogenous chemical substance that interferes with the hormonal action of the body (Alexander and Dill 1998; Chen et al. 2001; Dodds and Lawson 1936; Vandenberg et al. 2009). BPA was detected in urine, amniotic fluid, and tissues like blood, breast milk, and liver of humans (Calafat et al. 2008; Fernandez et al. 2007; Geens et al. 2012; Yamada et al. 2002; Ye et al. 2009). *In vitro* studies and animal experiments indicate that exposure to BPA can affect reproductive, cardiovascular, and thyroid function. Moreover, BPA may be related to oxidative stress, and metabolic diseases, including obesity and diabetes (Catenza et al. 2021; Ma et al. 2019). Besides, several adverse effects of BPA in wildlife were reported, including inhibition of development, malformations, and changes in the reproductive system. Thus, government regulations restricted the use of BPA and this compound was replaced with substances of a similar chemical structure called bisphenol analogues (BP) (Chen et al. 2016; Lee et al. 2015).

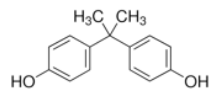
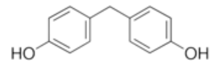
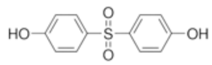
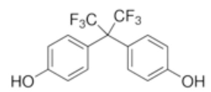
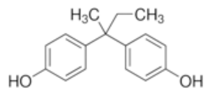
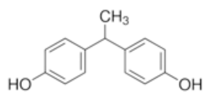
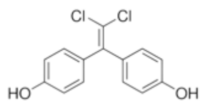
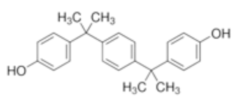
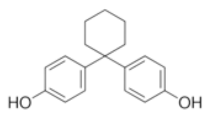
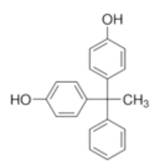
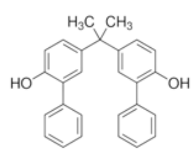
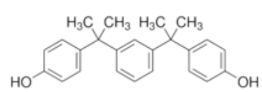
Nevertheless, bisphenol analogues are not safer than BPA. In humans, bisphenol analogues were associated with diseases such as cancer and diabetes, oxidative stress, and other complications, including obesity and asthma (Catenza et al. 2021; Pelch et al. 2019). Several bisphenol analogues listed in Table 1 have estrogenicity and toxicity similar to or greater than BPA, including the BPAF, BPF, BPB, and BPS (Chen et al. 2016; Chen et al. 2001; Lee et al. 2019; Tišler et al. 2016; Yang et al. 2017a). Despite the emergence of studies on bisphenol analogues, most toxicity studies still focus on BPA (Pelch et al. 2019). Therefore, given the potential impact of BP on living organisms, it is essential to understand the fate of bisphenol analogues in the environment and their toxicity.

1.1. Bisphenol analogues (BP)

The bisphenol analogues (BP) are composed of two phenol rings (Hu et al. 2019; Chen et al. 2016; Lee et al. 2015). They can be applied to several materials including polyamides, polyesters, and polymers (Chen et al. 2016; Noszczyńska and Piotrowska-Seget 2018). In the manufacture of polycarbonates, the main substitutes for BPA are BPS, BPF, and BPAF (Chen et al. 2016). Twelve bisphenol analogues were presented in Table 1, including the BPA and eleven substitutes.

The substitution of BPA with bisphenol analogues resulted in their wide distribution in environmental compartments. Bisphenol analogues have already been detected in sludges and effluents from treatment plants, sediment, fresh and marine water, dust, and soil (Česen et al. 2018; Chen et al. 2016; Chen et al. 2020; Hu et al. 2019; Lalwani et al. 2020; Perez et al. 2017; Sun et al. 2017; Yamazaki et al. 2015). Once in the environment, the fate of BP is dictated by its water solubility presented in Table 1. Thus, the hydrophobic compounds adsorb in soil, and the hydrophilic ones dissolve in water (Česen et al. 2018; Wang et al. 2019a).

Table 1 Bisfenol analogues and their respective chemical structures, nomenclature, solubility, and CAS number (Björnsdotter et al. 2017; PubChem 2021; Sigma-Aldrich 2021)

Compound	Chemical structure	Nomenclature (IUPAC)	Solubility in water (g/L)	CAS
BPA		4-[2-(4-hydroxyphenyl)propan-2-yl]phenol	120-300	80-05-7
BPF		4-[(4-hydroxyphenyl)methyl]phenol	190	620-92-8
BPS		4-(4-hydroxyphenyl)sulfonylphenol	1.1×10^{-3}	80-09-1
BPAF		4-[1,1,1,3,3,3-hexafluoro-2-(4-hydroxyphenyl)propan-2-yl]phenol	Insignificant	1478-61-1
BPB		4-[2-(4-hydroxyphenyl)butan-2-yl]phenol	< 1.0	77-40-7
BPE		4-[1-(4-hydroxyphenyl)ethyl]phenol	n.d	2081-08-5
BPC		4-[2,2-dichloro-1-(4-hydroxyphenyl)ethenyl]phenol	4.7	14868-03-2
BPP		4-[2-[4-[2-(4-hydroxyphenyl)propan-2-yl]phenyl]propan-2-yl]phenol	n.d	2167-51-3
BPZ		4-[1-(4-hydroxyphenyl)cyclohexyl]phenol	n.d	843-55-0
BPAP		4-[1-(4-hydroxyphenyl)-1-phenylethyl]phenol	1.1	1571-75-1
BPPH		4-[2-(4-hydroxy-3-phenylphenyl)propan-2-yl]-2-phenylphenol	n.d	24038-68-4
BPM		4-[2-[3-[2-(4-hydroxyphenyl)propan-2-yl]phenyl]propan-2-yl]phenol	n.d	13595-25-0

1.2. Biodegradation of bisphenol

In the environment, the degradation process dictates the course and toxicity of bisphenol analogues (Choi and Lee 2017; Kocaman and Ozhan 2019; Wang et al. 2019). BP is subjected to different types of environmental degradation including photodegradation, oxidation, and biodegradation. Biodegradation is the best choice for removing organic pollutants from the environment (Zhang et al. 2013). The biodegradation of organic pollutants results in products called metabolites. These metabolites often have a molecular structure less recalcitrant than the original molecule. Ideally, the mineralization end product should be simple chemical compounds such as water and carbon dioxide (Gaylarde et al. 2005). However, environmental factors such as temperature, pH, and supply of nutrients can interfere with biodegradation (Elthouky et al. 2020; Gaylarde et al. 2005; Ren et al. 2016).

Several organisms including bacteria, fungi, algae, and plants can degrade BPA in the environment (Eio et al. 2015; Im and Löffler 2016; Michałowicz 2014; Zhang et al. 2019a). However, bacterial degradation is the most relevant in biodegradation studies (Eltoukhy et al. 2020; Zhang et al. 2013; Zhang et al. 2007). In bacterial biodegradation, the process relies on bacteria metabolism (Zhang et al. 2013). The bacteria benefit from the pollutant molecules as a carbon source and substrate for the generation of bacterial energy (Noszczyńska and Piotrowska-Seget 2018; Gaylarde et al. 2005). Therefore, bacterial biodegradation can be handy in the bioremediation process removing or diminishing the environmental concentration of a contaminant (Gaylarde et al. 2005).

The number of studies approaching bisphenol analogues and their potential hazard to the biota is increasing over the years. Nevertheless, bacterial biodegradation of bisphenol A is still predominant (Björnsdotter et al. 2017; Naderi et al. 2014; Noszczyńska and Piotrowska-Seget 2018; Tišler et al. 2016; Usman et al. 2019; Yang et al. 2017a). BPA degrading bacteria have been isolated from compartments such as water, soil, sediment, and water treatment plants. However, studies regarding the environmental persistence and fate of bisphenol analogues are scarce (Chen et al. 2016). Therefore, this review aims to summarize the published information on bacterial biodegradation of bisphenol analogues. Furthermore, we hope this survey can contribute to the advance of this discussion, pointing out emerging trends that should be addressed in future studies.

2. Methods

This survey included papers published until December 2020 and available in *PubMed* and *Google Scholar* (*G-Scholar*) databases. The searches included the keywords "biodegradation" AND "bisphenol A", “bisphenol F” and “biodegradation”; “bisphenol S” AND “biodegradation”; "bisphenol E” AND “biodegradation ”; “bisphenol B” AND “biodegradation”; "bisphenol P" AND “biodegradation”; "bisphenol Z" AND “biodegradation”; "bisphenol C" AND "biodegradation", “bisphenol AF” AND “biodegradation”; “bisphenol AP” AND “biodegradation”; “bisphenol PH” AND “biodegradation”; “bisphenol M” AND ‘biodegradation”; "bisphenol A analogues" AND “biodegradation”.

The articles retrieved in the list of results were analyzed and selected according to the adherence of the title and abstract to the objective of this study. Reviews, books, and conference abstracts were excluded. Only original studies in English were selected for this survey. The inclusion criteria were experimental research comprising the ability of bacteria to degrade bisphenol analogues. Thus, we excluded studies about i) biodegradation with fungi; ii) biodegradation with algae; iii) biodegradation with isolated enzymes; iv) different compounds; v) monitoring; vi) sorption and desorption; vii) detection and occurrence; viii) ecotoxicology; iv) bioreactor and wastewater treatment plant (WWTP) membranes; x) biodegradation articles about different compounds together with some bisphenol analogue; xi) wetlands; xii) phytoremediation; xiii) photodegradation and xiv) human health. After this trial, we excluded duplicate articles.

3. Results And Discussion

3.1 Overview of BP biodegradation publishing

Table 2 presented the total number of papers published until 2020 without restriction, retrieved by keyword search at *Google Scholar* (*G-Scholar*) and *PubMed* databases. Table 2 also included the total number (n) and percentage (%) of papers restricted to bacterial biodegradation, and the number (*n*) of duplicated articles. The keywords “biodegradation” AND “bisphenol A” retrieved 17,200 papers on the *G-Scholar* search. However, only 71 (0.41%) were papers about bacterial biodegradation, and 49 were repeated in the *PubMed* list (Table 2).

Table 2
Total number of papers published until 2020 without restriction, the total number (*n)* and percentage (%) of papers restricted to bacterial biodegradation, and the number (*n)* of duplicated papers about bacterial biodegradation retrieved by keyword and database of search.

Keywords	Database of search	Total number of papers (*n*)	Papers about bacterial biodegradation		Number of duplicated papers (*n*)
			n	**%**	
“biodegradation” AND “bisphenol A”	*PubMed*	361	53	14.7%	49
	G-Scholar	17,200	71	0.41%	
“bisphenol F” AND “biodegradation”	*PubMed*	18	10	55.5%	10
	G-Scholar	863	11	1.27%	
“bisphenol S” AND “biodegradation”	*PubMed*	14	9	64.3%	9
	G-Scholar	765	12	1.8%	
“bisphenol E” AND “biodegradation”	*PubMed*	5	4	80%	4
	G-Scholar	97	6	6.2%	
“bisphenol B” AND “biodegradation”	*PubMed*	8	6	75%	6
	G-Scholar	250	9	3.6%	
“bisphenol P” AND “biodegradation”	*PubMed*	2	1	50%	1
	G-Scholar	50	3	6%	
“bisphenol Z” AND “biodegradation”	*PubMed*	3	2	66.7%	2
	G-Scholar	76	4	5.3%	
“bisphenol C” AND “biodegradation”	*PubMed*	2	1	50%	1
	G-Scholar	71	4	5.6%	
“bisphenol AF” AND “biodegradation”	*PubMed*	5	3	60%	3
	G-Scholar	309	6	1.9%	
"bisphenol AP" AND "biodegradation"	*PubMed*	2	1	50%	1
	G-Scholar	79	3	3.8%	
"bisphenol PH" AND "biodegradation"	*PubMed*	271	1	0.4%	1
	G-Scholar	8	1	12.5%	
"bisphenol M" AND "biodegradation"	*PubMed*	1	1	100%	1
	G-Scholar	22	1	4.5%	

“bisphenol A analogues” AND “biodegradation”	*PubMed*	1	1	100%	1
	G-Scholar	49	1	2%	

A total of 84 original papers about bacterial bioremediation were selected for this review. The selected papers were listed in **Online Resource, sheet SI1** (de Moraes Farias and Krepsky 2022). Figure 1 reveals an increasing trend in the number of studies about BP biodegradation in the past years ($p = 0.0044$). The first study investigating the biodegradation of other BP together with BPA was published in 1992 (Lobos et al. 1992). Fourteen years later, a second study about the biodegradation of bisphenol analogues was published (Ike et al. 2006). After this publishing hiatus, the number of studies on bacterial degradation of bisphenol analogues increased almost six times from 2000 ($n = 2$) to 2020 ($n = 11$) (Fig. 1). Meanwhile, the year 2019 was the most productive for BP. A total of 13 papers were published in 2019 concerning all analogues of bisphenol, especially BPA, BPS, and BPAF (Fig. 1). Then, in 2020, the biodegradation of bisphenol analogues other than BPA BPS, BPF, BPB, BPE, BPAF, BPZ, BPM, BPPH, and BPAP was most studied (Fig. 1).

Evidence of the BPA risk to human and environmental health may have encouraged researchers to investigate ways of removing this compound from the environment. Furthermore, the increase in BPA interest also influenced important government decisions. For example, in 2006 the European Food Safety Authority (EFSA) issued a risk assessment opinion for the use of BPA. The panel members established as tolerable a daily consumption of 50 μg kg^{-1} of BPA (EFSA 2015). Seven years after this issue, in 2013, studies started to establish a thorough assessment of the risks of BPA. The EFSA evaluation included the quantification of exposure from non-dietary sources. The most vulnerable groups of the population were also included in the focus of these studies, including pregnant women, babies, and children (EFSA 2015). In 2015, the maximum acceptable daily intake of BPA was diminished from 50 μg kg^{-1} to 4 μg kg^{-1} including dietary and non-dietary sources (EFSA 2015). In August 2015, the United States Environmental Protection Agency (U.S. EPA) released a list of 19 replacements, including other BP, to replace BPA in thermal papers (U.S. EPA 2015). In December 2016, the European Commission has added BPA to the list of restricted substances. Later, in January of 2017, a decree came into force prohibiting the use of BPA in concentrations greater than 0.02% in thermal papers after January 2nd, 2020 (Björnsdotter et al. 2017). In 2018, emerged the first restrictions for the use of BPA in canned food coatings (EU 2018). In Brazil, the Brazilian National Health Surveillance Agency (ANVISA) also banned the manufacture and import of baby bottles with BPA by a Resolution published in 2011 (Brazil 2011). Thus, increasing awareness may explain the increasing number of publications on bacterial biodegradation of BP in the years 2007, 2015, 2017, 2019, and 2020 (Fig. 1).

3.1.1 Bisphenol analogues

Most (95.2%, $n = 80$) of the publications analyzed investigated the bacterial biodegradation of BPA (Fig. 2). The wide use of BPA in several products and its constant release in nature turned BPA into a ubiquitous compound (Flint et al. 2012; Oehlmann et al. 2009). Consequently, research efforts on the biodegradation of bisphenol analogues are still focused on BPA. Nevertheless, the bisphenol analogues BPF and BPS are among the main substitutes for BPA in the manufacture of polycarbonates, epoxy resins, and thermal papers (Björnsdotter et al. 2017; Chen et al. 2016). Therefore, the detection of BPF and BPS in different environments is increasing yearly (Chen et al. 2016; Noszczyńska and Piotrowska-Seget 2018).

The increased environmental detection of BPF and BPS encouraged research on the bacterial biodegradation of these compounds. Indeed, our survey data showed that 20.2% and 17.9% of the publications explored the biodegradation of BPF and BPS, respectively (Fig. 2). However, this is not enough. Studies investigating the biodegradation of other BP should be encouraged. For example, BPC, BPZ, BPP, and BPB have higher levels of toxicity and estrogenicity when compared to other BP (Chen et al. 2001; Yang et al. 2017a; Zühlke et al. 2016; Zühlke et al. 2020). Besides, BPAF is an important BPA substitute in industry and can persist in the environment (Chen et al. 2016; Choi and Lee 2017; Choi et al. 2019; Frankowski et al. 2020; Zhou et al. 2020). The biodegradation of BPZ, BPE, and BPB analogues by indigenous microorganisms is not efficient enough (Frankowski et al. 2020; Ike et al. 2006; Zhou et al. 2020). Nevertheless, there are few studies about the biodegradation of these analogues (Fig. 2)

Furthermore, studies on the bacterial degradation of BP mixtures are even scarcer. Figure 3 demonstrates the studies where bacterial biodegradation of bisphenol analogues was considered. We represented in *purple* all studies focusing on a single BP published until 2020. Due to a large number of publications, studies focusing exclusively on bacterial biodegradation of BPA were listed in **Online Resource, sheet SI2** (de Morais Farias and Krepsky 2022). Importantly, only two studies analyzed the biodegradation of mixtures of BP (**Fig. 3**). In the environment, bisphenol analogues must not be isolated. Therefore, studies of BP mixtures can guide the bioremediation of the environment affected by more than one bisphenol analogue.

3.1.2 Environmental compartments

Figure 4 summarizes the environmental compartments assessed on bacteria biodegradation studies of bisphenol analogues until 2020. Water was the compartment most studied ($n = 21$) and with the highest number of studies on analogues different from BPA (Fig. 4). Considering the bisphenol analogues and the water compartment, BPA ($n = 20$) was the compound most analyzed, followed by BPS ($n = 6$) and by BPF ($n = 6$) (Fig. 4). Some authors also investigated the bacterial degradation of BPB ($n = 5$) and BPE ($n = 5$) in BPA studies (Frankowski et al. 2020; Ike et al. 2006; Inoue et al. 2008; Sakai et al. 2007; Zhou et al. 2020) (**Fig. 3 and** Fig. 4). However, studies with the other BP were rare. For example, the analogues BPP (Inoue et al. 2008; Ike et al. 2006), BPAF (Frankowski et al. 2020; Zhou et al. 2020), and BPZ (Zhou et al. 2020; Sakai et al. 2007) were included in two studies (Fig. 4). Moreover, one study evaluated the bacterial biodegradation of BPC (Sakai et al. 2007) or BPM (Zhou et al. 2020) (**Fig. 3 and** Fig. 4).

The popularity of BPA in bacterial biodegradation studies in environmental compartments can be attributed to its ubiquity and higher environmental concentration than other BP (Caban and Stepnowski 2020; Chen et al. 2020; Flint et al. 2012; Lalwani et al. 2020; Ozhan and Kocaman 2019; Peteffi et al.

2019). The most researched analogues coupled with BPA in water were BPF and BPS (**Fig. 3**). These three analogues (BPF, BPS, and BPA) were found in 53 surface water samples collected from different regions of India (Lalwani et al. 2020) and were also detected in water samples from China, Poland, Japan, and Korea (Caban and Stepnowski 2020; Yamazaki et al. 2015). In China, those analogues were detected in the Pearl River coupled with TBBPA (tetrabromobisphenol A) (Chen et al. 2020). In Poland, BPS was detected in concentrations similar to BPA in Gdansk (Caban and Stepnowski 2020). Besides, BPF was also reported in higher concentrations than BPA in Southeastern Asian rivers (Yamazaki et al. 2015).

Afterwards, water treatment plants were the second compartment most assessed ($n = 18$) in studies for biodegradation of BP (Fig. 4). In the water treatment plants category, we included studies on activated sludge and effluents. Activated sludge is the most popular technique for water treatment plants. This technique supports microbial communities able to remove nutrients and xenobiotics (Noszczyńska and Piotrowska-Seget 2018). Because of its high nutrient richness, the sludge can be used as a fertilizer. However, polluted fertilizers can contaminate the soil, and groundwater, and reach the food chain (Wang et al. 2019). Consequently, some studies focused on the degradation of BP in sludge. Three authors studied the biodegradation of BPA and BPF analogues (Frankowski et al. 2020; Lobos et al. 1992; Zühlke et al. 2016). Two papers included the biodegradation of the analogues BPAF and BPS (Frankowski et al. 2020; Choi et al. 2019), BPB (Lobos et al. 1992; Zühlke et al. 2016), BPZ (Lobos et al. 1992; Zühlke et al. 2016) and BPE (Frankowski et al. 2020; Zühlke et al. 2016). Nevertheless, one study investigated the biodegradation of BPC (Zühlke et al. 2016) (Fig. 4).

Effluents from treatment plants can be the main source of BP to the environment, including BPA (Caban and Stepnowski 2020; Sun et al. 2017; Zhang et al. 2019b). The analogues BPA, BPF, and BPS were predominant in water treatment plant sludge from Korea, China and India (Lalwani et al. 2020; Hu et al. 2019; Sun et al. 2017). Besides, these three BP dominate water and sewage sludge samples from other countries (Wang et al. 2019; Yamazaki et al. 2015). Lalwani et al. (2020) associated the highest concentration (14,800 $ng.L^{-1}$) of BPA in an Indian river with the discharge of untreated sewage effluent (Lalwani et al. 2020). Conversely, the analogues including BPB, BPZ, and BPAP were hardly reported in sludges (Hu et al. 2019). Although, the analogues BPB, BPZ, BPAP, BPP, and BPAF were detected in sewage treatment plants in India (Karthikraj and Kannan 2018). In Slovenia, the analogue BPZ was detected in effluent samples in higher concentrations than other BP, including BPB, BPC, BPE, BPAP, BPAF (Česen et al. 2018). In China, the sludge of water treatment plants in Xiamen City presented the highest concentrations of the analogues BPA, BPF, BPS, including BPAF and BPE (Sun et al. 2017). Pieces of evidence report that the analogues BPB, BPE, BPAP, and BPAF are little degraded in treatment plants (Sun et al. 2017; Wang et al. 2019a; Česen et al. 2018). Therefore, research efforts to investigate the biodegradation of other BP and their ideal conditions, especially in sewage and industrial effluents are imperative.

Besides, sediment ($n = 15$) and soil ($n = 15$) were the third compartments most popular in studies on BP biodegradation (Fig. 4). Likewise, BPA was the most investigated analogue in sediment and soil. Fourteen ($n = 14$) studies focused on the biodegradation of BPA in sediments and twelve ($n = 12$) in the soil compartment. One of those 14 studies regarding BPA biodegradation (Chang et al. 2014) in sediment, also included the BPF analogue (**Fig. 3**). Additionally, one single study (**Fig. 3**) focused on the bacterial degradation of BPS analogue in sediments (Wang et al. 2019b).

The presence of BPA in sediments was detected in various locations including India, Italy, and China (Li et al. 2019; Mukhopadhyay et al. 2020; Pignotti and Dinelli 2018). A previous study reported higher concentrations of BPA in the sediment than in the water column (Flint et al. 2012). Moreover, Huang et al. (2012) associated the concentrations of BPA in sediment with the high concentration of BPA found in water. Yamazaki et al. (2015) observed that BPF can deposit in the sediment, suggesting that more hydrophobic BP can accumulate in sediment. Nonetheless, the eventual release of bisphenols analogues from the sediment into the water can increase its concentration in the underlying water (Chen et al. 2020). Therefore, studies considering different BP should focus on this compartment.

Notwithstanding, soil studies investigated the biodegradation of more bisphenol analogues than sediment studies (Fig. 4). Indeed, the soil was the second compartment with papers assessing the biodegradation of different bisphenol analogues after the water compartment. For example, coupled with BPA, four studies on bacterial degradation in soil included BPS (Choi and Lee 2017; Elthouky et al. 2020; Frankowski et al. 2020; Oshiman et al. 2007) and BPF analogues (Elthouky et al. 2020; Frankowski et al. 2020; Ren et al. 2016; Zühlke et al. 2020). Three papers studied the degradation of BPB analogue in soil (Elthouky et al. 2020; Oshiman et al. 2007; Zühlke et al. 2020). A single study (Fig. 4**)** focused on the bacterial degradation of BPAF in soil (Choi and Lee 2017). Furthermore, some authors focused on the degradation of different bisphenol analogues in soil, excluding BPA from the investigation. For instance, Cao et al. (2020) studied the BPS, Lu et al. (2017) investigated the BPF, and Zühlke et al. (2020) analyzed the biodegradation of seven bisphenol analogues, including BPB, BPC, BPE, BPF, BPZ, BPAP and BPPH (**Fig. 3**). However, the last authors published a previous paper addressing exclusively BPA biodegradation in soil under the same experimental conditions (Zühlke et al. 2017).

Bisphenol analogues can reach soil from the discharge of landfills leachate, application of sewage sludge and biosolids as fertilizers, irrigation with wastewater effluents, and waste disposal (Corrales et al. 2015; Flint et al. 2012). Pérez et al. (2017) detected BPA in higher concentrations than other BP in the soil. In addition, these authors detected BPF in samples of soil from an industrial source and agricultural land irrigated with water recycled from a treatment plant (Pérez et al. 2017). Conversely, the analogue BPAF was detected only in the samples from agricultural land, but not in industrial soils (Pérez et al. 2017). Consequently, given the different sources of soil contamination and potential crop production contamination, further studies considering the biodegradation of other bisphenol analogues in soil are vital for food safety.

Last but not least, nine studies ($n = 9$) investigated the bacterial biodegradation of biphenol analogues in a bioreactor (Fig. 4). Again, BPA was the most popular bisphenol analogue in bioreactor studies. Eight studies ($n = 8$) focused on BPA degradation and a single one (Chang et al. 2014) included the analogues BPB and BPF (**Fig. 3**). Moreover, one single paper (Huang et al. 2019) focused on BPS biodegradation

(**Fig. 3 and** Fig. 4). The bioreactor is one of the methods approved for treatment stations. Bioreactor allows a longer retention time of the compost to be treated, higher biomass concentration, and, consequently, higher bacterial density, favouring biodegradation (Hu et al. 2019). Besides, bioreactors can be fed, for example, with water, sludge, and other matrices (Chang et al. 2014; Huang et al. 2019, Oh and Choi 2019; Sathyamoorthy et al. 2018). Therefore, it is important to identify the microorganisms capable of degrading bisphenols under the operating conditions characteristic of bioreactors, including the optimization of this process.

The number of papers published in each environmental compartment varied over time (Fig. 5). Water was the most studied compartment concerning the biodegradation of bisphenol analogues from 1967 to 2009 (Fig. 5). BPA has a water solubility of 120–300 mg/L at room temperature (Staples et al. 1998) and started to be detected in aquatic environments in the late 1990s (Corrales et al. 2015). Together, both factors may explain why the studies of bacterial biodegradation in water were carried out so readily. Meanwhile, studies with other environmental compartments intensified after 2014, including sediment, soil, treatment plant, and bioreactor (Fig. 5). All these compartments are the source or destination of bisphenol analogues to the environment. Thus, approaching bacterial biodegradation of diverse bisphenol analogues in different compartments is imperative to understand this process and control their damage.

3.1.3 Bacterial biodegradation

Ninety-one bacterial strains capable of BPA degradation were reported in the literature. We listed in **sheet SI3 of Online Resouce** (de Morais Farias and Krepsky 2022) the bacteria reported in studies capable of degrading several BP and its environmental sources. Figure 6 summarizes the dominant groups of bacteria and indigenous microorganisms in studies on the biodegradation of BP until 2020. Indigenous microorganisms were the most studied group regarding bacterial biodegradation (Fig. 6). The main genera investigated for BPA degradation were *Pseudomonas*, *Sphingomonas*, and *Bacillus* (Fig. 6). Besides BPA, *Sphingomonas* species could biodegrade up to six bisphenol analogues, including BPS, BPF, BPB, BPE, BPZ, and BPC (Fig. 6). Likewise, *Cupriavidus* also biodegraded six different BP, besides BPA (Fig. 6). Meanwhile, *Sphingobium* was able to degrade six analogues including BPA, BPS, BPF, BPB, BPE, and BPP (Fig. 6). *Bacillus* biodegradation comprised degradation of five analogues BPA, BPF, BPE, BPZ, and BPC (Fig. 6), and *Pseudomonas* presented degradation of only four analogues BPA, BPS, BPF, and BPB (Fig. 6).

Despite the degradation of a limited list of bisphenol analogues (Fig. 6), *Pseudomonas* was the most studied genus for the degradation of BPA. *Pseudomonas* is known for its ability to degrade a variety of organic molecules, including aromatic compounds like toluene, biphenyl, naphthalene, phthalates, and others (Díaz et al. 2008; Goldberg 2000; Kimura et al. 2018; Kim and Park 2018; Palleroni 2015; Palleroni 2010; Yu et al. 2020). This genus is an aerobic, Gram-negative, rod-shaped bacteria that can be found in different environments and are flexible to environmental changes (Palleroni 2015). Consequently, it was observed that a *Pseudomonas* consortium had the best percentages of degradation of BPA, BPF, and BPB

(Chang et al. 2014). Likewise, *Pseudomonas* was predominant in a consortium able to degrade BPS (Huang et al. 2019; Wang et al. 2019b) and Lu et al. (2017) identified a consortium with *Pseudomonas* that degraded BPF. Moreover, when the strain *Pseudomonas* sp HS-2 was isolated from this consortia, it was still efficient in BPF degradation (Lu et al. 2017).

Pseudomonas is also beneficial to plants, although it can be pathogenic to humans, animals, and plants (Palleroni 2015; Goldberg 2000). For example, *P. aeruginosa* is an opportunistic pathogen that can cause several infections and is resistant to several antibiotics (Hao et al. 2021). *P. aeruginosa* species can be used to improve BPA degradation, either by isolating it in nanofiber membranes (Liu al. 2015) or by using it in bioreactors (Mita et al. 2015). Louati et al. (2019) reported that *P. aeruginosa* Gb30 was able to degrade 60% of BPA in a concentration of 3 mM in 4 days (Louati et al. 2019). However, in the same study, the strain *P. putida* G320 presented the highest BPA degradation efficiency than other strains isolated from arid and desert soil (Louati et al. 2019). Indeed, another study showed that the strain *Pseudomonas putida* YC-AE1, isolated from a soil sample, can degrade BPA at high (50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000 mg/L) and low (0.5, 1, 2, 4, 6, 8, 10, 12 mg/L) concentrations (Eltoukhy et al. 2020). This strain showed variable efficiency of degradation according to the BP tested. For example, in a concentration of 100 mg/L, biodegradation of BPA in 72h was 100%, BPS 30%, BPF 67%, and BPB 60% (Eltoukhy et al. 2020). Conversely, *P. putida* isolated from river water degraded in 10 days 87% of BPA in the concentration of 1 mg/L (Kang and Kondo 2002b).

Sphingomonas was the second genus most studied on BP biodegradation until 2020. *Sphingomonas* consists of aerobic, rod-shaped or ovoid, Gram-negative bacteria that can be mobile or not (Yabuuchi and Kosako 2015). They can reside in natural or modified environments and can be opportunistic pathogens (Yabuuchi and Kosako 2015). *Sphingomonas* possesses a wide metabolic versatility (Yabuuchi and Kosako 2015) and can degrade several recalcitrant aromatic compounds, including biphenyl, chlorinated furan, carbazole, chlorinated phenols, polyethene glycol, different herbicides, and pesticides, in addition to endocrine disruptors such as estradiol and nonylphenol (Asaf et al. 2020; Yabuuchi and Kosako 2015; Stolz 2009; Willison 2004). Likewise, this genus can degrade BPA and other BP such as BPS, BPF, BPB, BPE, BPZ, and BPC (Fig. 6).

Regarding bisphenol analogues, the *Sphingomonas* sp BP-7 could degrade approximately 90%, 100%, 94%, and 100% of BPE, BPB, BPC, and BPZ, respectively, at a concentration of 100 mg/L (Sakai et al. 2007). However, this strain was not able to degrade BPF and BPS. Sakai et al. (2007) suggested that the biodegradation of BP relies on the methyl or methylene group present between the two aromatic rings in some BP. Although present in BPA, neither methyl nor methylene group is present in the BPF or BPS analogues (Table 1). Consequently, *Sphingomonas* degradation of BPA was reported in many studies. For example, the strains isolated from soil *Sphingomonas* sp SO11, *Sphingomonas* sp SO1a, and *Sphingomonas* sp SO4a could metabolize BPA at a concentration of 115 mg/L in a period of 12h to 48h (Matsumura et al. 2009). Aditionally, Sakai et al. (2007) observed that the *Sphingomonas* sp. SP-7 can degrade 95% of BPA in a concentration of 30 mg/L in 40 days. However, total BPA degradation could be much faster by coupling *Sphingomonas* sp. SP-7 with *Pseudomonas* sp. BP-14. For example, in 7 days this consortium degraded 100% of BPA in the concentration of 100 mg/L (Sakai et al. 2007). Likewise, Yu et al. (2019) reported an increase in BPA degradation efficiency when *Sphingomonas* was in a consortium with the *Pseudomonas.* Moreover, the *S. bisphenolicum* strain AO1 degraded between 30% and 100% of BPA at a concentration of 100 mg/L in 44h, according to the glucose concentration in the growth medium (Oshiman et al. 2007). The metabolism of *Sphingomonas bisphenolicum* AO1 was also analyzed in other studies (Sasaki et al. 2005; Sasaki et al. 2008). For example, this strain could increase the community of indigenous microorganisms and the efficiency of BPA degradation (Matsumura et al. 2015).

Bacillus was the third bacteria genus most studied on BP degradation, after *Pseudomonas* and *Sphingomonas* (Fig. 6). The genus *Bacillus* is comprised of aerobic, or anaerobic facultative, rod-shaped, Gram-positive bacteria. These bacteria can occur individually, in pairs, in chains, or as long filaments (Logan and Vos 2015). They are present in several environments such as freshwater, seawater, soil, air, plants, and animals. *Bacillus* can form endospores and resist adverse environmental conditions, including desiccation, radiation, and chemical substances (Logan and Vos 2015). Besides, *Bacillus* can overcome extreme conditions including high temperatures, acidic environments, and extremes of salinity (Logan and Vos 2015; Maughan and Van Der Auwera 2011). Some studies reported that *Bacillus* can degrade BPA, BPF, BPE, BPZ, and BPC (Fig. 6). However, most research with *Bacillus* focused on the efficiency of BPA degradation. For example, the strain isolated from soil *Bacillus* sp YA27 took 60 h to degrade 100% of BPA at a concentration of 50 mg/L (Matsumura et al. 2009). Nonetheless, the strain *Bacillus* sp. KU3, isolated from the marine environment, showed 61% of efficiency in the degradation of BPA at a concentration of 1,000 mg/L in 15 days (Kamaraj et al. 2014). Therefore, the degradation efficiency decreased as the concentration of BPA increased (Li et al. 2012).

In lower concentrations of BPA (10 and 25 mg/L), the strain *Bacillus pumilus*, isolated from fermented Kimchi food, was able to degrade 100% of BPA at concentrations in 16h and 3 days, respectively. Likewise, *B. pumilus* grown in a medium increased by 10% of NaCl degraded BPA at a concentration of 10 mg/L in 2 days. However, this strain was not able to degrade BPA at the concentration of 50 mg/L and 10 mg/L with more than 12.5% NaCl (Yamanaka et al. 2007). Moreover, some studies reported an increase in BPA biodegradation with the combination of some *Bacillus* species with the macrophyte *Dracaena sanderiana*. For example, *Bacillus thuringiensis* isolated from the endosphere of the plant *Dracaena sanderiana* degraded in 24h, 95% of BPA at a concentration of 100 μM (Suyamud et al. 2018). *Bacillus cereus* NI, together with macrophyte *Dracaena sanderiana* and endophyte strains obtained a removal rate of 100% BPA in 5 days (Suyamud et al. 2020). Both strains belong to the *Bacillus cereus* group. *B. thuringiensis* is entomopathogenic and is used in the production of pesticides (Ehling-Schulz et al. 2019) and *B. cereus* is responsible for poisoning food and infections (Ehling-Schulz et al. 2019).

Some studies associated the cytochrome P450 monooxygenase system with the hydroxylation of BPA during biodegradation with *Bacillus* sp. GZB (Das et al. 2019). *Bacillus* sp. GZB could degrade in 96h, 100% of BPA at a concentration of 10 mg/L under aerobic and anaerobic conditions. Genes encoding the cytochrome P450 monooxygenase system were detected in the genome of *Bacillus* sp. GZB (Das et al. 2019). The cytochrome P450 monooxygenase system comprises cytochrome P450, ferredoxin, and ferredoxin reductase. Das et al. (2019) affirmed this enzyme complex is vital for BPA degradation. The same investigation was conducted with *Sphingomonas bisphenolicum* AO1, and the cytochrome P450 monooxygenase system was also involved in the BPA biodegradation (Sasaki et al. 2005; Sasaki et al. 2008). Additionally, it was reported that *Bacillus* produces other enzymes including the spore-laccase enzyme, which was responsible for the BPA biotransformation into less complex molecules (Das et al. 2019). Indeed, the genus *Bacillus* produces laccase and this enzyme is capable of catalyzing the oxidation of aromatic compounds (Lu et al. 2012), including phenol and other recalcitrant compounds (Das et al. 2019; Lu et al. 2012; Le et al. 2006; Held et al. 2005).

Regarding the other BP, the *B. amyloliquefaciens* strain was able to degrade 77% of BPA, 69% of BPF, and 77% of BPE in concentrations of 60 mg/L (Zühlke et al. 2016). Likewise, *B. amyloliquefaciens* degraded 95% of BPC at a concentration of 20 mg/L (Zühlke et al. 2016). Zühlke et al. (2016) investigated the degradation of BPZ by *B. amyloliquefaciens*. However, BPZ was poorly soluble and only a small portion (one-sixth) of the soluble phase could be detected at the High-Performance Liquid Chromatography (Zühlke et al. 2016). The degradation of bisphenol analogues resulted in the formation of bisphenol and phosphate conjugates. The authors suggested that this may be a mechanism to reduce the toxicity of BP and thus avoid the growth inhibition of the strain. However, the transformation of BP in these products proved to be reversible because after the formation of the products they returned to the initial structure of BP (Zühlke et al. 2016).

Sphingobium was another important genus in the biodegradation of BP (Fig. 6). *Sphingobium* is one of three new genera derived from *Sphingomonas*, including *Novosphingobium*, *Sphingomonas stricto sensu*, and *Sphingopyxis* (Takeuchi et al. 2001). A fifth genus *Sphingosinicella* was proposed later (Maruyama et al. 2006). *Sphingobium* is characterized by grouping strictly aerobic, rod-shaped, Gram-negative bacteria with glycosphingolipids in their cell envelope, and chemoorganotrophic (Takeuchi et al. 2001). Members of this genus are capable of degrading aromatic compounds such as naphthalene, biphenyl, m-xylene, phenanthrene, herbicides, and pesticides (Cai et al. 2015; Liang et al. 2010; Pinyakong et al. 2003; Révész et al. 2018; Önneby et al. 2014).

Furthermore, *Sphingobium* could degrade most bisphenol analogues, including BPA, BPF, BPS, BPB, BPE, and BPP (Fig. 6). For example, the strains *Sphingobium fuliginis* TIK1 and *Sphingobium* sp. IT4 were both isolated from the rhizosphere of plants and degraded 0.5 mmol/L of those six BP with 100% degradation efficiency in 24h. However, the biodegradation efficiency of BPP was 78% for *S. fuliginis* TIK1 and 91% for *Sphingobium* sp. IT4 (Toyama et al. 2013). *Sphingobium* sp. IT4 degradation of BP resulted in the hydroquinone and p-benzoquinone metabolites. Meanwhile, *Sphingobium fuliginis* TIK1 generated metabolites resulting from hydroxylation and meta cleavage of BP, which were consistent with the findings from BPA degradation by *Sphingobium fuliginis* OMI (Toyama et al. 2013). Degradation by this strain resulted in the 3-hydroxy BPA, 2,2-bis(3,4-dihydroxyphenyl) propane, 3-(4-hydroxyphenyl)-3-methyl-2-butanone, and 3-(3,4-dihydroxyphenyl)-3-methyl-2-butanone metabolites, which indicate hydroxylation of one or two aromatic rings and further meta-cleavage of this molecule (Ogata et al. 2013). Therefore, from this metabolic pathway, it was proposed that BP like the BPF and BPS could be degraded regardless of the chemical group present in the connection between the aromatic rings (Ogata et al. 2013). In addition, *Sphingobium fuliginis* OMI, also isolated from the rhizosphere, showed 100% of degradation efficiency for almost all BP cited in a concentration of 1 mM in 24h. However, the BPP for this strain was the exception and obtained about 67% degradation (Ogata et al. 2013).

In another study with strains isolated from the rhizosphere, the *Sphingobium* strain *yanoikuyae* TYF-1 was able to degrade 90% and 92% of BPA and BPF, respectively, at a concentration of 25 mg/L, over a long period of 42 days (Toyama et al. 2009). The products that originated from BPF degradation were ditrimethylsilyl (4HB), hydroquinone (1,4-HQ), and p-benzoquinone (1,4-BQ). Initially, it was suggested that *Sphingobium* strain *yanoikuyae* TYF-1 had a BPF degradation pathway similar to *Sphingobium yanoikuyae* FM-2 strain (Toyama et al. 2009). Indeed, the *Sphingobium yanoikuyae* FM-2 isolated from riverine water was able to degrade 100% of BPF at a concentration of 0.5mM in 9h when previously acclimated with the BPF. This efficiency decreased to 95% of BPF in 16h when acclimated with glucose. Toyama et al. (2009) proposed a degradation pathway in which the connection between the BPF rings undergoes a rearrangement, releasing 1,4-hydroquinone and p-hydroxybenzoic acid. Then, both generated metabolites could be completely degraded later (Inoue et al. 2008). However, despite BPF degradation, the *Sphingobium yanoikuyae* FM-2 could not degrade other BP including BPA, BPE, BPB, BPP, and BPS (Inoue et al. 2008). Moreover, Inoue et al. (2008) suggested that the *Sphingobium yanoikuyae* FM-2 strain could only degrade the BP with no methyl groups on the connection between the aromatic rings or in the aromatic rings. Therefore, there were differences in metabolic pathways for both strains *Sphingobium fuliginis* TIK1 and *Sphingobium fuliginis* OMI (Ogata et al. 2013; Toyama et al. 2013).

Despite few studies with *Cupriavidus*, this bacteria genus was relevant to BP degradation (Fig. 6). Some members of the *Cupriavidus* genus can resist heavy metals, synthesize polyhydroxyalkanoate and degrade xenobiotics (Wang et al. 2017). For example, the *Cupriavidus basilensis* is capable of degrading xenobionts including biphenyl, dibenzo-furan, ochratoxin A, 9H-carbazol, and others (Becher et al. 2000; Ferenczi et al. 2014; Suenaga et al. 2015; Waldau et al. 2009; Wang et al. 2017). Likewise, *Cupriavidus basilensis* could degrade BPA, BPE, BPB, BPC, and BPS (Fig. 6).

Regarding BPA degradation, *Cupriavidus basilensis* JF1 showed slow degradation of BPA as the single source of carbon. However, BPA degradation was accelerated with the addition of phenol as a co-substrate. Phenol acted as a degradation biostimulant. Almost 66% of BPA in the concentration of 0.21 mM was degraded in 150h when phenol was added (Fischer et al. 2010). Similarly, the strain *Cupriavidus basilensis* SBUG 290 obtained higher BPA degradation efficiency when previously cultivated with biphenyl, achieving 78% degradation of 0.26 mM in 48h (Zühlke et al. 2017). Thus, Zühlke et al. (2017) cultivated *Cupriavidus basilensis* strains in biphenyl to carry out degradation experiments with BPF, BPE, BPB, BPZ, BPC, BPAP, and BPPH (Zühlke et al. 2020). *Cupriavidus basilensi*s SBUG 290 showed 98% efficiency in the degradation of BPC, 62% of BPB, 31% of BPE, and 6% of BPF, in 216 hours, at a concentration of 60 mg/L (Zühlke et al. 2020). Conversely, the low solubility of BPZ, BPAP, and BPPH made it impossible to investigate the degradation efficiency in *Cupriavidus basilensis* SBUG 290 (Zühlke et al. 2020). Investigations regarding the metabolic pathways for BP cleavage were published previously

(Zühlke et al. 2020; Zühlke et al. 2017; Fischer et al. 2010). Due to space limitations, it will not be discussed in our review.

Finally, indigenous microorganisms were another relevant group of microorganisms investigated in the biodegradation of BP (Fig. 6). The biodegradation of BPA, BPB, BPE, BPP, and BPF by indigenous microorganisms was previously observed in freshwater (Ike et al. 2000; Ike et al. 2006; Kang and Kondo 2002a; Klecka et al. 2001). Accordingly, Zhou et al. (2020) reported that indigenous microorganisms were able to degrade BPA, BPE, BPB, BPZ, BPF, and BPM in the concentration of 0.1 mg/L in freshwater. Each bisphenol analogue presented different biodegradation efficiency. The analogue BPA, BPE, BPB, and BPZ showed 70% of degradation, although BPF and BPM degraded, respectively, 60% and 30% (Zhou et al. 2020). However, in the only study published on BPM, Zhou et al. (2020) suggested that the increased adsorption of BPM to humic acid can increase its degradability (Zhou et al. 2020).

Moreover, Frankowski et al. (2020) evaluated the biodegradation of BPAF and other five BP in riverine water and activated sludge, including BPA, BPF, BPS, BPB, and BPE (Frankowski et al. 2020). The biodegradation of indigenous microorganisms from activated sludge samples reached approximately 100% efficiency for BPA and BPF at the concentration of 10 mg/L. At this same concentration, biodegradation of BPS was between 40% and 50% and around 40% for BPB and BPE. However, Frankowski et al. (2020) observed that the degradation of bisphenol analogues by indigenous microorganisms in riverine water was inefficient. For example, the efficiency of BPAF biodegradation was less than 20% under the same conditions at the concentration of 10 mg/L (Frankowski et al. 2020). Likewise, Zhou et al. (2020) reported low degradability of BPAF. Indeed, Zhou et al. (2020) showed high persistence of BPAF in lake water, remaining practically unchanged after 49 days of monitoring (Zhou et al. 2020). However, BPAF showed the highest affinity for humic acid and activated sludge particles than BPA, BPS, BPB, and BPM (Zhou et al. 2020; Choi et al. 2019). In addition, the biodegradation of BPAF increased in the presence of humic acid (Zhou et al. 2020).

Regarding the biodegradation of BPS in water, Ike et al. (2006) could not detect its degradation in riverine water under aerobic conditions. Likewise, it was not detected in marine water within sixty days (Danz et al. 2009). BPS was also not degraded during 49 days in lake water (Zhou et al. 2020). This could indicate that BPM, BPS, and BPAF were not easily degraded in the water. Conversely, Wang et al. (2019b) reported that 99% of BPS at a concentration of 50 mg/L was degraded in 10 days by a consortium isolated from a sediment microbial community after 28-day of acclimation (Wang et al. 2019b). Indigenous microorganisms comprise the microbial community native to the environment. Consequently, the addition of pollutants like BPS or BPA can modify the composition, diversity, and abundance of these microbial communities. For example, BPA can favour bacterial groups resistant to xenobiotics and inhibit sensible ones (Huang et al. 2017; Xiong et al. 2017). Indeed, the 28-day acclimatization selected the bacteria tolerant to BPS that could use this BP as a substrate for growth, including *Hyphomicrobium*, *Pandoraea*, and *Cupriavidus* (Wang et al. 2019). A similar observation was found during biodegradation in a bioreactor (Huang et al. 2019). BPS was degraded in about 10 days and the microbial community was modified over this period. time. Accordingly, Huang et al. (2019) reported an increase in the abundance of bacteria associated with BPS degradation, including *Pseudomonas*, *Devosia*, *Delftia*, *Acidovorax*, and *Rhodobacter.*

In addition to the presence of xenobiotics, environmental conditions interfere with bacterial metabolisms (Elthouky et al. 2020; Gaylarde et al. 2005; Ren et al. 2016). Table 3 gathered literature data on temperature and pH optimal for BP degradation. However, investigations of the ideal conditions for bacterial degradation comprised only BPA, BPF, and BPS. Papers that assess the ability of bacterial strains to degrade different concentrations of BP other than BPA are still scarce. Several studies have already identified differences in the efficiency of BPA degradation according to changes in compound concentration (Babatar et al. 2019; Chang et al. 2011; Elthouky et al. 2020; Klecka et al. 2001; Li et al. 2012; Vijayalakshmi et al. 2018; Zhang et al. 2007). However, there are still few studies that investigate this difference in other bisphenol analogues.

Table 3
Optimal conditions of temperature (T) and pH for the bacterial biodegradation of bisphenol analogues in diverse environmental compartments.

Compound	Matrix	Microorganism	T (ºC)	pH	Reference
BPA	river water	Indigenous microorganisms	30	7	Kang and Kondo 2002a
BPA	water marine sediment	*Pseudomonas* sp. KU1	n.d	7	Kamaraj et al. 2014
BPA	water marine sediment	*Pseudomonas* sp. KU2	n.d	7	Kamaraj et al. 2014
BPA	water marine sediment	*Bacillus* sp. KU3	n,d	7	Kamaraj et al. 2014
BPA	soil	*Arthrobacter* sp. YC-RL1	30	7	Ren et al. 2016
BPA	soil	*Pseudomonas putida* YC-AE1	25–30	7,2	Elthouky et al. 2020
BPA	soil	*Pseudomonas* sp. BG12	n.d	8	Noszczyńska et al. 2020
BPA	river sediment	*Sphingobium* sp. YC-JY1	30	5,5–8	Jia et al. 2020
BPA	river sediment	*Bacillus* sp. GZB	37	7	Li et al. 2012
BPA	solid waste leachate	*Achromobacter xylosoxidans*	35	7	Zhang et al. 2007
BPF	soil	consortium	35	7	Lu et al. 2017
BPS	river sediment	consortium	30	7	Wang et al. 2019

Legend: BPA - bisphenol A; BPF - bisphenol F; BPS - bisphenol S.

4. Conclusions

Most of the studies published until 2020 focused on the bacterial degradation of BPA, and then on the biodegradation of BPF and BPS. Indeed, BPA was the most studied analogue for all compartments and bacterial genera. Water was the preferred environmental compartment to access bacterial biodegradation of BPA and other analogues. Biodegradation studies of BPA on water treatment plants were the second most accessed after the water compartment. Furthermore, the soil was frequently accessed for the degradation of the other bisphenol analogues, whereas leachate was the compartment less studied. All the strains cited in published studies diminished bisphenol concentration in the environmental compartments. *Pseudomonas*, *Sphingomonas*, and *Bacillus* were the genera most investigated for biodegradation of BPA and other BP. Besides the number of publications, indigenous microorganisms, *Cupriavidus* and *Sphingobium* showed the highest degradation variability. Those groups degraded more than six BP analogues, including BPA, BPB and BPE. Meanwhile, *Pseudomonas* and *Bacillus* degraded up to three or four BP, respectively.

The degradation of BPA by bacterial consortia showed to be more efficient than with isolated strains (Chang et al. 2011; Kang and Kondo 2002b; Peng et al. 2015; Sakai et al. 2007; Sarma et al. 2019; Yu et al. 2019). However, only two studies evaluated the consortium degradation of an analogue different from BPA (Lu et al. 2017; Wang et al. 2019b). Thereby, bacterial degradation efficiency varies greatly depending on the microorganisms involved in the process, the environmental conditions, and the chemical structure of the compound to be degraded. Accordingly, biodegradation of Bisphenol A does not guarantee biodegradation of its replacement analogue. Therefore, research comparing the degradation of isolated bacteria and consortia must be executed with other bisphenol analogues, considering the particularities of each microorganism and compartments.

Additionally, studies on the biodegradation of mixtures of bisphenol analogues are scarce, whereas, in the environment, they usually occur combined with other pollutants. Moreover, research analyzing the degradation of bisphenol analogues with different chemical groups attached to the aromatic ring, such as BPAP and BPC, is rare. Consequently, studies covering various aspects of the bacterial biodegradation of bisphenol analogues are vital to better understanding its relation with the chemical and molecular structure of each analogue. Future research efforts should focus on clarifying the capacity of bacterial strains or consortiums in degrading the different bisphenol analogues. This includes determining the optimum pH and temperature for biodegradation and the effect of previous bacteria acclimatization on each BP biodegradation, notably the hydrophobic analogues like BPAF and BPM in water compartments. All this knowledge could assist in the choice of the most suitable microorganisms for bioremediation whether is a single BP or a mixture of BP.

Declarations

Data availability

All datasets analysed in this study are available as spreadsheets in **Online Resource**.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Funding

J. de Morais Farias received a grant from the initiation in the technological development and innovation program (PIBITI/CNPq) of the Directorate of Technological, Cultural and Social Innovation from the Federal University of the State of Rio de Janeiro (UNIRIO) and the Brazilian National Council for Scientific and Technological Development (CNPq).

Author contributions

All authors contributed to the conception and design of this study. Material preparation, data collection, and analysis were performed by J. de Morais Farias. The first draft of the manuscript was written by J. de Morais Farias and N. Krepsky critically revised the work. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Acknowledgements

The authors are grateful to R. A. F. Neves, S. G. M. Portugal and E. A. Rojas for critical reviewing of the manuscript and suggestions.

References

1. Alexander HC, Dill DC (1998) Environmental toxicology. In: Encyclopedia of Toxicology. pp 210–212
2. Asaf S, Numan M, Khan AL, Al-Harrasi A (2020) Sphingomonas: from diversity and genomics to functional role in environmental remediation and plant growth. Crit Rev Biotechnol 40:138–152. https://doi.org/10.1080/07388551.2019.1709793
3. Babatabar S, Zamir SM, Shojaosadati SA, et al (2019) Cometabolic degradation of bisphenol A by pure culture of Ralstonia eutropha and metabolic pathway analysis. J Biosci Bioeng 127:732–737. https://doi.org/10.1016/j.jbiosc.2018.12.001
4. Becher D, Specht M, Hammer E, et al (2000) Cometabolic degradation of dibenzofuran by biphenyl-cultivated Ralstonia sp. strain SBUG 290. Appl Environ Microbiol 66:4528–4531. https://doi.org/10.1128/AEM.66.10.4528-4531.2000
5. Bisphenol A (2016). A Global Market Overview. Report code: CP021, pp 194, 2016.
6. Björnsdotter MK, de Boer J, Ballesteros-Gómez A (2017) Bisphenol A and replacements in thermal paper: A review. Chemosphere 182
7. Brazil. Ministério da Saúde. Resolução RDC n° 41/2011, de 16 de setembro de 2011. https://bvsms.saude.gov.br/bvs/saudelegis/anvisa/2011/res0041_16_09_2011.html. Acessed 28 September 2021. (in Portuguese)
8. Briggs JP (2010) The zebrafish: a new model organism for integrative physiology. Am J Physiol Integr Comp Physiol 282:R3–R9. https://doi.org/10.1016/s1872-0854(10)04001-4

9. Caban M, Stepnowski P (2020) The quantification of bisphenols and their analogues in wastewaters and surface water by an improved solid-phase extraction gas chromatography/mass spectrometry method. Environ Sci Pollut Res 27:28829–28839. https://doi.org/10.1007/s11356-020-09123-2
10. Cai S, Shi C, Zhao JD, et al (2015) Sphingobium phenoxybenzoativorans sp. nov., a 2-phenoxybenzoic-acid-degrading bacterium. Int J Syst Evol Microbiol 65:1986–1991. https://doi.org/10.1099/ijs.0.000209
11. Calafat AM, Ye X, Wong LY, et al (2008) Exposure of the U.S. population to Bisphenol A and 4-tertiary-octylphenol: 2003-2004. Environ Health Perspect 116:39–44. https://doi.org/10.1289/ehp.10753
12. Cao S, Wang S, Zhao Y, et al (2020) Fate of bisphenol S (BPS) and characterization of non-extractable residues in soil: Insights into persistence of BPS. Environ Int 143:. https://doi.org/10.1016/j.envint.2020.105908
13. Catenza CJ, Farooq A, Shubear NS, Donkor KK (2021) A targeted review on fate, occurrence, risk and health implications of bisphenol analogues. Chemosphere 268:129273. https://doi.org/10.1016/j.chemosphere.2020.129273
14. Česen M, Lenarčič K, Mislej V, et al (2018) The occurrence and source identification of bisphenol compounds in wastewaters. Sci Total Environ 616–617:744–752. https://doi.org/10.1016/j.scitotenv.2017.10.252
15. Chang BV, Liu JH, Liao C Sen (2014) Aerobic degradation of bisphenol-A and its derivatives in river sediment. Environ Technol (United Kingdom) 35:416–424. https://doi.org/10.1080/09593330.2013.831111
16. Chang B V., Yuan SY, Chiou CC (2011) Biodegradation of bisphenol-A in river sediment. J Environ Sci Heal - Part A Toxic/Hazardous Subst Environ Eng 46:931–937. https://doi.org/10.1080/10934529.2011.586246
17. Chen D, Kannan K, Tan H, et al (2016) Bisphenol Analogues Other Than BPA: Environmental Occurrence, Human Exposure, and Toxicity - A Review. Environ Sci Technol 50:5438–5453. https://doi.org/10.1021/acs.est.5b05387
18. Chen P, Zhong Y, Chen K, et al (2020) The impact of discharge reduction activities on the occurrence of contaminants of emerging concern in surface water from the Pearl River. Environ Sci Pollut Res 30378–30389. https://doi.org/10.1007/s11356-020-09295-x
19. Choi YJ, Lee LS (2017) Aerobic Soil Biodegradation of Bisphenol (BPA) Alternatives Bisphenol S and Bisphenol AF Compared to BPA. Environ Sci Technol 51:13698–13704. https://doi.org/10.1021/acs.est.7b03889
20. Choi YJ, Nies LF, Lee LS (2019) Persistence of three bisphenols and other trace organics of concern in anaerobic sludge under methanogenic conditions. Environ Technol (United Kingdom) 0:1–10. https://doi.org/10.1080/09593330.2019.1668966
21. Corrales J, Kristofco LA, Baylor Steele W, et al (2015) Global assessment of bisphenol a in the environment: Review and analysis of its occurrence and bioaccumulation. Dose-Response 13:1–29. https://doi.org/10.1177/1559325815598308

22. Crain DA, Eriksen M, Iguchi T, et al (2007) An ecological assessment of bisphenol-A: Evidence from comparative biology. Reprod Toxicol 24:225–239. https://doi.org/10.1016/j.reprotox.2007.05.008
23. Cydzik-Kwiatkowska A, Zielińska M, Bernat K, et al (2020) Insights into mechanisms of bisphenol A biodegradation in aerobic granular sludge. Bioresour Technol 315:. https://doi.org/10.1016/j.biortech.2020.123806
24. Danzl E, Sei K, Soda S, et al (2009) Biodegradation of bisphenol A, bisphenol F and bisphenol S in seawater. Int J Environ Res Public Health 6:1472–1484. https://doi.org/10.3390/ijerph6041472
25. Das R, Li G, Mai B, An T (2018) Spore cells from BPA degrading bacteria Bacillus sp. GZB displaying high laccase activity and stability for BPA degradation. Sci Total Environ 640–641:798–806. https://doi.org/10.1016/j.scitotenv.2018.05.379
26. de Morais Farias, J, Krepsky, N (2022) Bacterial degradation of bisphenol A and its analogues: An overview, Mendeley Data, V1. https://doi.org/10.17632/5wxtn7p83h.1
27. Díaz LF, Muñoz R, Bordel S, Villaverde S (2008) Toluene biodegradation by Pseudomonas putida F1: Targeting culture stability in long-term operation. Biodegradation 19:197–208. https://doi.org/10.1007/s10532-007-9126-6
28. Dodds EC, Lawson W (1938) Molecular structure in relation to oestrogenic activity. Compounds without a phenanthrene nucleus. Proc R Soc London Ser B - Biol Sci 125:222–232. https://doi.org/10.1098/rspb.1938.0023
29. Dorn, Chou, Gentempo (1967) Degradation of bisphenol a in natural waters. Angew Chemie Int Ed 6(11), 951–952 13:15–38
30. EFSA (2015) Scientific Opinion on the risks to public health related to the presence of bisphenol A (BPA) in foodstuffs. EFSA J 13:. https://doi.org/10.2903/j.efsa.2015.3978
31. Ehling-Schulz M, Lereclus D, Koehler TM (2019) The bacillus cereus group: Bacillus species with pathogenic potential
32. Eio EJ, Kawai M, Tsuchiya K, et al (2014) Biodegradation of bisphenol A by bacterial consortia. Int Biodeterior Biodegrad 96:166–173. https://doi.org/10.1016/j.ibiod.2014.09.011
33. Eio EJ, Kawai M, Niwa C, et al (2015) Biodegradation of bisphenol A by an algal-bacterial system. Environ Sci Pollut Res 22:15145–15153. https://doi.org/10.1007/s11356-015-4693-2
34. Eltoukhy A, Jia Y, Nahurira R, et al (2020) Biodegradation of endocrine disruptor Bisphenol A by Pseudomonas putida strain YC-AE1 isolated from polluted soil, Guangdong, China. BMC Microbiol 20:1–14. https://doi.org/10.1186/s12866-020-1699-9
35. Epa (2015) BISPHENOL A ALTERNATIVES IN THERMAL PAPER Table of Contents
36. European Commission (2018) Commission Regulation (EU) 2018/213 of 12 February 2018 on the use of bisphenol A in varnishes and coatings intended to come into contact with food and amending Regulation (EU) No 10/2011 as regards the use of that substance in plastic food contact materi. Off J Eur Union 2001:20–30

37. Falcão O, Carneiro DDC (2020) Analyzing the toxicity of bisphenol-A to microalgae for ecotoxicological applications. Env Monit Assess
38. Ferenczi S, Cserháti M, Krifaton C, et al (2014) A new ochratoxin a biodegradation strategy using cupriavidus basilensis Or16 strain. PLoS One 9:. https://doi.org/10.1371/journal.pone.0109817
39. Fernandez MF, Arrebola JP, Taoufiki J, et al (2007) Bisphenol-A and chlorinated derivatives in adipose tissue of women. Reprod Toxicol 24:259–264. https://doi.org/10.1016/j.reprotox.2007.06.007
40. Fischer J, Kappelmeyer U, Kastner M, et al (2010) The degradation of bisphenol A by the newly isolated bacterium Cupriavidus basilensis JF1 can be enhanced by biostimulation with phenol. Int Biodeterior Biodegrad 64:324–330. https://doi.org/10.1016/j.ibiod.2010.03.007
41. Flint S, Markle T, Thompson S, Wallace E (2012) Bisphenol A exposure, effects, and policy: A wildlife perspective. J Environ Manage 104:19–34. https://doi.org/10.1016/j.jenvman.2012.03.021
42. Frankowski R, Zgoła-Grześkowiak A, Smułek W, Grześkowiak T (2020) Removal of Bisphenol A and Its Potential Substitutes by Biodegradation. Appl Biochem Biotechnol 191:1100–1110. https://doi.org/10.1007/s12010-020-03247-4
43. Fujiwara H, Soda S, Fujita M, Ike M (2016) Kinetics of bisphenol A degradation by Sphingomonas paucimobilis FJ-4. J Biosci Bioeng 122:341–344. https://doi.org/10.1016/j.jbiosc.2016.02.015
44. Gaylarde CC, Bellinaso MDL, Manfio GP (2005) Biorremediação: Aspéctos Biológicos e Técnicos da Biorremediação de Xenobióticos. Biotecnol Ciência e Desenvolv 36–43
45. Geens T, Goeyens L, Covaci A (2011) Are potential sources for human exposure to bisphenol-A overlooked? Int J Hyg Environ Health 214:339–347. https://doi.org/10.1016/j.ijheh.2011.04.005
46. Geens T, Neels H, Covaci A (2012) Distribution of bisphenol-A, triclosan and n-nonylphenol in human adipose tissue, liver and brain. Chemosphere 87:796–802. https://doi.org/10.1016/j.chemosphere.2012.01.002
47. Ghosh S, Chowdhury R, Bhattacharya P (2016) Mixed consortia in bioprocesses: role of microbial interactions. Appl Microbiol Biotechnol 100:4283–4295. https://doi.org/10.1007/s00253-016-7448-1
48. Goldberg JB (2000) Pseudomonas: Global bacteria. Trends Microbiol 8:55–57. https://doi.org/10.1016/S0966-842X(99)01671-6
49. Golshan M, Jorfi S, Jaafarzadeh Haghighifard N, et al (2019) Development of salt-tolerant microbial consortium during the treatment of saline bisphenol A-containing wastewater: Removal mechanisms and microbial characterization. J Water Process Eng 32:. https://doi.org/10.1016/j.jwpe.2019.100949
50. Hao M, Ma W, Dong X, et al (2021) Comparative genome analysis of multidrug- resistant Pseudomonas aeruginosa JNQH- PA57 , a clinically isolated mucoid strain with comprehensive carbapenem resistance mechanisms. 1–16
51. Held C, Kandelbauer A, Schroeder M, et al (2005) Biotransformation of phenolics with laccase containing bacterial spores. Environ Chem Lett 3:74–77. https://doi.org/10.1007/s10311-005-0006-1

52. Heidari H, Sedighi M, Zamir SM, Shojaosadati SA (2017) Bisphenol A degradation by Ralstonia eutropha in the absence and presence of phenol. Int Biodeterior Biodegrad 119:37–42. https://doi.org/10.1016/j.ibiod.2016.10.052
53. Hu Y, Zhu Q, Yan X, et al (2019) Occurrence, fate and risk assessment of BPA and its substituents in wastewater treatment plant: A review. Environ Res 178:. https://doi.org/10.1016/j.envres.2019.108732
54. Huang C, Xu P, Zeng G, et al (2017) The rapid degradation of bisphenol A induced by the response of indigenous bacterial communities in sediment. Appl Microbiol Biotechnol 101:3919–3928. https://doi.org/10.1007/s00253-017-8154-3
55. Huang YQ, Wong CKC, Zheng JS, et al (2012) Bisphenol A (BPA) in China: A review of sources, environmental levels, and potential human health impacts. Environ Int 42:91–99. https://doi.org/10.1016/j.envint.2011.04.010
56. Huang WC, Jia X, Li J, Li M (2019) Dynamics of microbial community in the bioreactor for bisphenol S removal. Sci Total Environ 662:15–21. https://doi.org/10.1016/j.scitotenv.2019.01.173
57. Ike M, Chen MY, Danzl E, et al (2006) Biodegradation of a variety of bisphenols under aerobic and anaerobic conditions. Water Sci Technol 53:153–159. https://doi.org/10.2166/wst.2006.189
58. Ike M, Jin CS, Fujita M (2000) Biodegradation of bisphenol A in the aquatic environment. 31–38
59. Im J, Löffler FE (2016) Fate of Bisphenol A in Terrestrial and Aquatic Environments. Environ Sci Technol 50:8403–8416. https://doi.org/10.1021/acs.est.6b00877
60. Inoue D, Hara S, Kashihara M, et al (2008) Degradation of bis(4-hydroxyphenyl)methane (bisphenol F) by *Sphingobium yanoikuyae* strain FM-2 isolated from river water. Appl Environ Microbiol 74:352–358. https://doi.org/10.1128/AEM.01708-07
61. Jia Y, Eltoukhy A, Wang J, et al (2020) Biodegradation of bisphenol A by *Sphingobium* sp. YC-JY1 and the essential role of cytochrome P450 Monooxygenase. Int J Mol Sci 21:. https://doi.org/10.3390/ijms21103588
62. Kamaraj M, Sivaraj R, Venckatesh R (2014) Biodegradation of Bisphenol A by the tolerant bacterial species isolated from coastal regions of Chennai, Tamil Nadu, India. Int Biodeterior Biodegrad 93:216–222. https://doi.org/10.1016/j.ibiod.2014.02.014
63. Kamaraj M, Rajeshwari S, Aravind J (2018) Isolation of Virgibacillus sp. strain KU4 from agricultural soil as a potential degrader of endocrine disruptor bisphenol-A. Int J Environ Sci Technol 15:2545–2550. https://doi.org/10.1007/s13762-017-1398-8
64. Kang JH, Kondo F (2002) Effects of bacterial counts and temperature on the biodegradation of bisphenol A in river water. Chemosphere 49:493–498. https://doi.org/10.1016/S0045-6535(02)00315-6
65. Kang JH, Ri N, Kondo F (2004) Streptomyces sp. strain isolated from river water has high bisphenol A degradability. Lett Appl Microbiol 39:178–180. https://doi.org/10.1111/j.1472-765X.2004.01562.x
66. Kang JH, Kondo F (2005) Bisphenol A degradation in seawater is different from that in river water. Chemosphere 60:1288–1292. https://doi.org/10.1016/j.chemosphere.2005.01.058

67. Kang JH, Kondo F (2006) Distribution and biodegradation of bisphenol A in water hyacinth. Bull Environ Contam Toxicol 77:500–507. https://doi.org/10.1007/s00128-006-1092-x
68. Kang JH, Aasi D, Katayama Y (2007) Bisphenol A in the aquatic environment and its endocrine-disruptive effects on aquatic organisms. Crit Rev Toxicol 37:607–625. https://doi.org/10.1080/10408440701493103
69. Karthikraj R, Kannan K (2017) Mass loading and removal of benzotriazoles, benzothiazoles, benzophenones, and bisphenols in Indian sewage treatment plants. Chemosphere 181:216–223. https://doi.org/10.1016/j.chemosphere.2017.04.075
70. Keskinkan O, Balci B (2018) Removal of Bisphenol-A from Aqueous Solutions by Pseudomonas aeruginosa in Batch Reactors: Effect of Carbon Source, Temperature and Concentrations. Int J Chem React Eng 16:1–9. https://doi.org/10.1515/ijcre-2017-0125
71. Kim J, Park W (2018) Genome analysis of naphthalene-degrading Pseudomonas sp. AS1 harboring the megaplasmid pAS1. J Microbiol Biotechnol 28:330–337. https://doi.org/10.4014/jmb.1709.09002
72. Kim SS, Hwang KS, Yang JY, et al (2020) Neurochemical and behavioral analysis by acute exposure to bisphenol A in zebrafish larvae model. Chemosphere 239:124751. https://doi.org/10.1016/j.chemosphere.2019.124751
73. Kimura N, Watanabe T, Suenaga H, et al (2018) Pseudomonas furukawaii sp. Nov., a polychlorinated biphenyl-degrading bacterium isolated from biphenyl-contaminated soil in Japan. Int J Syst Evol Microbiol 68:1429–1435. https://doi.org/10.1099/ijsem.0.002670
74. Klecka GARYMK, Gonsior S, West R, et al (2001) BIODEGRADATION OF BISPHENOL A IN AQUATIC ENVIRONMENTS : RIVER DIE-AWAY. Environ Toxicol Chem 20:2725–2735
75. Kocaman E, Ozhan K (2019) Degradation of Bisphenol A in Natural and Artificial Marine and Freshwaters in Turkey. Bull Environ Contam Toxicol 103:496–500. https://doi.org/10.1007/s00128-019-02680-4
76. Kolvenbach BA, Helbling DE, Kohler HPE, Corvini PFX (2014) Emerging chemicals and the evolution of biodegradation capacities and pathways in bacteria. Curr Opin Biotechnol 27:8–14. https://doi.org/10.1016/j.copbio.2013.08.017
77. Kumar LB, Gopal DVRS (2015) Effective role of indigenous microorganisms for sustainable environment. 3 Biotech 867–876. https://doi.org/10.1007/s13205-015-0293-6
78. Lalwani D, Ruan Y, Taniyasu S, et al (2020) Nationwide distribution and potential risk of bisphenol analogues in Indian waters. Ecotoxicol Environ Saf 200:110718. https://doi.org/10.1016/j.ecoenv.2020.110718
79. Le TT, Eymann C, Albrecht D, et al (2006) Differential gene expression in response to phenol and catechol reveals different metabolic activities for the degradation of aromatic compounds in Bacillus subtilis. Environ Microbiol 8:1408–1427. https://doi.org/10.1111/j.1462-2920.2006.01034.x
80. Lee S, Kim C, Shin H, et al (2019) Comparison of thyroid hormone disruption potentials by bisphenols A, S, F, and Z in embryo-larval zebrafish. Chemosphere 221:115–123.

https://doi.org/10.1016/j.chemosphere.2019.01.019

81. Li G, Zu L, Wong PK, et al (2012) Biodegradation and detoxification of bisphenol A with one newly-isolated strain Bacillus sp. GZB: Kinetics, mechanism and estrogenic transition. Bioresour Technol 114:224–230. https://doi.org/10.1016/j.biortech.2012.03.067
82. Li Z, Zhang W, Shan B (2019) The effects of urbanization and rainfall on the distribution of, and risks from, phenolic environmental estrogens in river sediment. Environ Pollut 250:1010–1018. https://doi.org/10.1016/j.envpol.2019.04.108
83. Liang Q, Lloyd-Jones G (2010) Sphingobium scionense sp. nov., an aromatic hydrocarbon-degrading bacterium isolated from contaminated sawmill soil. Int J Syst Evol Microbiol 60:413–416. https://doi.org/10.1099/ijs.0.008144-0
84. Liu F, Liu Q, Zhang Y, et al (2015) Molecularly imprinted nanofiber membranes enhanced biodegradation of trace bisphenol A by Pseudomonas aeruginosa. Chem Eng J 262:989–998. https://doi.org/10.1016/j.cej.2014.10.046
85. Lobos JH, Leib TK, Su TM (1992) Biodegradation of bisphenol A and other bisphenols by a gram-negative aerobic bacterium. Appl Environ Microbiol 58:1823–1831. https://doi.org/10.1128/aem.58.6.1823-1831.1992
86. Logan NA, Vos P De (2015) Bacillus. In Bergey’s Manual of Systematics of Archaea and Bacteria.
87. Louati I, Dammak M, Nasri R, et al (2019) Biodegradation and detoxification of bisphenol A by bacteria isolated from desert soils. 3 Biotech 9:1–11. https://doi.org/10.1007/s13205-019-1756-y
88. Lu H, Weng Z, Wei H, et al (2017) Simultaneous bisphenol F degradation, heterotrophic nitrification and aerobic denitrification by a bacterial consortium. J Chem Technol Biotechnol 92:854–860. https://doi.org/10.1002/jctb.5069
89. Lu L, Zhao M, Wang TN, et al (2012) Characterization and dye decolorization ability of an alkaline resistant and organic solvents tolerant laccase from Bacillus licheniformis LS04. Bioresour Technol 115:35–40. https://doi.org/10.1016/j.biortech.2011.07.111
90. Ma Y, Liu H, Wu J, et al (2019) The adverse health effects of bisphenol A and related toxicity mechanisms. Environ Res 176:. https://doi.org/10.1016/j.envres.2019.108575
91. Maruyama T, Park HD, Ozawa K, et al (2006) Sphingosinicella microcystinivorans gen. nov., sp. nov., a microcystin-degrading bacterium. Int J Syst Evol Microbiol 56:85–89. https://doi.org/10.1099/ijs.0.63789-0
92. Masuda M, Yamasaki Y, Ueno S, Inoue A (2007) Isolation of bisphenol A-tolerant/degrading Pseudomonas monteilii strain N-502. Extremophiles 11:355–362. https://doi.org/10.1007/s00792-006-0047-9
93. Matsumura Y, Akahira-Moriya A, Sasaki-Mori M (2015) Bioremediation of bisphenol-a polluted soil by *Sphingomonas bisphenolicum* AO1 and the microbial community existing in the soil. Biocontrol Sci 20:35–42. https://doi.org/10.4265/bio.20.35
94. Matsumura Y, Hosokawa C, Sasaki-Mori M, et al (2009) Isolation and characterization of novel bisphenol - A-degrading bacteria from soils. Biocontrol Sci. 14:161–169

95. Maughan H, Van der Auwera G (2011) Bacillus taxonomy in the genomic era finds phenotypes to be essential though often misleading. Infect Genet Evol 11:789–797. https://doi.org/10.1016/j.meegid.2011.02.001
96. Michałowicz J (2014) Bisphenol A - Sources, toxicity and biotransformation. Environ Toxicol Pharmacol 37:738–758. https://doi.org/10.1016/j.etap.2014.02.003
97. Mita L, Grumiro L, Rossi S, et al (2015) Bisphenol A removal by a *Pseudomonas aeruginosa* immobilized on granular activated carbon and operating in a fluidized bed reactor. J Hazard Mater 291:129–135. https://doi.org/10.1016/j.jhazmat.2015.02.072
98. Moreman J, Lee O, Trznadel M, et al (2017) Acute Toxicity, Teratogenic, and Estrogenic Effects of Bisphenol A and Its Alternative Replacements Bisphenol S, Bisphenol F, and Bisphenol AF in Zebrafish Embryo-Larvae. Environ Sci Technol 51:12796–12805. https://doi.org/10.1021/acs.est.7b03283
99. Moussavi G, Abbaszadeh Haddad F (2019) Bacterial peroxidase-mediated enhanced biodegradation and mineralization of bisphenol A in a batch bioreactor. Chemosphere 222:549–555. https://doi.org/10.1016/j.chemosphere.2019.01.190
100. Mu X, Huang Y, Li X, et al (2018) Developmental Effects and Estrogenicity of Bisphenol A Alternatives in a Zebrafish Embryo Model. Environ Sci Technol 52:3222–3231. https://doi.org/10.1021/acs.est.7b06255
101. Mukhopadhyay M, Sampath S, Muñoz-Arnanz J, et al (2020) Plasticizers and bisphenol A in Adyar and Cooum riverine sediments, India: occurrences, sources and risk assessment. Environ Geochem Health 42:2789–2802. https://doi.org/10.1007/s10653-020-00516-3
102. Naderi M, Wong MYL, Gholami F (2014) Developmental exposure of zebrafish (Danio rerio) to bisphenol-S impairs subsequent reproduction potential and hormonal balance in adults. Aquat Toxicol 148:195–203. https://doi.org/10.1016/j.aquatox.2014.01.009
103. Noszczyńska M, Chodór M, Jałowiecki Ł, Piotrowska-Seget Z (2020) A comprehensive study on bisphenol A degradation by newly isolated strains Acinetobacter sp. K1MN and Pseudomonas sp. BG12. Biodegradation 6:. https://doi.org/10.1007/s10532-020-09919-6
104. Noszczyńska M, Piotrowska-Seget Z (2018) Bisphenols: Application, occurrence, safety, and biodegradation mediated by bacterial communities in wastewater treatment plants and rivers. Chemosphere 201:214–223. https://doi.org/10.1016/j.chemosphere.2018.02.179
105. Oehlmann J, Schulte-Oehlmann U, Kloas W, et al (2009) A critical analysis of the biological impacts of plasticizers on wildlife. Philos Trans R Soc B Biol Sci 364:2047–2062. https://doi.org/10.1098/rstb.2008.0242
106. Ogata Y, Goda S, Toyama T, et al (2013) The 4-tert-butylphenol-utilizing bacterium sphingobium fuliginis OMI can degrade bisphenols via phenolic ring hydroxylation and meta-cleavage pathway. Environ Sci Technol 47:1017–1023. https://doi.org/10.1021/es303726h
107. Oh S, Choi D (2019) Microbial Community Enhances Biodegradation of Bisphenol A Through Selection of Sphingomonadaceae. Microb Ecol 77:631–639. https://doi.org/10.1007/s00248-018-

1263-4

108. Önneby K, Håkansson S, Pizzul L, Stenström J (2014) Reduced leaching of the herbicide MCPA after bioaugmentation with a formulated and stored Sphingobium sp. Biodegradation 25:291–300. https://doi.org/10.1007/s10532-013-9660-3
109. Oshiman KI, Tsutsumi Y, Nishida T, Matsumura Y (2007) Isolation and characterization of a novel bacterium, Sphingomonas bisphenolicum strain AO1, that degrades bisphenol A. Biodegradation 18:247–255. https://doi.org/10.1007/s10532-006-9059-5
110. Ozhan K, Kocaman E (2019) Temporal and Spatial Distributions of Bisphenol A in Marine and Freshwaters in Turkey. Arch Environ Contam Toxicol 76:246–254. https://doi.org/10.1007/s00244-018-00594-6
111. Palleroni NJ (2010) The pseudomonas story. Environ Microbiol 12:1377–1383. https://doi.org/10.1111/j.1462-2920.2009.02041.x
112. Palleroni NJ (2015) Pseudomonas. Bergey's manual of systematics of archaea and bacteria, p9 1-1
113. Pelch K, Wignall JA, Goldstone AE, et al (2019) A scoping review of the health and toxicological activity of bisphenol A (BPA) structural analogues and functional alternatives. Toxicology 424:152235. https://doi.org/10.1016/j.tox.2019.06.006
114. Peng YH, Chen YJ, Chang YJ, Shih Y hsin (2015) Biodegradation of bisphenol A with diverse microorganisms from river sediment. J Hazard Mater 286:285–290. https://doi.org/10.1016/j.jhazmat.2014.12.051
115. Pérez RA, Albero B, Férriz M, Tadeo JL (2017) Rapid multiresidue determination of bisphenol analogues in soil with on-line derivatization. Anal Bioanal Chem 409:4571–4580. https://doi.org/10.1007/s00216-017-0399-2
116. Peteffi GP, Fleck JD, Kael IM, et al (2019) Ecotoxicological risk assessment due to the presence of bisphenol A and caffeine in surface waters in the Sinos River Basin - Rio Grande do Sul - Brazil. Brazilian J Biol 79:712–721. https://doi.org/10.1590/1519-6984.189752
117. Pignotti E, Dinelli E (2018) Distribution and partition of endocrine disrupting compounds in water and sediment: Case study of the Romagna area (North Italy). J Geochemical Explor 195:66–77. https://doi.org/10.1016/j.gexplo.2018.02.008
118. Pinyakong O, Habe H, Yoshida T, et al (2003) Identification of three novel salicylate 1-hydroxylases involved in the phenanthrene degradation of Sphingobium sp. strain P2. Biochem Biophys Res Commun 301:350–357. https://doi.org/10.1016/S0006-291X(02)03036-X
119. Pubchem (2021). Bisphenol A. https://pubchem.ncbi.nlm.nih.gov/compound/6623. Accessed 07 September 2021
120. Pubchem (2021). Bisphenol AF. https://pubchem.ncbi.nlm.nih.gov/compound/73864. Accessed 07 September 2021
121. Pubchem (2021). Bisphenol AP. https://pubchem.ncbi.nlm.nih.gov/compound/623849. Accessed 07 September 2021

122. Pubchem (2021). Bisphenol B. https://pubchem.ncbi.nlm.nih.gov/compound/66166. Accessed 07 September 2021
123. Pubchem (2021). Bisphenol C. https://pubchem.ncbi.nlm.nih.gov/compound/84677. Accessed 07 September 2021
124. Pubchem (2021). Bisphenol E. https://pubchem.ncbi.nlm.nih.gov/compound/608116. Accessed 07 September 2021
125. Pubchem (2021). Bisphenol F. https://pubchem.ncbi.nlm.nih.gov/compound/12111. Accessed 07 September 2021
126. Pubchem (2021). Bisphenol M. https://pubchem.ncbi.nlm.nih.gov/compound/3292100. Accessed 07 September 2021
127. Pubchem (2021). Bisphenol P. https://pubchem.ncbi.nlm.nih.gov/compound/630355. Accessed 07 September 2021
128. Pubchem (2021). Bisphenol PH. https://pubchem.ncbi.nlm.nih.gov/compound/13059052. Accessed 07 September 2021
129. Pubchem (2021). Bisphenol S. https://pubchem.ncbi.nlm.nih.gov/compound/6626. Accessed 07 September 2021
130. Pubchem (2021). Bisphenol Z. https://pubchem.ncbi.nlm.nih.gov/compound/232446. Accessed 07 September 2021
131. Ren L, Jia Y, Ruth N, et al (2016) Biotransformations of bisphenols mediated by a novel Arthrobacter sp. strain YC-RL1. Appl Microbiol Biotechnol 100:1967–1976. https://doi.org/10.1007/s00253-015-7076-1
132. Révész F, Tóth EM, Kriszt B, et al (2018) Sphingobium aquiterrae sp. Nov., a toluene, meta- and para-xylene-degrading bacterium isolated from petroleum hydrocarbon-contaminated groundwater. Int J Syst Evol Microbiol 68:2807–2812. https://doi.org/10.1099/ijsem.0.002898
133. Ronen Z, Abeliovich A (2000) Anaerobic-aerobic process for microbial degradation of tetrabromobisphenol A. Appl Environ Microbiol 66:2372–2377. https://doi.org/10.1128/AEM.66.6.2372-2377.2000
134. Rubin BS, Soto AM (2009) Bisphenol A: Perinatal exposure and body weight. Mol Cell Endocrinol 304:55–62. https://doi.org/10.1016/j.mce.2009.02.023
135. Sakai K, Yamanaka H, Moriyoshi K, et al (2007) Biodegradation of bisphenol A and related compounds by Sphingomonas sp. strain BP-7 isolated from seawater. Biosci Biotechnol Biochem 71:51–57. https://doi.org/10.1271/bbb.60351
136. Santana FS, Gracioso LH, Karolski B, et al (2019) Isolation of Bisphenol A-Tolerating/degrading Shewanella haliotis Strain MH137742 from an Estuarine Environment. Appl Biochem Biotechnol 189:103–115. https://doi.org/10.1007/s12010-019-02989-0
137. Sarma H, Nava AR, Manriquez AME, et al (2019) Biodegradation of bisphenol A by bacterial consortia isolated directly from river sediments. Environ Technol Innov 14:100314.

https://doi.org/10.1016/j.eti.2019.01.008

138. Sasaki M, Akahira A, Oshiman KI, et al (2005) Purification of cytochrome P450 and ferredoxin, involved in bisphenol A degradation, from Sphingomonas sp. strain AO1. Appl Environ Microbiol 71:8024–8030. https://doi.org/10.1128/AEM.71.12.8024-8030.2005
139. Sasaki M, Maki JI, Oshiman KI, et al (2005) Biodegradation of bisphenol A by cells and cell lysate from Sphingomonas sp. strain AO1. Biodegradation 16:449–459. https://doi.org/10.1007/s10532-004-5023-4
140. Sasaki M, Tsuchido T, Matsumura Y (2008) Molecular cloning and characterization of cytochrome P450 and ferredoxin genes involved in bisphenol a degradation in Sphingomonas bisphenolicum strain AO1. J Appl Microbiol 105:1158–1169. https://doi.org/10.1111/j.1365-2672.2008.03843.x
141. Sathyamoorthy S, Hoar C, Chandran K (2018) Identification of Bisphenol A-Assimilating Microorganisms in Mixed Microbial Communities Using 13C-DNA Stable Isotope Probing. Environ Sci Technol 52:9128–9135. https://doi.org/10.1021/acs.est.8b01976
142. Sigma Aldrich (2021). Bisphenol A. https://www.sigmaaldrich.com/BR/pt/substance/bisphenola2282980057. Accessed 07 September 2021
143. Sigma-Aldrich (2021). Bisphenol AF. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-af?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20AF. Accessed 07 September 2021
144. Sigma-Aldrich (2021). Bisphenol AP. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-ap?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20AP&type. Accessed 07 September 2021
145. Sigma-Aldrich (2021). Bisphenol B. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-b?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20B&type. Accessed 07 September 2021
146. Sigma-Aldrich (2021). Bisphenol C. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-c?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20C. Accessed 07 September 2021
147. Sigma-Aldrich (2021). Bisphenol E. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-e?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20E. Accessed 07 September 2021
148. Sigma-Aldrich (2021). Bisphenol F. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-f?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20F. Accessed 07 September 2021
149. Sigma-Aldrich (2021). Bisphenol M. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-m?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20M. Accessed 07 September. 2021

150. Sigma-Aldrich (2021). Bisphenol P. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-p?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20P&type=product. Accessed 07 September 2021
151. Sigma-Aldrich (2021). Bisphenol PH. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-ph?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20PH. Accessed 07 September 2021
152. Sigma-Aldrich (2021). Bisphenol Z. https://www.sigmaaldrich.com/BR/pt/search/bisphenol-z?focus=products&page=1&perPage=30&sort=relevance&term=Bisphenol%20Z. Accessed 07 September 2021
153. Spivack J, Leib TK, Lobos JH (1994) Novel pathway for bacterial metabolism of bisphenol A. Rearrangements and stilbene cleavage in bisphenol A metabolism. J Biol Chem 269:7323–7329. https://doi.org/10.1016/s0021-9258(17)37287-3
154. Staples CA, Adams WJ, Parkerton TF, et al (1997) Environmental Toxicology Review aquatic toxicity of eighteen phthalate esters. Environ Toxicol Chem 16:875–891
155. Stolz A (2009) Molecular characteristics of xenobiotic-degrading sphingomonads. Appl Microbiol Biotechnol 81:793–811. https://doi.org/10.1007/s00253-008-1752-3
156. Suenaga H, Atsushi Y, Hosoyama A, et al (2015) Draft Genome Sequence of the Polychlorinated Biphenyl-Degrading Bacterium Cupriavidus basilensis KF708 (NBRC 110671) Isolated from Biphenyl-Contaminated Soil. Genome Announc 3:2–3. https://doi.org/10.1128/genomeA.01214-15
157. Sun Q, Wang Y, Li Y, et al (2017) Fate and mass balance of bisphenol analogues in wastewater treatment plants in Xiamen City, China. Environ Pollut 225:542–549. https://doi.org/10.1016/j.envpol.2017.03.018
158. Suyamud B, Inthorn D, Panyapinyopol B, Thiravetyan P (2018b) Biodegradation of Bisphenol A by a Newly Isolated Bacillus megaterium Strain ISO-2 from a Polycarbonate Industrial Wastewater. Water Air Soil Pollut 229:. https://doi.org/10.1007/s11270-018-3983-y
159. Suyamud B, Thiravetyan P, Panyapinyopol B, Inthorn D (2018) Dracaena sanderiana endophytic bacteria interactions: Effect of endophyte inoculation on bisphenol A removal. Ecotoxicol Environ Saf 157:318–326. https://doi.org/10.1016/j.ecoenv.2018.03.066
160. Suyamud B, Thiravetyan P, Gadd GM, et al (2020) Bisphenol A removal from a plastic industry wastewater by Dracaena sanderiana endophytic bacteria and Bacillus cereus NI. Int J Phytoremediation 22:167–175. https://doi.org/10.1080/15226514.2019.1652563
161. Takeo M, Akizuki J, Kawasaki A, Negoro S (2020) Degradation potential of the nonylphenol monooxygenase of Sphingomonas sp. NP5 for bisphenols and their structural analogs. Microorganisms 8:. https://doi.org/10.3390/microorganisms8020284
162. Takeuchi M, Hamana K, Hiraishi A (2001) Proposal of the genus Sphingomonas sensu stricto and three new genera, Sphingobium, Novosphingobium and Sphingopyxis, on the basis of phylogenetic and chemotaxonomic analyses. Int J Syst Evol Microbiol 51:1405–1417. https://doi.org/10.1099/00207713-51-4-1405

163. Tišler T, Krel A, Gerželj U, et al (2016) Hazard identification and risk characterization of bisphenols A, F and AF to aquatic organisms. Environ Pollut 212:472–479. https://doi.org/10.1016/j.envpol.2016.02.045

164. Toyama T, Ojima T, Tanaka Y, et al (2013) Sustainable biodegradation of phenolic endocrine-disrupting chemicals by Phragmites australis-rhizosphere bacteria association. Water Sci Technol 68:522–529. https://doi.org/10.2166/wst.2013.234

165. Toyama T, Sato Y, Inoue D, et al (2009) Biodegradation of bisphenol A and bisphenol F in the rhizosphere sediment of Phragmites australis. J Biosci Bioeng 108:147–150. https://doi.org/10.1016/j.jbiosc.2009.03.011

166. Usman A, Ikhlas S, Ahmad M (2019) Occurrence, toxicity and endocrine disrupting potential of Bisphenol-B and Bisphenol-F: A mini-review. Toxicol Lett 312:222–227. https://doi.org/10.1016/j.toxlet.2019.05.018

167. Vandenberg LN, Maffini M V., Sonnenschein C, et al (2009) Bisphenol-a and the great divide: A review of controversies in the field of endocrine disruption. Endocr Rev 30:75–95. https://doi.org/10.1210/er.2008-0021

168. Vijayalakshmi V, Senthilkumar P, Mophin-Kani K, et al (2018) Bio-degradation of Bisphenol A by *Pseudomonas aeruginosa* PAb1 isolated from effluent of thermal paper industry: Kinetic modeling and process optimization. J Radiat Res Appl Sci 11:56–65. https://doi.org/10.1016/j.jrras.2017.08.003

169. Waldau D, Methling K, Mikolasch A, Schauer F (2009) Characterization of new oxidation products of 9H-carbazole and structure related compounds by biphenyl-utilizing bacteria. Appl Microbiol Biotechnol 81:1023–1031. https://doi.org/10.1007/s00253-008-1723-8

170. Wang H, Liu Z hua, Zhang J, et al (2019a) Insights into removal mechanisms of bisphenol A and its analogues in municipal wastewater treatment plants. Sci Total Environ 692:107–116. https://doi.org/10.1016/j.scitotenv.2019.07.134

171. Wang S, Zhang MN, Bai NL, et al (2017) Construction, properties, and application of the pCB5 plasmid, a novel conjugative shuttle vector with a Cupriavidus basilensis origin of replication. Appl Microbiol Biotechnol 101:1217–1226. https://doi.org/10.1007/s00253-016-7936-3

172. Wang X, Chen J, Ji R, et al (2019b) Degradation of Bisphenol S by a Bacterial Consortium Enriched from River Sediments. Bull Environ Contam Toxicol 103:630–635. https://doi.org/10.1007/s00128-019-02699-7

173. Wang W, Yu H, Qin H, et al (2020) Bisphenol A degradation pathway and associated metabolic networks in Escherichia coli harboring the gene encoding CYP450. J Hazard Mater 388:121737. https://doi.org/10.1016/j.jhazmat.2019.121737

174. Willison JC (2004) Isolation and characterization of a novel sphingomonad capable of growth with chrysene as sole carbon and energy source. FEMS Microbiol Lett 241:143–150. https://doi.org/10.1016/j.femsle.2004.10.012

175. Xiong J, An T, Li G, Peng P (2017) Accelerated biodegradation of BPA in water-sediment microcosms with Bacillus sp. GZB and the associated bacterial community structure. Chemosphere 184:120–126. https://doi.org/10.1016/j.chemosphere.2017.05.163
176. Yabuuchi E, Kosako Y (2015) Sphingomonas. In Bergey's Manual of Systematics of Archaea and Bacteria.
177. Yamada H, Furuta I, Kato EH, et al (2002) Maternal serum and amniotic fluid bisphenol A concentrations in the early second trimester. Reprod Toxicol 16:735–739. https://doi.org/10.1016/S0890-6238(02)00051-5
178. Yamanaka H, Moriyoshi K, Ohmoto T, et al (2007) Degradation of bisphenol a by Bacillus pumilus isolated from kimchi, a traditionally fermented food. Appl Biochem Biotechnol 136:39–51. https://doi.org/10.1007/BF02685937
179. Yamanaka H, Moriyoshi K, Ohmoto T, et al (2008) Efficient Microbial Degradation of Bisphenol A in the Presence of Activated Carbon. J Biosci Bioeng 105:157–160. https://doi.org/10.1263/jbb.105.157
180. Yamazaki E, Yamashita N, Taniyasu S, et al (2015) Bisphenol A and other bisphenol analogues including BPS and BPF in surface water samples from Japan, China, Korea and India. Ecotoxicol Environ Saf 122:565–572. https://doi.org/10.1016/j.ecoenv.2015.09.029
181. Yang Q, Yang X, Liu J, et al (2017) Exposure to Bisphenol B Disrupts Steroid Hormone Homeostasis and Gene Expression in the Hypothalamic–Pituitary–Gonadal Axis of Zebrafish. Water Air Soil Pollut 228:. https://doi.org/10.1007/s11270-017-3282-z
182. Yang Q, Yang X, Liu J, et al (2017) Effects of BPF on steroid hormone homeostasis and gene expression in the hypothalamic–pituitary–gonadal axis of zebrafish. Environ Sci Pollut Res 24:21311–21322. https://doi.org/10.1007/s11356-017-9773-z
183. Yang Y, Wang Z, He T, et al (2015) Sediment Bacterial Communities Associated with Anaerobic Biodegradation of Bisphenol A. Microb Ecol 70:97–104. https://doi.org/10.1007/s00248-014-0551-x
184. Yang Y, Wang Z, Xie S (2014) Aerobic biodegradation of bisphenol A in river sediment and associated bacterial community change. Sci Total Environ 470–471:1184–1188. https://doi.org/10.1016/j.scitotenv.2013.10.102
185. Ye X, Pierik FH, Angerer J, et al (2009) Levels of metabolites of organophosphate pesticides, phthalates, and bisphenol A in pooled urine specimens from pregnant women participating in the Norwegian Mother and Child Cohort Study (MoBa). Int J Hyg Environ Health 212:481–491. https://doi.org/10.1016/j.ijheh.2009.03.004
186. Ying GG, Kookana RS (2003) Degradation of five selected endocrine-disrupting chemicals in seawater and marine sediment. Environ Sci Technol 37:1256–1260. https://doi.org/10.1021/es0262232
187. Yu H, Wang L, Lin Y, et al (2020) Complete metabolic study by dibutyl phthalate degrading Pseudomonas sp. DNB-S1. Ecotoxicol Environ Saf 194:110378. https://doi.org/10.1016/j.ecoenv.2020.110378

188. Yu K, Yi S, Li B, et al (2019) An integrated meta-omics approach reveals substrates involved in synergistic interactions in a bisphenol A (BPA)-degrading microbial community. Microbiome 7:1–13. https://doi.org/10.1186/s40168-019-0634-5
189. Zaki DNH (2020) Effect of Bacterial Isolates From Soil Samples on Bisphenol A. Al-Mustansiriyah J Sci 31:15. https://doi.org/10.23851/mjs.v31i1.686
190. Zeng G, Zhang C, Huang G, et al (2006) Adsorption behavior of bisphenol A on sediments in Xiangjiang River, Central-south China. Chemosphere 65:1490–1499. https://doi.org/10.1016/j.chemosphere.2006.04.013
191. Zhang C, Lu J, Wu J, Luo Y (2019) Phycoremediation of coastal waters contaminated with bisphenol A by green tidal algae Ulva prolifera. Sci Total Environ 661:55–62. https://doi.org/10.1016/j.scitotenv.2019.01.132
192. Zhang C, Zeng G, Yuan L, et al (2007) Aerobic degradation of bisphenol A by Achromobacter xylosoxidans strain B-16 isolated from compost leachate of municipal solid waste. Chemosphere 68:181–190. https://doi.org/10.1016/j.chemosphere.2006.12.012
193. Zhang G, Wang Y, Jiang J, Yang S (2017) Bisphenol A Removal by Submerged Macrophytes and the Contribution of Epiphytic Microorganisms to the Removal Process. Bull Environ Contam Toxicol 98:770–775. https://doi.org/10.1007/s00128-017-2071-0
194. Zhang H, Zhang Y, Li J, Yang M (2019) Occurrence and exposure assessment of bisphenol analogues in source water and drinking water in China. Sci Total Environ 655:607–613. https://doi.org/10.1016/j.scitotenv.2018.11.053
195. Zhang W, Yin K, Chen L (2013) Bacteria-mediated bisphenol A degradation. Appl Microbiol Biotechnol 97:5681–5689. https://doi.org/10.1007/s00253-013-4949-z
196. Zhao J, Li Y, Zhang C, et al (2008) Sorption and degradation of bisphenol A by aerobic activated sludge. J Hazard Mater 155:305–311. https://doi.org/10.1016/j.jhazmat.2007.11.075
197. Zhou NA, Kjeldal H, Gough HL, Nielsen JL (2015) Identification of Putative Genes Involved in Bisphenol A Degradation Using Differential Protein Abundance Analysis of Sphingobium sp. BiD32. Environ Sci Technol 49:12231–12241. https://doi.org/10.1021/acs.est.5b02987
198. Zhou N, Liu Y, Cao S, et al (2020) Biodegradation of bisphenol compounds in the surface water of Taihu Lake and the effect of humic acids. Sci Total Environ 723:138164. https://doi.org/10.1016/j.scitotenv.2020.138164
199. Zühlke MK, Schlüter R, Henning AK, et al (2016) A novel mechanism of conjugate formation of bisphenol A and its analogues by *Bacillus amyloliquefaciens*: Detoxification and reduction of estrogenicity of bisphenols. Int Biodeterior Biodegrad 109:165–173. https://doi.org/10.1016/j.ibiod.2016.01.019
200. Zühlke MK, Schlüter R, Mikolasch A, et al (2017) Biotransformation and reduction of estrogenicity of bisphenol A by the biphenyl-degrading Cupriavidus basilensis. Appl Microbiol Biotechnol 101:3743–3758. https://doi.org/10.1007/s00253-016-8061-z

201. Zühlke MK, Schlüter R, Mikolasch A, et al (2020) Biotransformation of bisphenol A analogues by the biphenyl-degrading bacterium Cupriavidus basilensis - a structure-biotransformation relationship. Appl Microbiol Biotechnol 104:3569–3583. https://doi.org/10.1007/s00253-020-10406-4

Figures

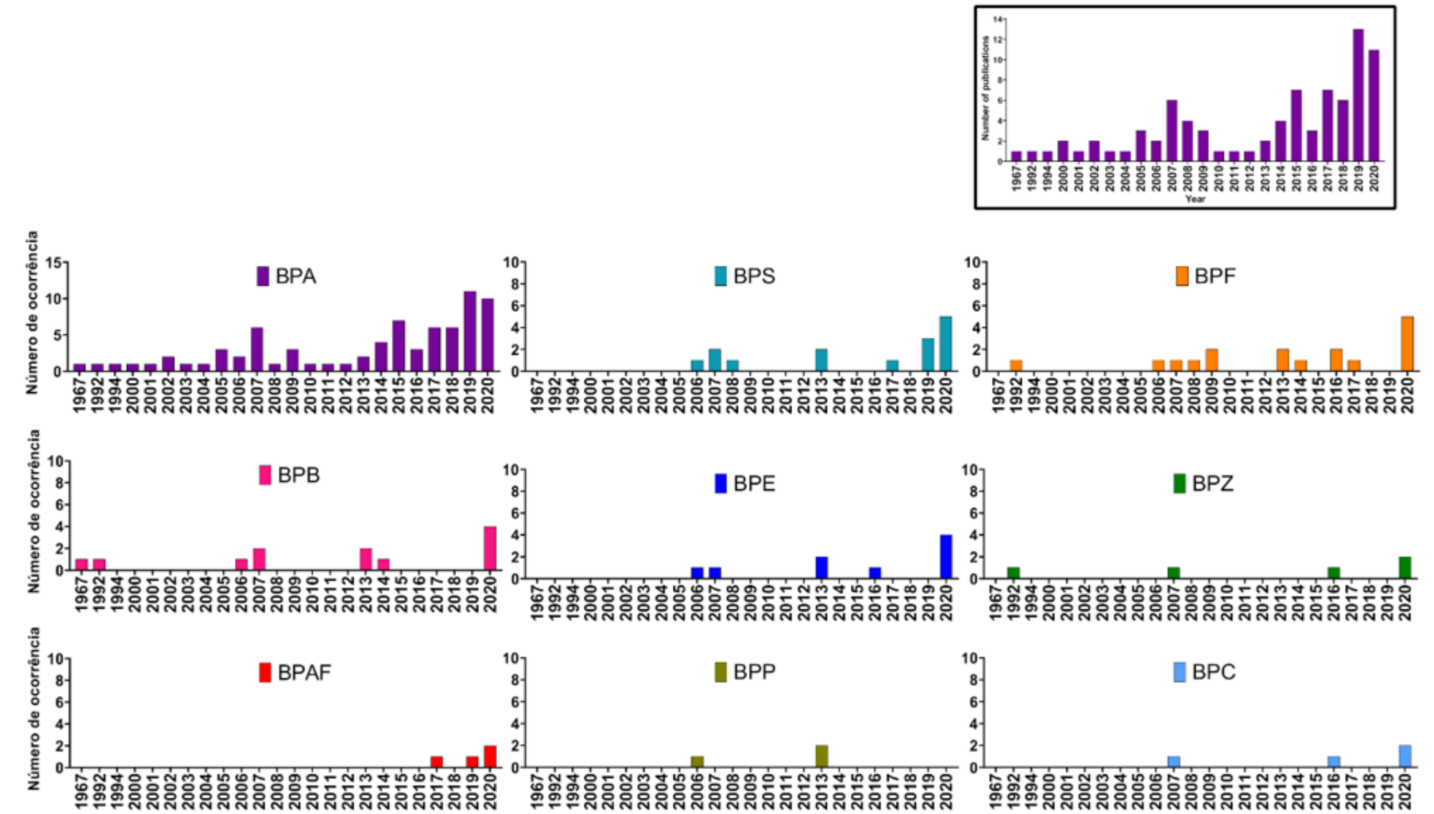


Figure 1

Absolute number of publications on bisphenol analogues until 2020 (detail) and total publications grouped by bisphenol analogues until 2020. Legend: BPA - bisphenol A; BPS - bisphenol S; BPF - bisphenol F; BPB - bisphenol B; BPE - bisphenol E; BPZ - bisphenol Z; BPAF - bisphenol AF; BPP - bisphenol P; BPC - bisphenol C; BPPH - bisphenol PH; BPM - bisphenol M; BPAP - bisphenol AP.

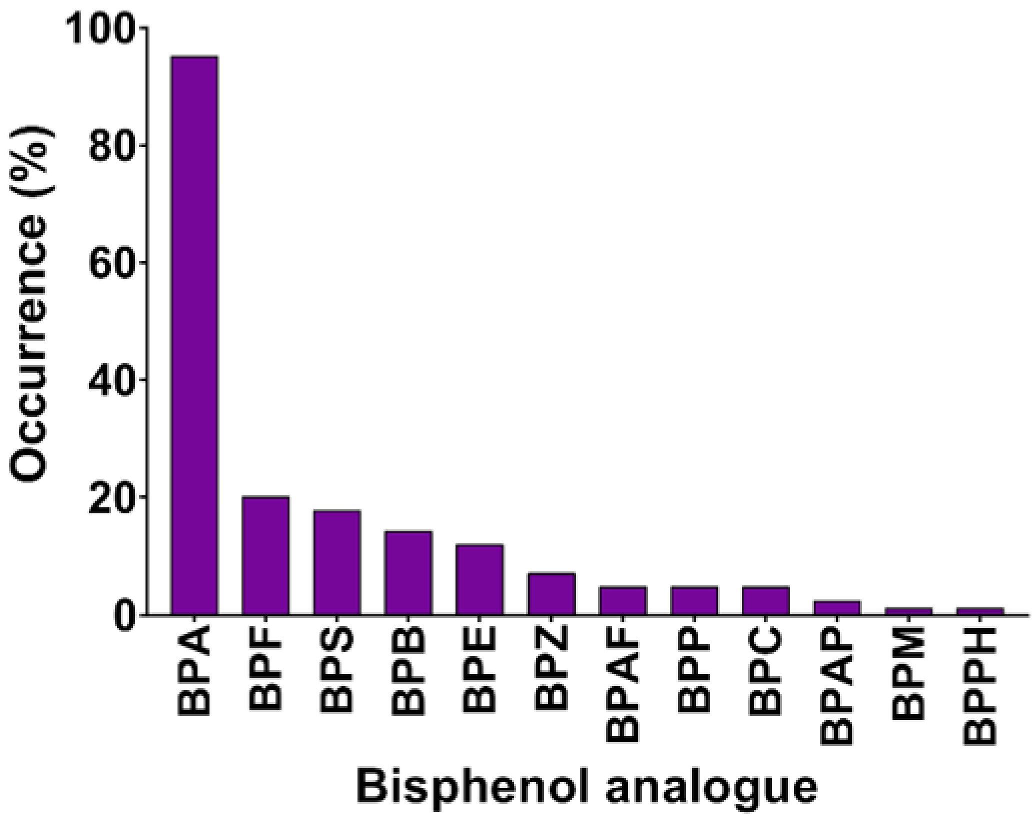


Figure 2

Percentage (%) of studies about bacterial degradation of bisphenol analogues published until 2020. Legend: BPA - bisphenol A; BPS - bisphenol S; BPF - bisphenol F; BPB - bisphenol B; BPE - bisphenol E; BPZ - bisphenol Z; BPAF - bisphenol AF; BPP - bisphenol P; BPC - bisphenol C; BPPH - bisphenol PH; BPM - bisphenol M; BPAP - bisphenol AP.

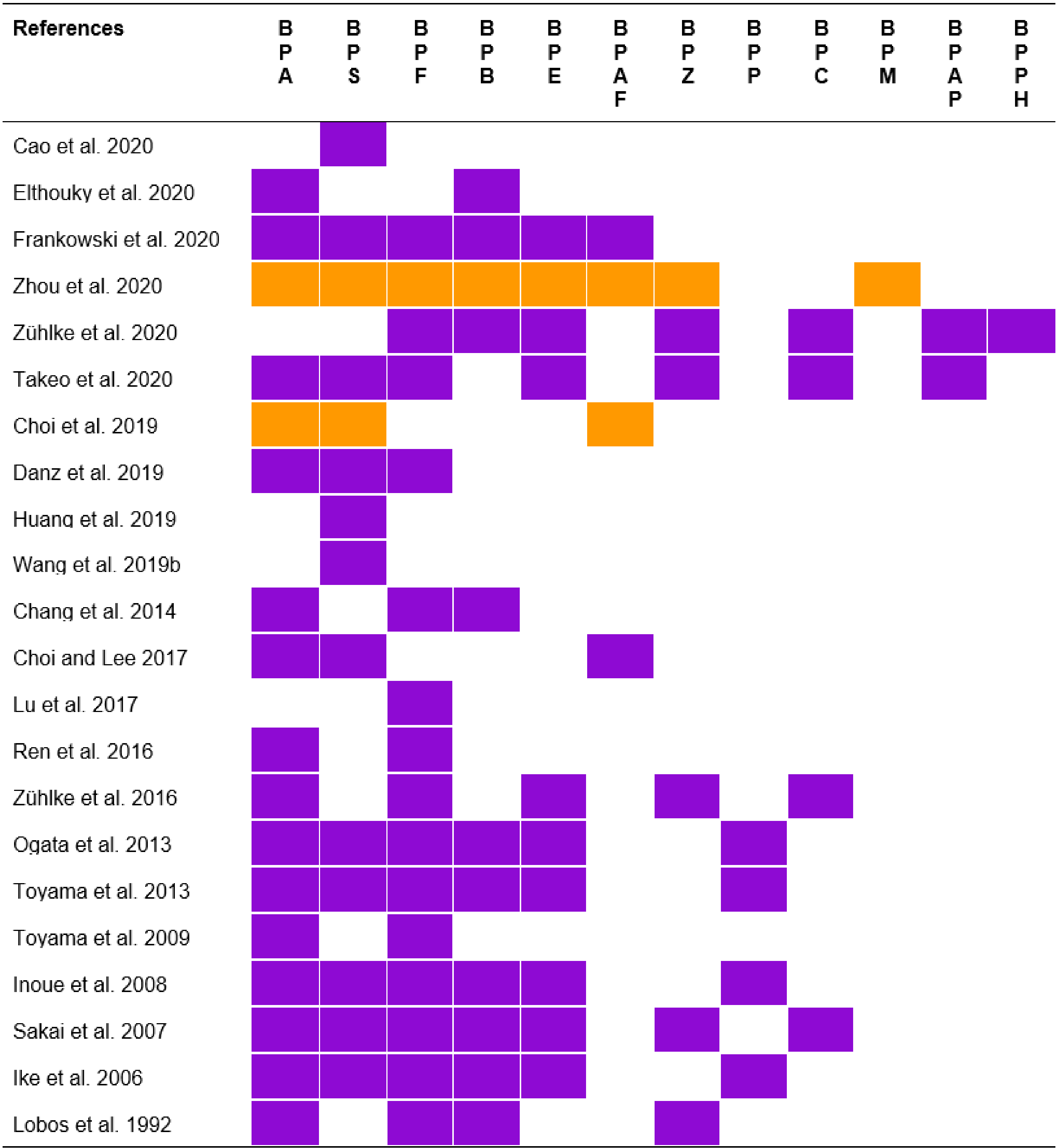


Figure 3

Color scheme showing the studies investigating bacterial biodegradation of the bisphenol analogues published until 2020. *Purple*: indicate studies with single BP; *Orange*: indicate studies of bacterial biodegradation with mixtures of BP. Legend: BPA - bisphenol A; BPS - bisphenol S; BPF - bisphenol F; BPB - bisphenol B; BPE - bisphenol E; BPZ - bisphenol Z; BPAF - bisphenol AF; BPP - bisphenol P; BPC - bisphenol C; BPPH - bisphenol PH; BPM - bisphenol M; BPAP - bisphenol AP.

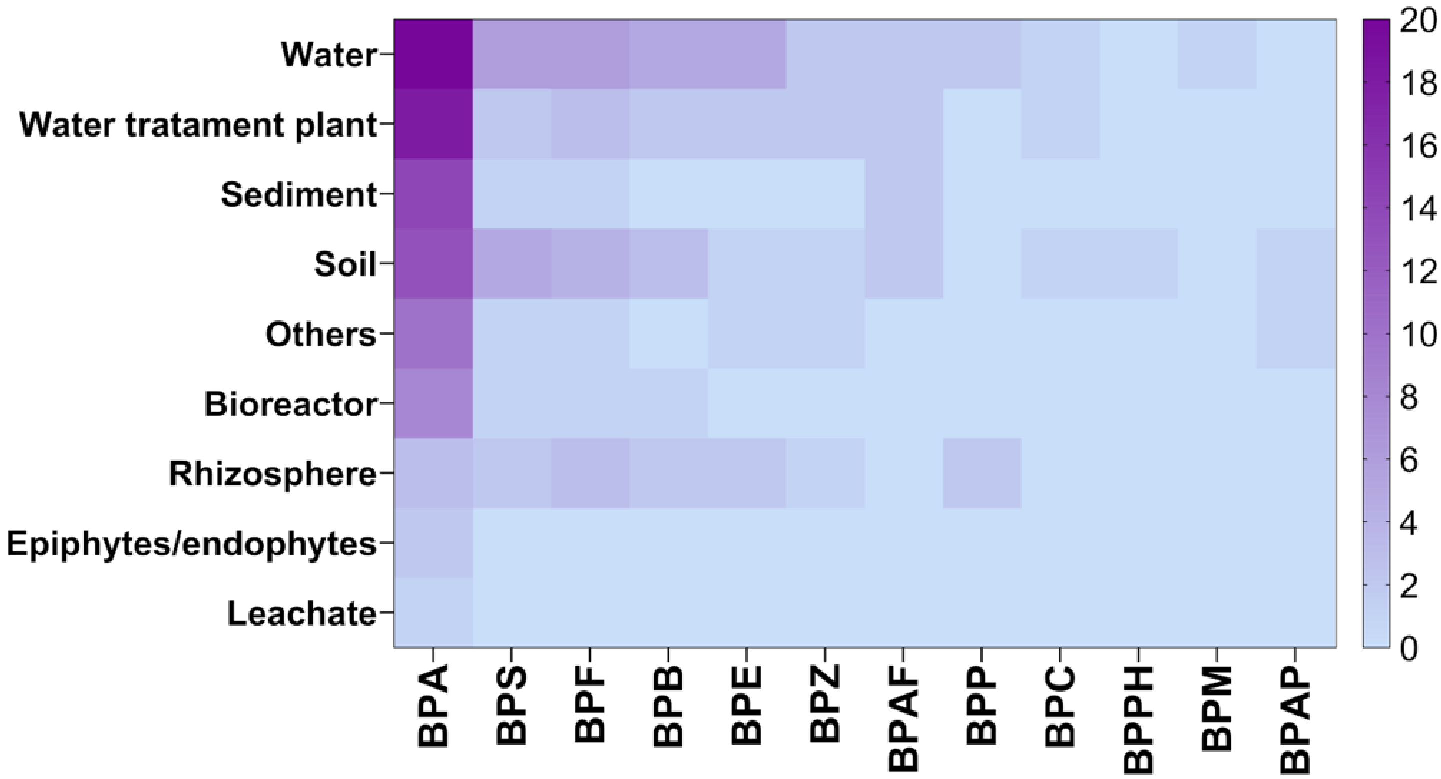


Figure 4

Heat map scheme of environmental compartments where bacteria biodegradation of bisphenol analogues was studied in papers published until 2020. The colour scale represents the number of published papers on the subject. Others include microorganisms from fermented food and laboratory culture. Legend: BPA - bisphenol A; BPS - bisphenol S; BPF - bisphenol F; BPB - bisphenol B; BPE - bisphenol E; BPZ - bisphenol Z; BPAF - bisphenol AF; BPP - bisphenol P; BPC - bisphenol C; BPPH - bisphenol PH; BPM - bisphenol M; BPAP - bisphenol AP.

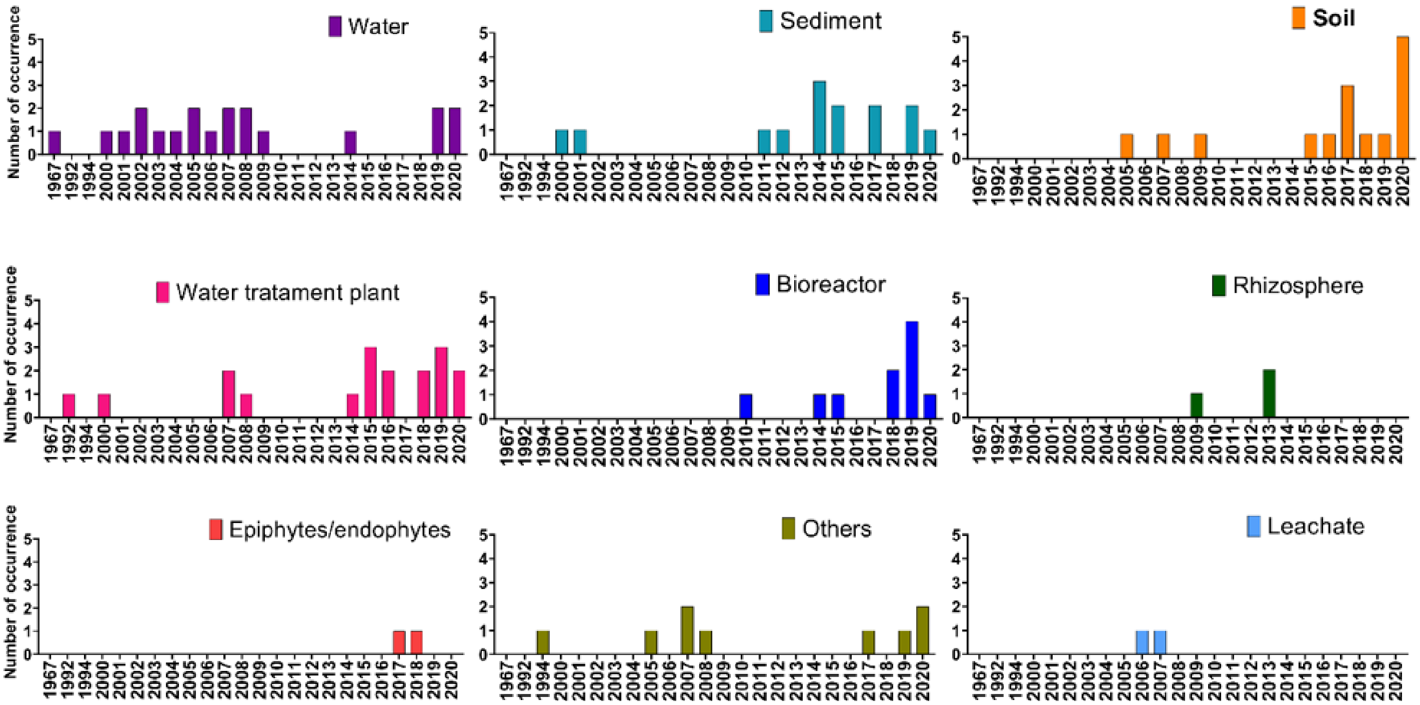


Figure 5

Number of papers per year considering bacterial biodegradation of bisphenol analogues in each environmental compartment published until 2020. Others include microorganisms from fermented food and laboratory culture.

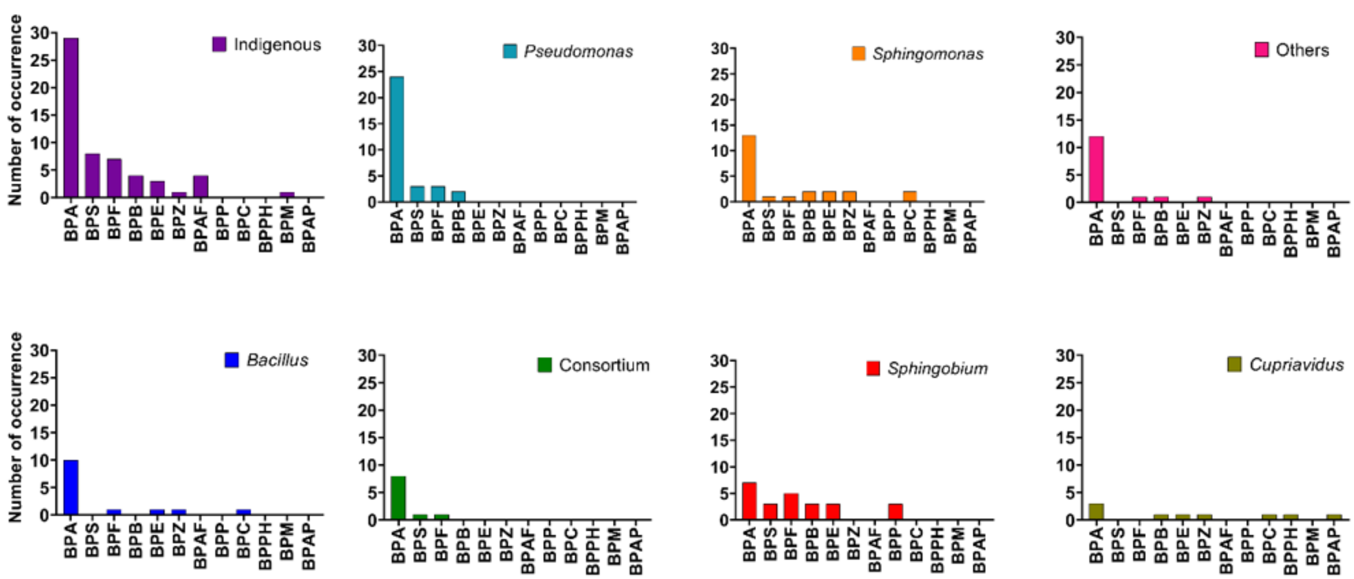


Figure 6

Number of bisphenol analogues assessed in biodegradation studies by bacterial groups and indigenous microorganisms studied in papers published until 2020. Legend: BPA - bisphenol A; BPS - bisphenol S; BPF - bisphenol F; BPB - bisphenol B; BPE - bisphenol E; BPZ - bisphenol Z; BPAF - bisphenol AF; BPP - bisphenol P; BPC - bisphenol C; BPPH - bisphenol PH; BPM - bisphenol M; BPAP - bisphenol AP.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ESPR2022ONLINERESOURCES100522.xlsx