Effects of Xenobiotics and Their Degradation in Aquatic Life

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1 Introduction

With advancements in scientific technologies, industrialisation, or globalisation, human lives are affected in both ways, be it positive or negative. Since advancements in technologies are definitely bringing change in our lives, but nonetheless there are growing concerns about the fact that globalisation or industrialisation has impacted heavily and negatively on aquatic bodies. Among the negative aspects, one major concern is the introduction of new substances into these waterbodies. The sources of these new substances are medicines, by-products of various personal care products, among others, and finally ending up in waterbodies. The term xenobiotics is actually a combination of two words with xenos meaning foreign (something which is not natural) and bios standing for life. So, xenobiotics represent a class of chemicals or substances that are not naturally present in any given water ecosystem. The non-biodegradable nature of these substance makes it impossible for wastewater treatment plants to effectively remove them from waste water, making it possible to end up in various food chains and infecting and affecting human lives.

Water-soluble environmental chemicals can enter the body via the gills of aquatic creatures, whereas hydrophobic xenobiotics can enter the body via contaminated food. Respiratory work of aquatic organisms is generally carried by gills (Carvalho

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2011; Ray and Ringø 2014). The functions of gills other than those of respiration include waste excretion, maintenance of homeostasis, including pH, hormone production, etc. (Foyle et al. 2020; Zhang et al. 2021). Even though the gill structure of most bivalves has underwent secondary evolution to serve as feeding appendages, however, the prime function remains osmoregulation. Less emphasis has been placed on ion transport (Riisgård et al. 2015; Moreira et al. 2015). Whether we talk of fish or mollusc gill, gill structure represents an important and vital link between aquatic fauna and environment as it is the structure that comes in contact (frequently) with aquatic environment. Since gills are lined with selective barriers, controlling uptake of nutrients as well as removal of toxic xenobiotics is needed (Armitage et al. 2013; Wang and Wang 2015). The presence of such selective barriers throughout the digestive tract confers fishes the property to control absorption of many small molecules. According to the study carried out by Collinder et al. (2009), and Karasov and Douglas (2013), the digestive structure of both terrestrial and aquatic animals is essentially the same. However, the variation observed in relative length and volumes of various regions like oesophagus, stomach, with an oesophagus, stomach, midgut, and hindgut is attributed to food and nutrient extraction and absorption. In case of both fish and humans, the epithelia of small and large intestines is largely responsible for nutrient uptake, including water and ions (Sundell and Rønnestad 2011; Kiela and Ghishan 2016), and this process (i.e. nutrient uptake whether micro- or macronutrients) is mediated by simple diffusion, kind of enhanced permeability, or the involvement of secondary active transport coupled with electrical potentiality (Sundell and Rønnestad 2011). According to the studies carried out by Müller et al. (2017) and Nicklisch and Hamdoun (2020), an absolute integration of solute carrier (SLC) proteins and ABC transporters, found on the apical and basolateral membranes of enterocytes, on the other hand, inhibits the absorption of dietary toxins and contaminants, including xenobiotics and biotoxins.

Despite the differences in gastrointestinal macro- and microanatomy between aquatic and terrestrial species, there is limited knowledge regarding the chemical composition, amounts of food intake, and xenobiotic defence mechanisms in the digestive tracts of fish and like organisms. Furthermore, knowledge of the molecular interactions of water and foodborne pathogens with these transportation networks, as well as how these interactions may change nutritional homeostasis and hazardous contaminant bioaccumulation, is lacking.

2 Epithelial Transport in Aquatic Organisms' Digestive System

Since the prime function associated with digestive system is absorption of nutrients, water and minerals form the food to produce energy used for growth and development. In addition to this function, this digestive system serves as an environmental barrier, preventing xenobiotic absorption and its accumulation. As already discussed, integration of several SLC and ATP binding cassette transporters present in the gills as well as intestines of many aquatic organisms, including fishes, performs a key role in xenobiotic efflux, ion flux, cell signalling processes, and absorption of nutrient material.

2.1 Transporters of Nutrients and Endogenous Substrates

Secondary active transporters of the solute carrier (SLC) family typically mediate transepithelial transfer of nutrients in the gastrointestinal system. SLCs are the most common type of secondary active membrane transporter in humans (Höglund et al. 2011; Hediger et al. 2013). SLCs can facilitate bidirectional transport (Kottra et al. 2002; Winter et al. 2011); however, they are mostly involved in nutrient and ion uptake (Zhang et al. 2018; Felmlee et al. 2020; Song et al. 2020). In spite of their role in nutrient absorption and metabolic equilibrium, these transporters are, however, infamously understudied both in humans and aquatic creatures (César-Razquin et al. 2015; Barat et al. 2016).

3 Impact of Xenobiotics on Aquatic Life/Fauna

Advancements in the system of industrialisation as well as urbanisation have given birth to a wide range of pollutants of which xenobiotics have found a top-notch place in the toxic list of pollutants. Azole, phenolic, polycyclic aromatic hydrocarbon (PAH), halogenated, personal care product (PCP), pharmaceutical active ingredient (PhAC), pesticide, nitroaromatic, triazine, and chlorinated chemicals have an adverse effect on the environment due to their long-term durability and sluggish to nonexistent biodegradation in ecosystems. Anthropogenic sources such as urbanisation and population expansion are producing xenobiotic contamination in the environment. Massive volumes of toxic substances discharged into the environment pollute whole ecosystems. The list includes sediments, aromatic hydrocarbons, pesticides, fertilisers, herbicides, among others.

Anthropogenic activities, including urban transportation, spraying housing, industrial production, and building construction, are large contributors of both ground and surface water pollution in urban environments through diffusive and point contributions. Numerous investigations have revealed the presence of various chemicals and signs of human intervention in urban water systems (Strauch et al. 2008). Mishra et al. (2019) examined various trace metals, xenobiotic pollutants, and synthetic organic pollutants with the likes of phthalates, PAHs, and pesticides, among others, in diverse bodies of water. Xenobiotic chemicals can infiltrate water bodies via a variety of routes. These include (a) continual inputs from commercial and fossil fuel products, as well as sewage effluents; (b) surface water runoff from highways and land surfaces; (c) particle deposition in the air; and (d) solid waste burning (Essumang 2010). Also, through the leaching process, xenobiotic chemicals also reach the water table, affecting the very ecology of various aquatic ecosystems (Fent et al. 2006). In the presence of xenobiotic contaminants, aquatic organisms experience oxidative stress. Recently, research carried out by Ibor et al. (2019) at the artificial Eleyele lake in Nigeria showed elevation in oxidative stress response in fish fauna in the presence of xenobiotic contamination.

Xenobiotics negatively imparts the metabolism of marine organisms, particularly growing fish embryos, leading to morphological deformities, functional abnormalities, stunned growth, and eventual death. Additionally, fish with altered body forms, physiological abnormalities, delayed hatching, and mortality have been seen (Arya and Haq 2019). Dyes and paints are xenobiotics even in trace doses because they obstruct sunlight penetration and gas exchange (Abdelkader et al. 2011). The major xenobiotic pollutants of marine life include pesticides and herbicides. In agricultural and everyday life, chemicals like organophosphates, nitrophenols, morpholine, pyrethroids, and carbamates are routinely used; these chemicals eventually wind up in many bodies of water, such as the sea and ocean. Insecticides like -cypermethrin are very dangerous to marine life and invertebrates (Zhang et al. 2011). Environmental xenobiotics are any manufactured substances that are not ordinarily anticipated to occur in any organism. The presence of various environmental xenobiotics greatly and negatively affects both ecosystems and humans. Pesticides, polychlorinated biphenyls, persistent organic pollutants, dangerous heavy metals, etc., are some fine examples of environmental xenobiotics, and there is a wealth of scientific data demonstrating the adverse health effects that these substances are having on people. Among the various health concerns connected with environmental xenobiotics, neurotoxicity, immunotoxicity, nephrotoxicity, hepatotoxicity, and cancer are the most commonly highlighted. However, the general population is less aware of their potential toxicity and different routes of exposure. As a result, an attempt was made in this research to critically examine current literature in order to help future investigations on the health effects of xenobiotics so that the findings of such studies can address the situation on the ground. As a result, this chapter in nutshell discusses a number of particular xenobiotic compounds, as well as the ways in which they can be ingested and the long-term repercussions of doing so.

4 Impacts of Xenobiotics on the Ecosystem

Around 24% of world illnesses and some 13 million deaths are attributed to environmental pollutants. Today, detectable quantities of pharmaceutical preparations can be detected in water and foods, including rivers and oceans, as either the original drug or a metabolite (Banjoko 2014). The impact of medication on people and animals goes beyond the fundamental goals of conventional medical care. The majority of APIs (active pharmaceutical ingredients) derived from medications, whose by-products may contaminate the environment, are contributed by the pharmaceutical sector.

Pollution is detected physiologically by aquatic creatures. Fent et al. (2006) examined the presence and effects of pharmaceuticals in the aquatic environment, discussed putative mechanisms of action based on research on mammals, and assessed the acute and long-term effects on species of ecotoxicity. Pharmaceuticals find their way into the environment either in original shape or in the form of metabolites. Humans normally eliminate chemicals through digestion, excretion, and wastewater disposal. Human drugs are the most prevalent type of medication discovered in municipal wastewater. Pharmaceuticals can be found in high amounts in hospital wastewater, industrial wastewater, and landfill leachates, finding their ways into rivers, lakes, etc., and maybe in drinking water and ending up in damaging ecosystems and associated fauna. Sewage used for agricultural purposes also poses a high risk of contamination. Medication that has an environmental impact typically has a high manufacturing volume, long-term environmental persistence, and biological activity. According to recent research, rising levels of pharmaceuticals identified in surface waterways throughout the world have raised concerns, notably concerning their impact on aquatic vegetation and animals. Fish are the aquatic organisms with whom humans have the most pharmaceutical targets. Medicines' long-term impacts on aquatic species are little known. According to the study carried out by Cuklev et al. (2012), fish when subjected to a dose of l g/L diclofenac, both gene expression and organ histology are found to be altered. NSAIDs like diclofenac, ibuprofen, among others, were detected at 27 sites along the Kaveri velar and Tami rapini rivers of south India, posing the greatest toxicity risk for all those depending on these rivers for water purposes (Shanmugam et al. 2013). Several therapeutic concoctions have been found in both streams and rivers. It has been discovered that antidiabetic and antihistamines diphenhydramine greatly discombobulate the biofilm population, which is vital to the ecology. Microbe aggregates known as biofilms are actually the cells that adhere to one another and/or a surface and are usually encased in a self-produced matrix of extracellular polymeric polymers. Impacts of pollutants like diphenylamine on biofilm can be determined by the fact that organisms in food web such as fish and insects are largely impacted because these biofilms are food suppliers for vertebrates, which in turn are easily accessed by higher food web organisms (Rosi-Marshall 2013). Some mussels spawn prematurely as a result of antidepressants, disturbing aquatic homeostasis. Furthermore, fluoxetine and propranolol have been found to be toxic to many zooplankton and benthic species. Microbes produce biofilms in response to cellular identification of specific or nonspecific attachment sites, nutritional signals, and planktonic cell exposure to subinhibitory antibiotic dosages (Karatan and Watrick 2009). In female sea snails exposed to tributyltin, imposex (masculinisation) was seen. Dichloro-diphenyldichloroethylene (DDE) -induced eggshell thinning in birds is one of the best examples of reproductive harm leading to significant population declines in a variety of European and North American raptor species. Over time, DDT exposure in male western gulls has been linked to ovo-testis. The majority of cleaning products contain the broad-spectrum antibacterial chemical triclosan (TCS) to prevent the growth of bacteria, fungi, and mildew. Domestic wastewater, leaking septic systems, and sewage overflows all cause triclosan to infiltrate streams. Long-term usage of these antibiotics breeds germs that are resistant to them, potentially diminishing the effectiveness of crucial treatments (Drury et al. 2013).

The most well-known effects of EDC in aquatic animals include reduced reproduction and development (Kid et al. 2007). Recent studies discovered many brain targets for EDC that are present in meaningful quantities in surface waters. PCBs have been demonstrated to reduce reproductive and immunological function in Wadden Sea harbour seals, as well as Baltic grey and ringed seals in field studies (polychlorinated biphenyls). Other food-chain animals that may be harmed include the guinea pigs, polar bears, and rabbits. A chemical spill in Florida resulted in altered genital development in alligators. Furthermore, DDT-complicated experimental research employing alligator eggs has been linked to the reported androgenic and oestrogenic effects.

Although urbanisation, population growth, commercialisation, and globalisation have both positive and bad consequences on our lives, they are undeniably causing change (Bulucea et al. 2012). International links, technical innovation, and market expansion intensify global concerns such as economic centralisation and the relaxation and ease of the movement of commodities and services. Nonetheless, despite the benefits, globalisation has a detrimental impact on the environment from an economic and political aspect, and a healthy environment is a need for a good level of life (Banerjee et al. 2008). Technology development, increased longevity, better access to medical care (for humans and animals), routine use of personal care items, and/or pesticides all result in new substances being released into the environment (Jaffe 2005; Eugine and Vincent 2016). A thorough study should be done on these substances' immediate and long-term impacts on people, animals, and the ecosystem because they have the potential to be hazardous either alone or in combination (air, water, and soil). Environmental problems have been caused by poor usage of education and drug disposal, along with the disregard for the environment demonstrated by some businesses, despite the fact that knowledge of the issue is growing (Wu 1999). Pollution develops as a result of man-made toxins that either do not dissolve or disintegrate extremely slowly in the environment (El-Saad and Elgerbed 2010). Science has yet to discover a good and practical artificial deterioration approach that meets all requirements. The term 'xenobiotics' refers to foreign materials in living form and is derived from the Greek terms 'xenos' (foreign) and 'bios' (life) (life). Wastewater treatment plants and rainwater runoff are primarily responsible for the occurrence of xenobiotics in freshwater (Ahlborg et al. 1992; Anetor et al. 2008; Cataudella et al. 2012). The removal of xenobiotics from wastewater by wastewater treatment facilities is frequently insufficient, allowing xenobiotics to infiltrate public sewers, enter the food chain, and directly damage people (Rosas and Eskenazi 2008; Neal and Guilarte 2012), as well as contributing to micropollutant pollution of aquatic bodies (Julvez and Grandjean 2009; Soderland et al. 2010; Descamps and Deschamps 2012). Even though colonies of bacteria and other microorganisms have been discovered to be successful in breaking down particular xenobiotics, activated sludge is typically insufficient for this task.

Communities would have to adapt to xenobiotics and operating parameters in wastewater (Garcia et al. 2012; Singh et al. 2017) that are financially unviable in typical plants. A lot of effort is being put into developing and refining biological or physicochemical mechanisms that are more effective in removing xenobiotics from water; these processes will be discussed later. Pharmaceuticals and personal care products, for example, were shown to have a substantial impact on removal efficiency due to technical developments (PPCPs), and secondary treatment procedures were found to be varied (and inefficient) in eliminating pharmaceutical pollutants (Ozaydin 2017). Various international organisations like US EPA, EMA, and EEA, among others, have been carrying out the high-end research to lessen the harmful nature/toxic effects of various xenobiotics and to look for the ones (pollutants) that need urgent readdressing. However, in order to prevent or minimise the negative impacts of xenobiotics and identify the most pressing pollutants, it is required to know the amounts of contaminants in the environment that are affecting both people and animals. Xenobiotics are distinct, have an impact on both the environment and public health, and their potential for harm is not fully recognised, claims the US EPA. Many directives and laws which are in place aim to enhance environmental quality by continuously looking and monitoring a list of harmful compounds. It is critical to identify pollution sources and implement the most cost-effective and ecologically friendly strategies to reduce pollutant emissions at their source. (Kim et al. 2015), and environmental quality standards (EQS) for those priority compounds were established by Directive 2008/105/EC. This list is being continuously updated based on data sets on toxicological impacts. In the sphere of water policy, Directive 2013/60/EC includes a list of 45 priority compounds. The most latest scientific and technological information is provided in the EQS for those substances. The research 'Modes of action of the current Priority Chemicals list under the Water Framework Directive and other chemicals of interest' is one of several papers on the modes of action (MoA) and impacts of priority substances and other compounds on the WFD's Watch List (WL). The research includes information on assessing these chemicals using effect-based methodologies (biomarkers and bioassays), with an emphasis on combinations of drugs and their possible interactions in the aquatic environment. Second, chemicals on the priority list are divided into 17 groups, while those on the watch list are divided into 8 groups. The European Medicines Agency (https://www.ema.europa.eu/en, accessed on 5 June 2021) offers scientific advice on the best strategy for meeting regulatory requirements that apply to medical goods in the European Union.

5 Biodegradation of Xenobiotics

The degradation of non-biodegradable complex materials into products that are acceptable in the environment includes carbon dioxide, water, and biomass. These compounds are redistributed into the environment through ecological cycles like the

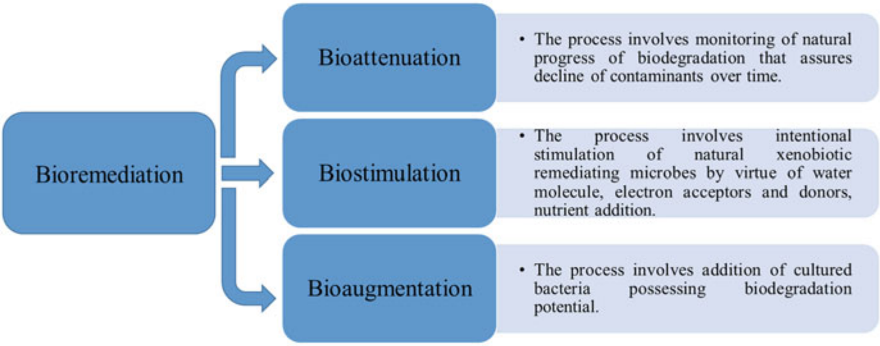

Fig. 1 General methods employed by microbes in the bioremediation process

sulphur cycle, nitrogen cycle, and carbon cycle. The degradation process is accomplished by the metabolic action of certain microorganisms including bacteria in natural environmental conditions (Karak 2012). Microorganisms play a key role in biodegradation, with the advancement in technology and molecular biology genetically engineered microorganisms are being extensively used to counter environmental problems such as the addition and accretion of xenobiotics into the biosphere. Over the decades the acceleration in environmental pollution by xenobiotics has emerged as a serious concern (Rathore et al. 2022). The microbes employ different method for the bioremediation of xenobiotics. some of the methods are shown in Fig. 1.

Xenobiotics like phenolics, azodyes, personal care products, halogenated compounds, pharmaceuticals active compounds, polycyclic aromatic hydrocarbon, nitroaromatic compounds, triazines, pesticides, antibiotics, and chlorinated compounds negatively impact the environment owing to their non- or slow biodegradable nature and their ability of persistence in the environment. The most serious threat of xenobiotics is biomagnification apart from causing adverse effects at each tropic level by making their way into the food chain (Zhou et al. 2022). All life forms, plants, and animals, including human and environmental health, are adversely affected by major xenobiotic compounds.

The aquatic habitat forms the pool of accumulation of xenobiotics and has emerged as a sink for the hazardous complex polymers that are usually non-biodegradable. Efforts have been made to eliminate these compounds from the ecosystem; these methods include degradation by coagulation, adsorption, filtration, electrolysis, chemical precipitation, and ozonation. However, the microbial degradation of xenobiotics has evolved promptly as a reliable approach for being eco-friendly and cost-effective.

Among the different strategies, the research of microbial enzymes for bioremediation is growing in significance, nevertheless, on a worldwide scale. The advancement and use of cutting-edge molecular approaches are providing new insights into the structural and functional characteristics of complex microorganisms. These techniques include proteomics, metagenomics, transcriptomics, metabolomics, etc.

For bioremediation of xenobiotics methods like phytoremediation, bioaugmentation, landfarming, rhizo-filtration, bio-stimulation, composting and bioreactors have been used widely (Azubuike et al. 2016). Bioremediation uses the service of various microorganisms for destruction, eradication, immobilisation, or detoxification of a wide range of chemical wastes and other harmful chemicals from the ecosystem/ environment. Bioremediation involves the systems of living organisms, most importantly, bacteria, fungi, plants, and their enzymes (Ijoma and Tekere 2017). Especially microbes, bacteria, and fungi possess the capability to degrade xenobiotics by means of endo- and exo-enzymes systems (Singh 2014). Microorganisms involve two basic mechanisms for the biodegradation process; aerobic and anaerobic biodegradation (Sharma and Fulekar 2009). The basic equations for the aerobic and anaerobic bioremediation of xenobiotics can be mentioned as follows):

$$\text{Xenobiotics} + O_2\ ^{(\text{Microbes})} \rightarrow CO_2 + H_2O + \text{residue (Aerobic)}$$

$$\text{Xenobiotics}\ ^{(\text{Microbes})} \rightarrow CO_2 + CH_4 + H_2O + \text{residue (Anaerobic)}$$

6 Degradation of Xenobiotics Through Bacteria

Xenobiotics find their way into environments as a result of anthropogenic activities, resulting in ecosystem damages and environmental pollutions. Opposed to this, certain metabolites of bacteria have xenobiotic degrading capabilities. Bacterial strains from several genera, including *Burkholderia, Bacillus, Pseudomonas, Sphingomonas, Kocuria, Chromohalobacter* and *Achromobacter*, are known to degrade xenobiotics completely or mineralise when subjected to axenic and anoxic environments (Zhang et al. 2020). Microorganisms have a remarkable capacity for catabolism involved in the biodegradation process because of a wide range of genes and enzymes. The capability of bacteria to multiply rapidly and adapt to diverse environmental conditions is important. Certain bacterial species have been identified and cultured for the bioremediation process (Table 1); however, such microbes are very limited though with incomparable capabilities to degrade xenobiotic compounds. Apart from the culture-dependent technique, more modern techniques like genomics/metagenomics and transcriptomics have led to the identification of specific genes that actually impart the biodegradation character to a microbe. These techniques have also led to the characterisation of a wider community of microbes that were otherwise uncultured and left unidentified. Genome investigations of bacterial strains that break down xenobiotics have revealed that these strains evolved recently by integrating genes for xenobiotic degradation, with mobile genetic components being essential for gene acquisition (Nagata et al. 2019). However, the origin and evolution of such genes in the microbiome are yet not clear. Below, Fig. 2 represents the different degrading enzymes produced by bacteria against xenobiotics.

Table 1 Promising microbes against different xenobiotics

S. no.	Bacteria	Promising against	Reference
1	*Pseudomonas*	Aliphatic hydrocarbon degradation	
2	*Microbacterium D-2*	Pesticide degradation (dicofol)	Lu et al. (2019)
3	*Enterobacter*	Polyethylene, plastic	Ren et al. (2019)
4	*Micrococcus*		
5	*Alcaligenes*		
6	Sphingopyxis,		Russell et al. (2021)
7	*Hyphomicrobiaceae*		
8	*Achromobacter*		
9	*Purpureocillium*		
10	Mesorhizobium,		
11	*Aeromonas*		
12	*Gordonia*	Oil degradation	
13	*Rhodococcus*		
14	*Sphingobium*		
15	*Penicillium*		
16	*Candida*		
17	*Sphingopyxis*		Russell et al. (2021)
18	*Trichoderma*		
19	*Rhodotorula*		
20	*Rhodopseudomonas,*		
21	*Thalassolituus*	Oil-degradation	
22	*Afipia*		Russell et al. (2021)
23	*Bacillus amyloliquefaciens*	Organophosphorous pesticide (phoxim) degradation	
24	*Stenotrophomonas*		Russell et al. (2021)
25	*Oligotropha*		Russell et al. (2021)
26	*Mesorhizobium*		
27	*Rhodopseudomonas palustris*	Hexabromocyclododecane degradation	
28	*Oleispira*	Oil-degradation	
29	*Trichoderma hamatum*	DDT-degradation	
30	*Burkholderia sp. strain C3*	N-methyl carbamates pesticides	Seo et al. (2013)
31	*Photobacterium ganghwense*	Cyfluthrin degradation	Singh et al. (2018)

(continued)

Table 1 (continued)

S. no.	Bacteria	Promising against	Reference
32	*Mycobacterium sp.* DBP42	Phthalate and plasticisers	Wright et al. (2020)
33	*Halomonas sp.* ATBC 28	Phthalate and plasticisers	
34	*Drechslera sp. 678*	Methyl tertiary-butyl ether (MtBE), an additive used in gasoline	d'Errico et al. (2021)
35	*Fusarium verticillioides*	Lactam and lactone xenobiotic degradation	Gao et al. (2022)
36	*Sphingobium chungbukense*	PAH-degrading	

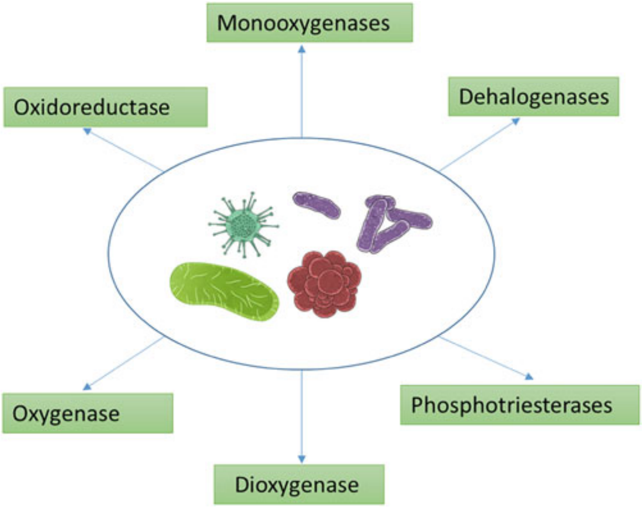

Fig. 2 Xenobiotic degrading enzymes produced by bacteria

Many bacterial metabolic enzymes like cytochrome P450s, cellulase, laccases, proteases, phytase, lipase, among others, are believed to play a vital role in the management and breakdown of a good number of xenobiotics by degrading the dyes, aromatic hydrocarbons, and halogenated compounds. The first step in enzymatic biodegradation is identifying an appropriate enzyme for bioremediation application; this enzyme needs to be able to convert the target contaminants into less-toxic by-products (Gangola et al. 2019). Aliphatic hydrocarbons are broken down either by mono- or dioxygenases, resulting in the creation of peroxide, which is then transformed into fatty acids (Okolafor and Ekhaise 2022). The fatty acid molecule oxidises to create intermediates in the TCA cycle, which are ultimately broken down into carbon dioxide and water.

7 Degradation of Xenobiotics Through Fungi

Apart from bacteria, fungi are top-notch players for bioremediation of xenobiotic compounds and the process is also referred to as ‘mycoremediation’, wherein fungi are utilised in the bioremediation of hazardous contaminants including hazardous phenolics, dyes, polycyclic aromatic hydrocarbons, polythene, among others. The degradation of xenobiotics via fungal metabolism involves the adsorption of the compounds to the chitinous cell wall of the fungi and as such has highlighted the significance of xenobiotic breakdown by an intracellular enzymatic process (Mishra et al. 2021).

Many members of the group have been recognised to possess biodegradation capabilities, including *Aspergillus, Trichoderma, Penicillium, Fusarium, Cryptococcus*, *Rhodotorula, Pichia, Candida, Exophiala,* and *Aureobasidium* (Bhatt et al. 2020). Fungi, because of their diversity and genetic functionality, are responsible for the evolution of novel traits for bioremediation of xenobiotics. According to Bosshard (2011), various members (species) of genus *Aspergillus*, *A. niger, A. flavus,* and *A. oryzae,* are frequently utilised in the management (breakdown) of low-density polyethylene (LDPE) because of their intrinsic potential to grow easily and extensively at soil and other waste sites, and are thought to have longer incubation period compared with other fungal members (species). A study by Sangale et al. (2019), identified *Aspergillus sydowii* strain PNPF15/TS and *Aspergillus terreus* strain MANGF1/WL effective against polythene degradation. *Metarhizium brunneum* ARSEF has been characterised as metabolic biodegrading fungi against herbicides (ametryn and s-triazene) (Szewczyk et al. 2018). Among other fungi used in bioremediation, white rot fungi (WRF) have evolved as an important candidate for the bioremediation of xenobiotics by producing numerous enzymes for the degradation process.

However, research has demonstrated that fungal consortium yields a better outcome than the usage of single species for the bioremediation process (Saroj et al. 2015). Saroj et al. (2015) developed a fungal consortium by combining three fungal strains, *Aspergillus niger* SAR-6, *Penicillium oxalicum* SAR-3, and *Aspergillus flavus* SAB-3 and the consortium had a comparatively elevated capability to break down azo dyes. Another consortium developed by Wang et al. (2022) consisted of *Trametes hirsuta* BYL-3, *T. versicolor* BYL-7, and *T. hirsuta* BYL-8, the consortium exhibited enhanced lignin degradation. The degradation capability is measurable, and different techniques employed are (Table 2).

8 Conclusion

Advancements in the techniques and methods in molecular biology and bioinformatics have provided new perceptions of bioremediation. The bioremediation process can be enhanced with the application of techniques like genome editing, which

Table 2 Techniques employed for measuring degradability

Polymer deterioration	Scanning electron microscopy	Zahra et al. (2010)
Bio-fragmentation	Size-exclusion chromatography	Sangale et al. (2019)
	High-performance liquid chromatography	
	Fourier-transform infrared spectroscopy	
Plastic degradation by fungi	Spectroscopic methods	
	Fourier-transform infrared spectroscopy)	

enables the modification of microbial strains with the boosted capability of degrading many xenobiotics simultaneously and/or with a rapid rate of degradation (Janssen and Stucki 2020). Breakthroughs in the very advancement of genetic modification technologies have opened the doors of knowledge and information, thus providing a platform for exploring the potential of highly competent microorganisms in the breakdown of xenobiotics and their biodegradation.

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