Nature Environment and Pollution Technology
An International Quarterly Scientific Journal
p-ISSN: 0972-6268 (Print copies up to 2016)
e-ISSN: 2395-3454
Vol. 22 | No. 3 | pp.1155-1167 | 2023
Original Research Paper
https://doi.org/10.46488/NEPT.2023.v22i03.006
Open Access Journal

Environmental Toxicity, Human Hazards and Bacterial Degradation of Polyethylene

N. Yoezer*†, D. B. Gurung* and K. Wangchuk**
*Department of Forest Science, College of Natural Resources, Royal University of Bhutan, Punakha, Bhutan
**Department of Food Science and Technology, College of Natural Resources, Royal University of Bhutan, Punakha, Bhutan
†Corresponding author: N. Yoezer; yoezernima12@gmail.com

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 25-01-2023
Revised: 26-03-2023
Accepted: 28-03-2023

Key Words:
Bacteria
Biodegradation
Toxicology
Environmental pollution
Plastics
Polyethylene

ABSTRACT

Plastics are the most rapidly growing materials in terms of production and consumption. The durability, inertness, light weight, flexibility, and low cost are the key characteristics that make plastic suitable for application in various fields, including the construction, automotive, electronics, and packaging industries. Due to widespread usage in daily life and many industrial processes and operations, more than 300 million tons of plastic waste are produced globally annually. Indiscriminate use of plastics such as polyethylene causes environmental pollution and impacts human health due to irreversible changes in the ecological cycle. Due to its low biodegradability, polyethylene accumulation has recently emerged as a momentous environmental concern. The conventional methods, such as recycling or disposing of polyethylene, are exorbitant, and incineration results in the emission of toxic chemical compounds. Therefore, the most recent research progressively focused on the biodegradation of polyethylene with the application of bacteria as novel approaches to counteract plastic waste. This review summarizes the type of polyethylene and the environmental issues. It also briefly discussed the genes and enzymes of bacteria involved in the degradation of polyethylene. In addition, it attempts to address factors influencing degradation and techniques used for monitoring degradation.

INTRODUCTION

The etymology of plastic is derived from the Greek word "plastikós," which defines materials as being able to be molded into different desired shapes and sizes due to their chemical composition of carbon, chlorine, hydrogen, nitrogen, oxygen, and silicon. Plastics are polymer macromolecules with long chains, and other compounds are added to alter properties such as stability and processability (Bardají et al. 2020). The introduction of plastics into archaeological and geologic history may serve as the defining characteristic of anthropogenic pollution, and the twentieth century is referred to as the "Plastic Age" (Mytum & Meek 2021). Plastics have generally substituted paper and packaging materials due to superior tensile properties, lightweight nature, and low susceptibility to microbial degradation (Muhonja et al. 2018).

Around 80% of all plastics used globally are petrochemical plastics, including polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate esters (PET) (Urbanek et al. 2018). Although plastic materials are indispensable to the world economy, serious complications associated with their widespread use must not be omitted (Chu et al. 2023). The everyday use of plastic has increased global plastic production exponentially, reaching 367 metric tons in 2020 (Plastics Europe 2021), and the amount is significantly increasing annually due to extremely efficient applications. It is estimated that approximately 710 million metric tons of plastic will be accumulated in the environment or landfills by 2040 if the current management practices, use, and production endure (Lau et al. 2020). Hefty amounts of plastic waste are produced primarily due to the short product lifecycle. In 40% of cases, the lifespan of thermoplastic plastic products is anticipated to be less than one month (Hahladakis et al. 2018). Furthermore, plastic waste management has lagged significant manufacturing output, resulting in environmental pollution (Geyer et al. 2017).

Polyethylene is the most significant consumer plastic, primarily used to manufacture plastic bags, bottles, and

ORCID details of the authors:

N. Yoezer: https://orcid.org/0000-0003-1638-9404

containers (Mercy et al. 2023). With 86.08 metric tons, PE accounts for 22% of all plastic produced globally. In comparison to low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE), which make up 12%, high-density polyethylene (HDPE) comprises 10% of global plastic (Šišková et al. 2021). However, PE's resistance to degradation due to high molecular weight, antioxidants, and stabilizers, promotes environmental pollution after a short period of use. The resistance to biodegradation of PE through enzymatic cleavage via oxidative reaction is also due to the carbon-carbon (C–C) backbone and semi-crystal structure (Andler et al. 2022).

The plastic waste entering freshwater and terrestrial environments results in the formation of mesoplastics (0.5–5 cm), microplastics (MP; 1 μm–5 mm), and nanoplastics (NP; < 1μm) due to mechanical abrasion and degradation of larger plastic debris (Bianco & Passananti 2020). Plastic debris such as MPs has ecotoxicological effects on chemical and physical properties, nutrient cycling, and flora and fauna of terrestrial soil (Ya et al. 2021). The presence of LDPE–MPs can affect terrestrial ecosystems. Several alterations were demonstrated in the kidney, liver, pancreas, muscles, gills, spinal cord, notochord, and intestine of *Oreochromis niloticus* (tilapia), affecting survival due to MPs (Hamed et al. 2021). The NPs have a considerable impact compared to other plastic particles due to their capacity to enter cells and tissues and cause molecular impairment besides the toxicity of the polymers. Thus, decreasing the surface of PE increases damage to fish tissue (Hamed et al. 2022). The toxic effects of PE are an emerging concern for aquatic environments. People are exposed to various polymers, including PE, through dermal contact, ingestion, and inhalation due to their occurrence in foods, water, air, and consumer products (Rahman et al. 2021).

Furthermore, toxic chemical compounds such as Bisphenol A (BPA), phthalates, antiminitroxide, flame retardants, and polyfluorinated compounds are also found in plastics. These substances pose environmental and public health risks (Proshad et al. 2018). Hence, it is necessary to reduce plastic pollution through environmentally friendly methods. Conventional methods such as recycling, dumping, and incineration are not feasible and generates toxic substances as a by-product (Venkatesan et al. 2022).

Actinomycetes, bacteria, and fungi are among the microorganisms capable of degrading PE (Dang et al. 2018, Saritha et al. 2021). Bacteria degrading PE include *Phormidium lucidum, Oscillatoria subbrevis* (Sarmah & Rout 2018), *Bacillus wudalianchiensis*, and *Pseudomonas aeruginosa* (Bakht et al. 2020). Those potential microorganisms are isolated from different soil types, including landfill soil (Montazer et al. 2018), to water bodies (Dhanraj et al. 2022). This indicates that the bacteria exist in most places and in sufficient numbers to cause PE biodegradation.

Biodegradation is defined as the capability of microbes to degrade plastic materials into simpler molecules with the help of enzymes by altering the chemical structures of the plastics into an easily degradable property (Gaur et al. 2022). Temperature, crystallinity, hydrophobicity, structure, and enzymes influence the mechanism of PE's biodegradation. Therefore, this review focuses on the toxicity, bacterial degradation, and factors affecting the degradation mechanism of PE. Moreover, it summarizes the technique used to investigate the biodegradation and bacterial enzymes responsible for the degradation of PE and suggests future research scopes.

GLOBAL PLASTIC AND POLYETHYLENE PRODUCTION

Every year, the world witnesses an unprecedented production of plastics. 335 million tons of plastic were produced worldwide in 2016 and 367 million tons in 2020. Europe produced 55 million tons of plastics in 2020 (Plastics Europe 2021). It was estimated that Asia produced 49% of the global plastics, with China as the leading manufacturer (28%). Furthermore, Europe and North America contributed approximately 19% of global plastics production in 2015, while the rest of the country contributed negligible production, but not necessarily of plastic usage (Worm et al. 2017). According to Hahladakis et al. (2018), European nations primarily used plastic for wrapping (38%), infrastructure tools (21%), motorized (7%), electrical applications (6%), as well as other segments (28%). In India, PE had the highest demand (33%) in 2020, followed by PP (32%), and worldwide consumption of PE was growing at a rate of 12% per year (Venkatesan et al. 2022). Bhutan generates over 170 metric tons of waste daily, encompassing various types. Plastics, including HDPE, soft plastics, and PET bottles, contribute to approximately 17% of this overall waste production (Namgay 2020).

CLASSIFICATION OF POLYETHYLENE

The polymerization of ethylene monomers yields polyethylene, also known as polyethylene, a thermoplastic polymer. The chemical formula for ethylene is C_2H_4, while PE has the formula $(C_2H_4)_n$. The Ziegler-Natta and metallocene catalysts are used for the polymerization of polyethylene. Polyethylene is a polyolefin resin family that is the most commonly used plastic worldwide for various

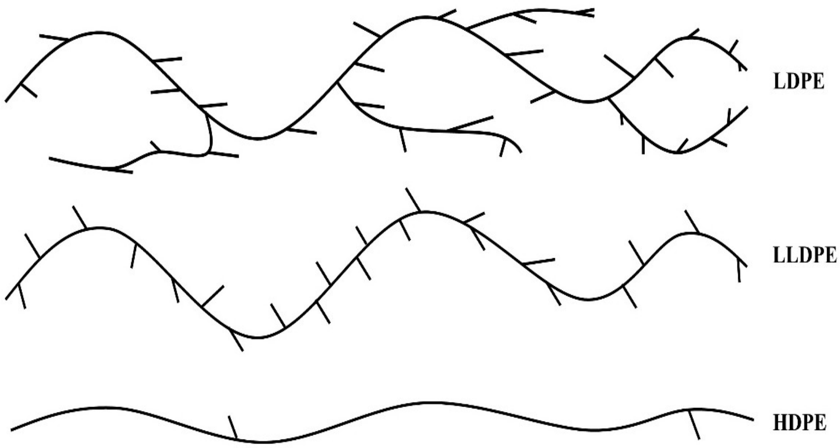

Fig. 1: Polyethylene structures.

purposes, such as wrapping, films, packaging, and nursery bags. There are mainly three types of PE: LDPE, LLDPE, and HDPE (Fig. 1). The fundamental distinction between HDPE, LDPE, and LLDPE is the branching degree at the microstructural level. High-density polyethylene has the lowest or no branching, LLDPE incorporates a high degree of short chain, and LDPE contains an irregular distribution of short and long branches (Rani et al. 2020, Varyan et al. 2022).

THE EFFECT OF PE POLLUTION

The effect of polyethylene on aquatic, terrestrial, and human health are illustrated in Fig. 2.

THE EFFECT OF PE ON AQUATIC LIFE

The main source of plastics in the water is anticipated to be from the terrestrial environment. Microplastics are diluted as transport from the deposition hotspot downstream. Therefore, ineffective waste management practices lead to environmental contamination. Several plastic materials, encompassing PP, PVC, PE, PET, and nylon, as well as particle shapes such as fragments, sheets, and threads, have been found in the *Megaptera novaeangliae* (humpback whales) intestinal tract (Guzzetti et al. 2018). Microplastic accumulation in the hindguts of Lysianassoidea amphipod populations is found at depths ranging from 7,000 m to 10,890 m in the Pacific Ocean (Cózar et al. 2017). This suggests that MP contamination can occur in the ocean beds as well.

Histological fluctuations were detected in the intestine and liver of *Dicentrarchus labrax* (European sea bass) exposed to PE-MPs. Polyethylene microplastics suppress immunity and antioxidant enzyme activity, signifying the oxidative response/stress, and longer exposure resulted in irreversible damage to fish health (Espinosa et al. 2019). Antioxidants, biochemistry, cholinesterase activity, erythron profile, hematological, histological, and immune parameters were altered in young *Cyprinus carpio* (common carps), divulging to PE particles (Hamed et al. 2022).

Polyethylene microplastic ingestion alters morphology, erythrocyte mutagenicity, and cytotoxicity in *Physalaemus cuvieri* tadpoles, affecting their development and health (da Costa Araújo et al. 2020). The gut examination of *Phalaropus fulicarius* carcasses in Canada found that most commonly ingested plastics such as PE and PP likely contributed to mortality (Teboul et al. 2021). Polyethylene microplastics induce oxidative damage and alter the functioning of antioxidant enzymes in *Mytilus galloprovincialis* (mussels) at environmentally relevant concentrations (Abidli et al. 2021). Apart from disruption of metabolic activity in an organism, plastic waste in the rivers also contributes to the spatial distribution of invasive species leading to competition with native species (Hasnat & Rahman 2018). Thus, through ingestion, PE-MPs and NPs can enter organisms' bodies and continue to be transferred along food chains.

POLYETHYLENE IMPACT ON THE TERRESTRIAL ENVIRONMENT

Plastic mulching and shading materials protect crops from pests, and harsh weather suppresses weeds (Maraveas 2020). However, plastic mulch significantly impacts soil properties such as pH, electrical conductivity, infiltration, nutrient exchange, and microbial community (Sintim et al. 2019). Polyethylene microplastics escalate the movement of pollutants while decreasing the retention capacities of the soil. For instance, the holding capacity of cadmium was reduced in MP-contained soil, thereby increasing the possibilities of lethal heavy metal accumulation in agriculture products and groundwater and bestowing additional risks on the environment (Zhang et al. 2020). Plants exposed to PE particles had lower biomass, slow photosynthetic rates, and abnormal mineral nutrient metabolism. This indicates that various PE particles with different molecular weights could adversely affect the soil-plant physiology (Fu et al. 2022).

Low-density polyethylene fragments affect the microarthropod and nematode but slightly influence the biomass and soil microorganism (Lamichhane et al. 2022). Polymers such as LDPE and HDPE have been found in terrestrial species *Armadillo, Porcellio*, *Lumbricus terrestris*, *Scolopendra, Eobania vermiculata,* and *Rumina decollata* causing adverse effects on metabolic function and survival (Al Malki et al. 2021). Low-density polyethylene microplastics affect manure worms' nervous system, morphology, and oxidative response. The result illustrates that the MPs may have adverse biochemical effects on earthworms (Chen et al. 2020). The intestinal tract of terrestrial birds also contains cellulose, PE, and PET-MPs (Carlin et al. 2020). This indicates the abundance and variety of plastics on terrestrial land.

EFFECT OF PE ON HUMAN HEALTH

Microplastics and NPs enter humans through ingestion, inhalation, and dermal contact with water, air, food, and consumer products containing plastics (Karami et al. 2018). Moreover, humans consume plastic directly through table salts (Renzi & Blašković 2018), seafood (De-la-Torre 2020), and canned sardines and sprats (Karami et al. 2018). The most common plastic materials in foodstuffs are PP, PE, PET, polyether (PES), PVC, PS, PA, and nylon (Karbalaei et al. 2018). The various MPs of polycarbonate (PC), polyoxymethylene (POM), polyurethane (PUR), PA, PE, PET, PS, PP, and PVC were found in human stool. Among the nine plastic types, PP (62.8%), PET (17.0%), PS (11.2%), and PE (4.8%) were the most abundant (Schwabl et al. 2019). The inhalation and ingestion of high concentrations of PE-MPs with their rough structures increases the risk of cytotoxicity in epithelial cells and triggers the release of pro-inflammatory cytokines. Polyethylene microplastics also cause the production of reactive oxygen species and nitric oxide in cells (Choi et al. 2021, Gautam et al. 2022). Depending on the hydrophilic nature, dimensions, and surface energy, inhaled airborne MPs can enter the bloodstream with increased epithelial or endothelial diffusion. Most MP particles (PE) measured in abdominal lymph nodes were 1–50 µm (Zarus et al. 2021).

The presence of MPs and NPs causes disruption of molecular and cellular function in humans. Ingestion of such plastic causes various types of cancer, particularly in industrial workers, because of exposure to high intensities of air pollutants (Wang et al. 2020). Human dopaminergic neurons and neurospheres in culture can absorb PE-NPs, which modifies gene expression and elevates malondialdehyde levels, signaling the initiation of

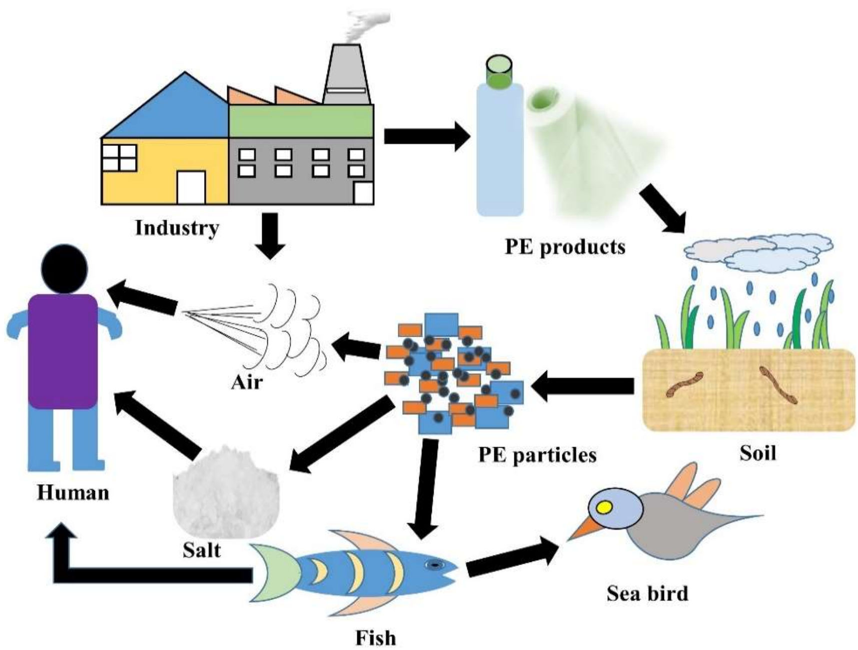

Fig. 2: Effect of plastic particles in aquatic, terrestrial, and human.

oxidative metabolism (Windheim et al. 2022). In addition to potentially endangering the pulmonary and digestive systems, researchers have proposed NPs can significantly increase levels of DNA damage that causes mutagenic processes (Rubio et al. 2020). All that evidence suggests that PE, especially micro and nano, may be prevalent in human foodstuffs, ultimately creating health problems.

MICROBIAL POLYMER DEGRADATION MECHANISM

The mechanism of PE degradation occurs in four stages, as shown in Fig. 3.

Biodeterioration: This process encompasses biotic and abiotic factors that cause erosion of the polymer surface, altering the chemical, mechanical, and physical characteristics. The LDPE exposure to different physicochemical treatments and biotic conditions increases biodeterioration as treatment changes hydrophobicity and surface roughness. Chemical alteration, such as generating polar groups and crosslink formation, also occurs (Gómez-Méndez et al. 2018). The biofilm that develops on the plastic enlarges the aperture dimension and accentuates cracks, compromising the polymer's physical properties (physical deterioration) or releasing chemicals that alter the pH inside the hole to cause structural changes known as chemical deterioration (Jacquin et al. 2019).

Biofragmentation: The lytic phenomenon crucial for reducing large molecules into subunits. The microorganisms cleave polymers using a variety of mechanisms, comprising secretion of particular extracellular enzymes such as oxidoreductases (monooxygenases and dioxygenases), hydrolases (cellulases, amylases, and cutinases), and free radicals (Ali et al. 2021). Enzymes cleave polymer carbon chains or bonds, producing low molecular weight, such as monomers, oligomers, and dimers (Kalidas et al. 2021). Due to low molecular weight, the cell can assimilate. Therefore, biofragmentation of the process involves enzymatic activities to reduce low molecular weight and oxidize the polymer. Depolymerization is another name for this process.

Bioassimilation: The low molecular weight polymer formed through the biofragmentation is absorbed into the cytoplasm of the microbes. The fragmented products are assimilated into cells through the cell membrane using specific membrane carriers. While unassimilated oligomers, dimers, and monomers have to undergo biotransformation reactions to be absorbed by microbial cells with the help of intracellular enzymes (Danso et al. 2019).

Mineralization: It is the final phase in the biodegradation of polymers. The term "mineralization" denotes the complete degradation of molecules with the production of oxidized metabolites. Microorganisms can either aerobically or anaerobically mineralize monomers, dimmers, and oligomers. Water, carbon dioxide, and biomass are produced as end products during aerobic degradation. Under anaerobic biodegradation conditions, by-products are water, carbon dioxide, and methane (Tamoor et al. 2021).

FACTORS INFLUENCING THE BACTERIAL DEGRADATION OF PE

The several factors that affect the bacterial degradation of PE depend on polymer properties and exposure conditions (Fig. 4). Polymer properties include additives, crystallinity, functional groups, hydrophobicity, molecular weight, shape, and size. The exposure conditions include biosurfactants,

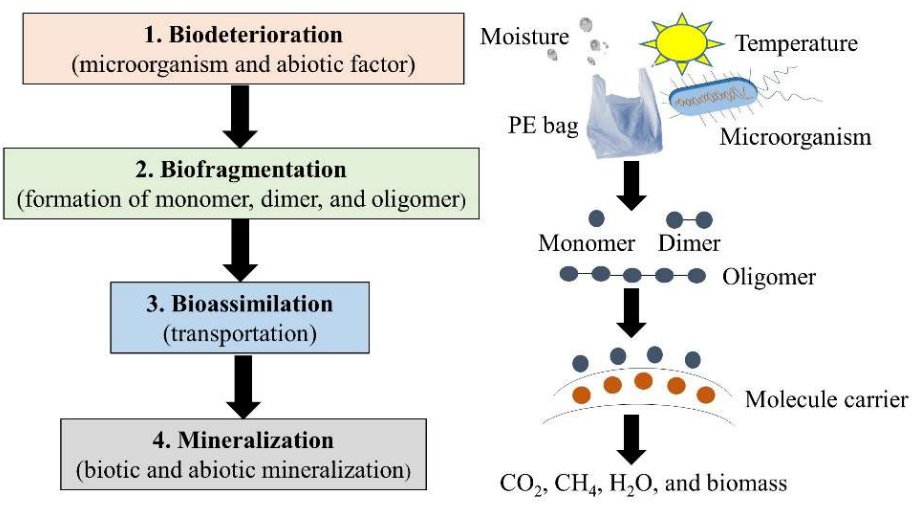

Fig. 3: Mechanism of PE degradation.

enzymes, and microorganisms as biotic factors and moisture, pH, and temperature as abiotic factors.

Exposure Conditions

The moisture provides favorable conditions for respiration, increasing the population of microbes. Furthermore, the chain scission of the polymers takes place in the presence of moisture (Mistretta et al. 2020). In the modification of the PE chemical bond, *Streptomyces* sp. performed better at pH 8, and *Arthrobacter* sp. was more effective at pH 6 with incubation in Czapek–Dox medium and liquid carbon-free basal medium containing PE (Han et al. 2020). Thermophile microorganisms can grow at high temperatures ranging from 45 to 122°C, while psychrophilic microorganisms need temperatures between –20 and 20°C, and temperatures lower than 15°C are considered optimal growth and produce numerous enzymes (Atanasova et al. 2021). However, denaturation of enzymes may occur in psychrophilic bacteria due to high temperature, decreasing the enzymatic degradation of PE (Chamas et al. 2020). The biosurfactant in biofilm growth significantly decreased hydrophobicity and increased hydrophilic functional groups, devising PE sensitive to microbial attack (Tu et al. 2020).

Polymer Properties

The prooxidant additives present in polymer weaken the microstructure, leading to dissociation and allowing microorganism consumption that produces humus, carbon dioxide, and water (Al-Salem et al. 2019). Furthermore, weight loss and structural change with the formation of the new functional group of polymer can occur due to additives (Zhang et al. 2022). Thus, additives and impurities are required to remove before the investigation of biodegradation. High molecular weight polymers are stable and less susceptible to degradation than low molecular weight (Priya et al. 2022). Semi-crystalline polymers (PP, PE, and PET) display greater toughness, strength, and resistance compared to amorphous (Issac & Kandasubramanian 2021), making them less susceptible to enzymatic degradation. The PE backbone consists of linear alkyl chains, and the absence of polar characteristics or hydrolyzable functional groups renders it inactive to degradation. The biotic and abiotic treatments increase PE’s hydrophilicity, microbial colonization, and degradation rapidity (Taghavi et al. 2021). The increase in surface area, water, and microorganism availability promotes biodegradation as the high surface area provides space for the growth of organisms.

Role of Bacterial Gene and Emzyme in Biodegradation of PE

The specialized bacteria and their genes and enzymes are imperative to PE biodegradation. It was found that the alkane hydroxylase (alkB) genes in the *Pseudomonas* sp. The E4 strain degraded 28.6% of organic carbon in 80 days. The ability of the alkB gene was verified by selecting the *Escherichia coli* BL21 strain as a host for gene expression

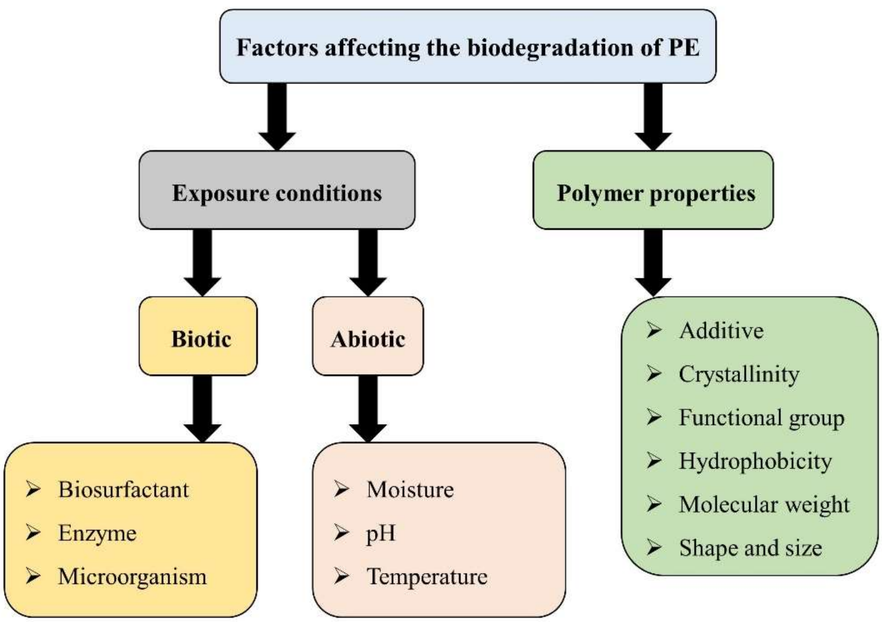

Fig. 4: Factors affecting PE biodegradation.

and achieving a degradation potential of 19.3% for the PE's organic carbon (Priya et al. 2022). Similarly, three putative PE degrading enzymes (esterase, hydrolase, and hydrolase) were expressed in an *E. coli* cell, and their effects on PE films showed significant degradation (Gao & Sun 2021). It was also found that *P. aeruginosa* E7 isolated from an oil-contaminated area possesses alkane hydroxylase. The rubredoxin and rubredoxin reductase transport electrons, and the alkB gene participate in the mineralization of low molecular weight PE (Chen et al. 2020).

Moreover, *Pseudomonas knackmussii* N1-2 and *P. aeruginosa* RD1-3 have 26 and 20 genes, respectively, in their genomes that encode monooxygenases, dioxygenases, and hydroxylases (Hou et al. 2022). Similarly, the genome of *Streptomyces albogriseolus* LBX-2 also embraces 53 oxygenase genes, including monooxygenases and dioxygenases. Thus, *S. albogriseolus* LBX-2 utilized unprocessed PE films as an exclusive carbon source, causing surface deterioration and indicating enzyme-assisted degradation (Shao et al. 2019). The genome of *Alcanivorax* sp. revealed enzymes such as esterases, peroxidases, and laccase that could play an imperative role in biodegradation (Zadjelovic et al. 2020). There are potential genes in Brevibacillus borstelensis AK1 responsible for the breakdown of PE and hydrocarbons. The genes encode enzymes involved in plastic degradation, including cutinase, laccases, hydroxylases, lipases, proteases, and polyphenol oxidase (Khalil et al. 2018). The ligninolytic and hydrolyzing enzymes degrade different plastics, including PE, at 37°C after two days of incubation. Furthermore, the activities of laccase increase by 13 times with 20 µm of copper treatment (Jaiswal et al. 2020).

MATERIALS AND METHODS

Analytical Tools for Determination of Polythene Degradation

Various analytical techniques are applied to determine the biodegradation of PE (Table 1). Fourier transform infrared spectroscopy (FTIR) is used to identify the occurrence of new functional groups. The changes in peak values and functional groups, which typically vary in the double bond and carbonyl group formation, supported the conformational change of the polymer surface (Montazer et al. 2018). Scanning electron microscopy (SEM) assessed the alteration of physical structure on the surface of polyethylene films due to the microorganism's degradative activities through biofilm development (Soleimani et al. 2021). Higher resolution analysis of surface modification can be obtained using Atomic Force Microscopy (AFM), although SEM provides evidence of the polymers' biodeterioration. Atomic Force Microscopy makes it possible to map the topography of a polymer surface (Sullivan et al. 2018). Gel permeation chromatography (GPC) analysis determines the number average molecular weight (Mn), and weight average molecular weight (Mw), and molecular weight distribution (MWD). These parameters are the primary indicator of modification, depolymerization, and polymer degradation (Peng et al. 2020). The major method for assessing polymer degradation is weight loss as microorganism growth and their activities cause the polymer to reduce weight (Waqas et al. 2021). Additional techniques for assessing PE biodegradation include Raman spectroscopy, Nuclear Magnetic Resonance spectroscopy (NMR), Thermogravimetric Analysis (TGA), Electrospray Ionization Mass Spectrometry Analysis (ESI-MS), Different Scanning Calorimetry Analysis (DSC), Carbon, Hydrogen, and Nitrogen (CHN) Analyzer, and Universal Testing Machine (UTM), Sturm test, and Bacterial Adherence to Hydrocarbons (BATH) assay.

RESULTS AND DISCUSSION

Bacterial Biodegradation

The degradation rate of polythene was observed in various microorganisms (Table 1). The six *Bacillus* sp. isolated from landfills and dumping sites were identified as LDPE-degrading bacteria. The degradation potential rates in mineral agar and mineral broth were found that *B. carboniphilus* (34.55% and 25%), *B. sporothermodurans* (36.54% and 21%), *B. coagulans* (18.37% and 16%), *B. neidei* (36.07% and 14%), *B. smithii* (16.40% and 8%), and *B. megaterium* (34.48% and 21%), respectively. Those bacteria were incubated for two months at 30˚C (Shrestha et al. 2019). Pretreated LLDPE particles were incubated with the marine bacteria *Microbulbifer hydrolyticus* IRE-3 for up to 30 days. SEM images revealed the creation of cracks at various locations on the polymer surface, which was also confirmed using FTIR analysis with the formation of hydroxyl and carbonyl functional groups (Li et al. 2020). A consortium of *Enterobacter* and *Pseudomonas* reduced 64.25% of PE (Skariyachan et al. 2021), indicating the mixture has a higher degradation rate. The weight of LDPE and HDPE with consortia of *Lysinibacillus* sp. and *Salinibacterium* sp. decreased to higher than 20% after 60 days and11.1% at 6 months, respectively (Syranidou et al. 2017). The bacterial consortia of *Enterobacter* sp. (IS2), *Enterobacter* sp. (IS3), and *Pantoea* sp. (IS5) degrade 38% and 81% of LDPE pellets and strips, respectively, after 120 days. Further, consortia of *P. putida* (MTCC1), *P. stutzeri* (MTCC2), and *B. subtilis* (MTCC3) 20% LDPE pellets and 49% for LDPE strips after 120 days of incubation respectively

Table 1: Bacteria species reported for biodegradation of PE.

Sl. No.	Bacteria strains	Sources	Substrates	Incubation period (days)	Techniques used to assess degradation	Main experimental outcomes	References
1.	*Bacillus weihenstephanensis*	Garbage soil	LDPE and HDPE	180	Weight loss and FTIR	7.02%, 7.08%, and formation of new functional carbonyl.	(Ingavale & Raut 2018)
2.	*Brevibacillus borstelensis*	Coastal region	HDPE	20	FTIR and SEM	Formation of acids, ester groups, aldehydes, ketones, and surface erosion.	(Mohanrasu et al. 2018)
3.	*Bacillus amyloliquefaciens*	Composting plant	Treated LLDE	60	Weight loss, FTIR, GPC, DSC, TGA, and ESI-MS	3.20%, decrease of the carbonyl band and flattening, decrease in Mn and Mw, decrease of crystallinity, improved thermal stability, and disappearance of LLDPE oligomers.	(Novotný et al. 2018)
4.	Alcanivorax borkumensis	Sea water	LDPE	80	Weight loss, SEM, and ATR-FTIR	3.50%, chemical modifications, and appearance of holes, and cracks.	(Delacuvellerie et al. 2019)
5.	*Pseudomonas aeruginosa* strain SKN1	Waste disposal	LDPE	60	Weight loss, FTIR, and SEM	10.32%, changes in the C–C and C–H bands, and surface degradation.	(Nourollahi et al. 2019)
6.	*Nostoc carneum*	Domestic sewage water	LDPE	42	SEM, FTIR, CHN analysis, TGA-DSC, UTM, and NMR	Surface damage, occurrence of a new C–H stretching band, utilization of about 3% carbon, reduction in melting point, and appearance of new organic substances.	(Sarmah & Rout 2019)
7.	*Bacillus paramycoides*	Biomedical plastic disposal site	Treated LDPE and HDPE	70	Weight loss	36.30% and 31.11%.	(Fibriarti et al. 2021)
8.	*Lysinibacillus* sp. JJY0216	Soil grove	LDPE	26	SEM and GC-MS	9%, increase in rough surface, and detected various carboxylic acids of the hydrocarbon family.	(Jeon et al. 2021)
9.	*Serratia* sp.,*Stenotrophomonas* sp. and *Pseudomonas* sp.	Solid waste-dumping sites	LDPE	150	Loss in weight and FTIR	40%, 32%, 21%, and change in functional group.	(Nadeem et al. 2021)
10.	*Alcaligens faecalis*	Sea water	LDPE	70	FTIR, SEM, XRD, and AFM	Reduction of the carbonyl index, formation of bacterial biofilm, and reduction in crystallinity.	(Nag et al. 2021)
11.	*Micrococcus luteus* CGK112	Cow dung	HDPE	90	Weight loss, BATH test, FE-SEM, EDX, and FTIR	3.85%, increase hydrophobicity, biofilm formation, surface modification, reduction of carbon content, alternation of functional groups, and an increase in the carbonyl index.	(Gupta et al. 2022)

Table Cont....

Sl. No.	Bacteria strains	Sources	Substrates	Incubation period (days)	Techniques used to assess degradation	Main experimental outcomes	References
12.	*Bacillus cereus, Citrobacter koseri,* and *Pseudomonas tuomurensis*	Municipal landfill	HDPE	30	Weight loss and GC-MS	1.78%, 1.31%, and 0.34% and detected degradation products.	(Kopecká et al. 2022)
13.	*Exiguobacterium* sp. strain LM-IK2	Plastic dumped soil	Pretreated LDPE	90	FE-SEM, FTIR, and XRD	5.70%, surface erosion, production of carbonyl peaks, decrease in carbonyl index, and increase in percent crystallinity.	(Maroof et al. 2022)
14.	*Alcaligenes faecalis* MK517568	Municipal dumpsites	LLDPE, HDPE	40	Weight loss, Sturm test, FTIR, SEM, AFM, and BATH assay	3.50%, 5.80%, CO2 produced, changes in the infrared spectra, the formation of rough surfaces, scions, and high hydrophobicity.	(Tareen et al. 2022)
15.	*Methylobacterium radiotolerans* MN525302, *Methylobacterium fujisawaense* KT720189, and *Lysinibacillus fusiformis*	Solid waste disposal area	LDPE	60	Weight loss, FTIR, and SEM	42.87%, 37.20%, 23.87%, generation of new functional groups, and deformation of the LDPE film.	(Nademo et al. 2023)

(Skariyachan et al. 2016). However, pure or consortia of bacteria degradation also depends on the polymer and incubation period.

CONCLUSIONS

The massive accretion of plastic has emerged as a main concern across the world. PE's toxicity to the environment and human health is obvious, but research is still in its infancy. It is significant to have sustainable and robust technologies to combat plastic pollution and its impacts. Microbial degradation of PE is an environmentally friendly technique to reduce plastic waste. The biodeterioration and biofragmentation mechanisms are explicitly illustrated, but few reports on the bioassimilation or mineralization of PE exist. Thus, most investigation in the field of microbial degradation of PE is superficial rather than intrinsic. The biotic and abiotic factors, as well as the PE properties, substantially influence biodegradation. Therefore, it is critical to thoroughly consider the role of various factors when evaluating PE biodegradation.

The study found that most potential polyethylene-degrading bacteria are conducted in pure culture. This clearly illustrates that the high diversity of bacteria in various habitats has not been fully utilized. Moreover, bacteria consortiums have superior proficiency in plastic degradation due to synergism between the bacteria and enzymes involved. The enzymes responsible for PE degradation have been identified in bacteria; however, enzyme properties have not been thoroughly investigated for enzyme engineering. Therefore, a deep understanding of the mechanism of enzyme action is valuable for improving degradation efficiency. Further research into the mechanism of enzymatic degradation will lead to the discovery of efficient, biodegradable plastic.

Since the bacteria constantly adapt to their surroundings, viable PE-degrading bacteria are also expected to be acquired and developed commercially. In many studies, a variety of techniques are used to evaluate biodegradation. However, the lack of a standard protocol creates discrepancies in assessing biodegradation. Therefore, it is fundamental to establish a standardized protocol to acquire reliable and consistent outcomes. It is also indispensable to eliminate the additives and impurities and examine the pretreatment for a better result in the biodegradation of PE.

REFERENCES

Abidli, S., Pinheiro, M., Lahbib, Y., Neuparth, T., Santos, M.M. and Trigui El Menif, N. 2021. Effects of environmentally relevant levels of polyethylene microplastic on *Mytilus galloprovincialis* (Mollusca: Bivalvia): filtration rate and oxidative stress. Environ. Sci. Pollut. Res., 28(21): 26643-26652. https://doi.org/10.1007/s11356-021-12506-8.

Afrin, S., Uddin, M.K. and Rahman, M.M. 2020. Microplastic contamination in the soil from the urban landfill site, Dhaka, Bangladesh. Heliyon, 6(11): e05572. https://doi.org/10.1016/j.heliyon.2020.e05572

Al Malki, J.S., Hussien, N.A., Tantawy, E.M., Khattab, Y. and Mohammadein, A. 2021. Terrestrial biota as bioindicators for microplastics and potentially toxic elements. Miner. Nutr. Livest., 11(10): 1152. https://doi.org/10.1079/9781845934729.0489.

Ali, S.S., Elsamahy, T., Koutra, E., Kornaros, M., El-Sheekh, M., Abdelkarim, E. A., Zhu, D. and Sun, J. 2021. Degradation of conventional plastic wastes in the environment: A review on current status of knowledge and future perspectives of disposal. Sci. Total Environ., 771: 144719. https://doi.org/10.1016/j.scitotenv.2020.144719.

Al-Salem, S.M., Al-Hazza'a, A., Karam, H.J., Al-Wadi, M.H., Al-Dhafeeri, A.T. and Al-Rowaih, A.A. 2019. Insights into the evaluation of the abiotic and biotic degradation rate of commercial pro-oxidant-filled polyethylene (PE) thin films. J. Environ. Manage., 250: 109475. https://doi.org/10.1016/j.jenvman.2019.109475.

Andler, R., Tiso, T., Blank, L., Andreeßen, C., Zampolli, J., D'Afonseca, V., Guajardo, C. and Díaz-Barrera, A. 2022. Current progress on the biodegradation of synthetic plastics: From fundamentals to biotechnological applications. Rev. Environ. Sci. Biotechnol., 21(4): 829-850. https://doi.org/10.1007/s11157-022-09631-2.

Atanasova, N., Stoitsova, S., Paunova-krasteva, T. and Kambourova, M. 2021. Plastic degradation by extremophilic bacteria. Int. J. Mol. Sci., 22(11): 5610. https://doi.org/doi.org/10.3390/ijms22115610

Bakht, A., Rasool, N. and Iftikhar, S. 2020. Characterization of plastic degrading bacteria isolated from landfill sites. Int. J. Clin. Microbiol. Biochem. Technol., 3(1): 030–035. https://doi.org/10.29328/journal.ijcmbt.1001013.

Balzani, P., Galeotti, G., Scheggi, S., Masoni, A., Santini, G. and Baracchi, D. 2022. Acute and chronic ingestion of polyethylene (PE) microplastics has mild effects on honey bee health and cognition. Environ. Pollut., 305: 119318. https://doi.org/10.1016/j.envpol.2022.119318.

Bardají, D.K.R., Moretto, J.A.S., Furlan, J.P.R. and Stehling, E.G. 2020. A mini-review: current advances in polyethylene biodegradation. World J. Microbiol. Biotechnol., 36(2): 32. https://doi.org/10.1007/s11274-020-2808-5.

Beltrán-Sanahuja, A., Benito-Kaesbach, A., Sánchez-García, N. and Sanz-Lázaro, C. 2021. Degradation of conventional and biobased plastics in soil under contrasting environmental conditions. Sci. Total Environ., 787: 147678. https://doi.org/10.1016/j.scitotenv.2021.147678.

Bianco, A. and Passananti, M. 2020. Atmospheric micro and nanoplastics: An enormous microscopic problem. Sustainability, 12(18): 7327. https://doi.org/10.3390/SU12187327.

Budhiraja, V., Urh, A., Horvat, P. and Krzan, A. 2022. Synergistic adsorption of organic pollutants on weathered polyethylene microplastics. Polymers, 14(13): 2674. https://doi.org/10.3390/polym14132674.

Carlin, J., Craig, C., Little, S., Donnelly, M., Fox, D., Zhai, L. and Walters, L. 2020. Microplastic accumulation in the gastrointestinal tracts in birds of prey in central Florida, USA. Environ. Pollut., 264: 114633. https://doi.org/10.1016/j.envpol.2020.114633.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L. and Suh, S. 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng., 8(9): 3494-3511. https://doi.org/10.1021/acssuschemeng.9b06635.

Chen, C.C., Dai, L., Ma, L. and Guo, R.T. 2020. Enzymatic degradation of plant biomass and synthetic polymers. Nat. Rev. Chem., 4(3): 114-126. https://doi.org/10.1038/s41570-020-0163-6.

Chen, Y., Liu, X., Leng, Y. and Wang, J. 2020. Defense responses in earthworms (*Eisenia fetida*) exposed to low-density polyethylene microplastics in soils. Ecotoxicol. Environ. Saf., 187: 109788. https://doi.org/10.1016/j.ecoenv.2019.109788.

Choi, D., Hwang, J., Bang, J., Han, S., Kim, T., Oh, Y., Hwang, Y., Choi, J. and Hong, J. 2021. In vitro toxicity from a physical perspective of polyethylene microplastics based on statistical curvature change analysis. Sci. Total Environ., 752: 142242. https://doi.org/10.1016/j.scitotenv.2020.142242.

Chu, J., Zhou, Y., Cai, Y., Wang, X., Li, C. and Liu, Q. 2023. Flows and waste reduction strategies of PE, PP, and PET plastics under plastic limit order in China. Resour. Conserv. Recycl., 188:106668. https://doi.org/10.1016/j.resconrec.2022.106668.

Cózar, A., Martí, E., Duarte, C. M., García-de-Lomas, J., Van Sebille, E., Ballatore, T. J., Eguíluz, V. M., Ignacio González-Gordillo, J., Pedrotti, M. L., Echevarría, F., Troublè, R. and Irigoien, X. 2017. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the Thermohaline Circulation. Sci. Adv., 3(4): e1600582. https://doi.org/10.1126/sciadv.1600582.

da Costa Araújo, A. P., de Melo, N. F. S., de Oliveira Junior, A. G., Rodrigues, F. P., Fernandes, T., de Andrade Vieira, J. E., Rocha, T. L. and Malafaia, G. 2020. How much are microplastics harmful to the health of amphibians? A study with pristine polyethylene microplastics and *Physalaemus cuvieri*. J. Hazard. Mater., 382: 121066. https://doi.org/10.1016/j.jhazmat.2019.121066.

Dang, T.C.H., Nguyen, D.T., Thai, H., Nguyen, T.C., Hien Tran, T.T., Le, V.H., Nguyen, V.H., Tran, X B., Thao Pham, T.P., Nguyen, T.G. and Nguyen, Q.T. 2018. Plastic degradation by thermophilic *Bacillus* sp. BCBT21 isolated from composting agricultural residual in Vietnam. Adv. Nat. Sci. Nanosci. Nanotechnol., 9(1): 015014. https://doi.org/10.1088/2043-6254/aaabaf.

Danso, D., Chow, J. and Streita, W.R. 2019. Plastics: Environmental and biotechnological perspectives on microbial degradation. Appl. Environ. Microbiol., 85(19): e01095-19. https://doi.org/10.1128/AEM.01095-19.

de Assis, G.C., de Jesus, R.A., da Silva, W.T.A., Ferreira, L.F.R, Figueiredo, R.T. and de Oliveira, R.J. 2021. Conversion of plastic waste into supports for nanostructured heterogeneous catalysts: Application in environmental remediation. Surfaces, 5(1): 35-66. https://doi.org/10.3390/surfaces5010002.

Delacuvellerie, A., Cyriaque, V., Gobert, S., Benali, S. and Wattiez, R. 2019. The plastisphere in the marine ecosystem hosts potential specific microbial degraders, including *Alcanivorax borkumensis,* as a key player in the low-density polyethylene degradation. J. Hazard. Mater., 380: 120899. https://doi.org/10.1016/j.jhazmat.2019.120899.

De-la-Torre, G.E. 2020. Microplastics: An emerging threat to food security and human health. J. Food Sci. Technol., 57(5): 1601-1608. https://doi.org/10.1007/s13197-019-04138-1.

Dhanraj, N.D., Hatha, A.A.M. and Jisha, M. S. 2022. Biodegradation of petroleum-based and bio-based plastics: approaches to increase the rate of biodegradation. Arch. Microbiol., 204(5): 258. https://doi.org/10.1007/s00203-022-02883-0.

Espinosa, C., Esteban, M.Á. and Cuesta, A. 2019. Dietary administration of PVC and PE microplastics produces histological damage, oxidative stress, and immunoregulation in European sea bass (*Dicentrarchus labrax* L.). Fish Shellfish Immunol., 95: 574-583. https://doi.org/10.1016/j.fsi.2019.10.072.

Fibriarti, B.L., Feliatra, A.B. and Darwis, B. 2021. Biodegradation of LDPE plastic by the local strain of bacillus sp. Isolated from dump soil of Pekanbaru, Indonesia. Biodiversitas, 22(12): 5484-5490. https://doi.org/10.13057/biodiv/d221232.

Fu, Q., Lai, J.L., Ji, X.H., Luo, Z.X., Wu, G. and Luo, X.G. 2022. Alterations of the rhizosphere soil microbial community composition and metabolite profiles of Zea mays by polyethylene-particles of different molecular weights. J. Hazard. Mater., 423(Pt A): 127062. https://doi.org/10.1016/j.jhazmat.2021.127062.

Gao, R. and Sun, C. 2021. A marine bacterial community capable of degrading poly(ethylene terephthalate) and polyethylene. J. Hazard. Mater., 416: 125928. https://doi.org/10.1016/j.jhazmat.2021.125928.

Gaur, V. K., Gupta, S., Sharma, P., Gupta, P., Varjani, S., Srivastava, J. K., Chang, J. S. and Bui, X. T. 2022. Metabolic cascade for remediation of plastic waste: A case study on microplastic degradation. Curr. Pollut. Reports, 8(1): 30-50. https://doi.org/10.1007/s40726-021-00210-7.

Gautam, R., Jo, J. H., Acharya, M., Maharjan, A., Lee, D. E., Pramod, P. B., Kim, C. Y., Kim, K. S., Kim, H. A. and Heo, Y. 2022. Evaluation of potential toxicity of polyethylene microplastics on human-derived cell lines. Sci. Total Environ., 838: 156089. https://doi.org/10.1016/j.scitotenv.2022.156089.

Geyer, R., Jambeck, J.R. and Law, K.L. 2017. Production, use, and fate of all plastics ever made. Sci. Adv., 3(7): 25-29. https://doi.org/10.1126/sciadv.1700782.

Gómez-Méndez, L. D., Moreno-Bayona, D. A., Poutou-Piñales, R.A., Salcedo-Reyes, J.C., Pedroza-Rodríguez, A.M., Vargas, A. and Bogoya, J.M. 2018. Biodeterioration of plasma pretreated LDPE sheets by *Pleurotus ostreatus*. PLoS One, 13(9): e0203786. https://doi.org/10.1371/journal.pone.0203786.

Gupta, K.K., Sharma, K.K. and Chandra, H. 2022. *Micrococcus luteus* strain CGK112 isolated from cow dung demonstrated efficient biofilm-forming ability and degradation potential toward high-density polyethylene (HDPE). Arch. Microbiol., 204(7): 1-13. https://doi.org/10.1007/s00203-022-03023-4.

Guzzetti, E., Sureda, A., Tejada, S. and Faggio, C. 2018. Microplastic in marine organism: Environmental and toxicological effects. Environ. Toxicol. Pharmacol., 64: 164-171. https://doi.org/10.1016/j.etap.2018.10.009.

Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E. and Purnell, P. 2018. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal, and recycling. J. Hazard. Mater., 344: 179-199. https://doi.org/10.1016/j.jhazmat.2017.10.014.

Hamed, M., Monteiro, C. E. and Sayed, A. E. D. H. 2022. Investigation of the impact caused by different sizes of polyethylene plastics (nano, micro, and macro) in common carp juveniles, *Cyprinus carpio* L., using multi-biomarkers. Sci. Total Environ., 803: 149921. https://doi.org/10.1016/j.scitotenv.2021.149921.

Hamed, M., Soliman, H.A.M., Badrey, A.E.A. and Osman, A.G.M. 2021. Microplastics induced histopathological lesions in some tissues of tilapia (*Oreochromis niloticus*) early juveniles. Tissue Cell, 71: 101512. https://doi.org/10.1016/j.tice.2021.101512.

Han, Y.N., Wei, M., Han, F., Fang, C., Wang, D., Zhong, Y.J., Guo, C.L., Shi, X.Y., Xie, Z.K. and Li, F.M. 2020. Greater biofilm formation and increased biodegradation of polyethylene film by a microbial consortium of *Arthrobacter* sp. and *Streptomyces* sp. Microorganisms, 8(12): 1979. https://doi.org/10.3390/microorganisms8121979.

Hasnat, A. and Rahman, M.A. 2018. A review paper on the hazardous effect of plastic debris on marine biodiversity with some possible remedies. Asian J. Med. Biol. Res., 4(3): 233-241. https://doi.org/10.3329/ajmbr.v4i3.38461.

Hou, L., Xi, J., Liu, J., Wang, P., Xu, T., Liu, T., Qu, W. and Lin, Y.B. 2022. Biodegradability of polyethylene mulching film by two *Pseudomonas* bacteria and their potential degradation mechanism. Chemosphere, 286(3): 131758. https://doi.org/10.1016/j.chemosphere.2021.131758.

Ingavale, RR. and Raut, P.D. 2018. Comparative biodegradation studies of LDPE and HDPE using *Bacillus weihenstephanensis* isolated from garbage soil. Nat. Environ. Pollut. Technol., 17(2): 649-655.

Issac, M.N. and Kandasubramanian, B. 2021. Effect of microplastics in water and aquatic systems. Environ. Sci. Pollut. Res., 28(16): 19544-19562. https://doi.org/10.1007/s11356-021-13184-2.

Jacquin, J., Cheng, J., Odobel, C., Pandin, C., Conan, P., Pujo-Pay, M., Barbe, V., Meistertzheim, A.L. and Ghiglione, J.F. 2019. Microbial ecotoxicology of marine plastic debris: A review on colonization and biodegradation by the "plastisphere." Front. Microbiol., 10: 865. https://doi.org/10.3389/fmicb.2019.00865.

Jaiswal, S., Sharma, B. and Shukla, P. 2020. Integrated approaches in microbial degradation of plastics. Environ. Technol. Innov., 17: 100567. https://doi.org/10.1016/j.eti.2019.100567.

Jeon, J.M., Park, S.J., Choi, T.R., Park, J.H., Yang, Y.H. and Yoon, J.J. 2021. Biodegradation of polyethylene and polypropylene by *Lysinibacillus* species JJY0216 isolated from soil grove. Polym. Degrad. Stab., 191: 109662. https://doi.org/10.1016/j.polymdegradstab.2021.109662.

Kalidas, V.K., Pavendhan, R., Sudhakar, K., Sumanth, T.P., Sharvesh, R.A., Santhosh, K.S. and Yeswanth, K.K. 2021. Study of synthesis and analysis of bio-inspired polymers-review. Mater. Today Proc., 44(5): 3856-3860. https://doi.org/10.1016/j.matpr.2020.12.831.

Karami, A., Golieskardi, A., Choo, C.K., Larat, V., Karbalaei, S. and Salamatinia, B. 2018. Microplastic and mesoplastic contamination in canned sardines and sprats. Sci. Total Environ., 612: 1380-1386. https://doi.org/10.1016/j.scitotenv.2017.09.005.

Karbalaei, S., Hanachi, P., Walker, T.R. and Cole, M. 2018. Occurrence, sources, human health impacts and mitigation of microplastic pollution. Environ. Sci. Pollut. Res., 25(36): 36046-36063. https://doi.org/10.1007/s11356-018-3508-7.

Khalil, A.B., Sivakumar, N., Arslan, M., Saleem, H. and Qarawi, S. 2018. Insights into *Brevibacillus borstelensis* AK1 through whole genome sequencing: A *Thermophilic* Bacterium isolated from a hot spring in Saudi Arabia. Biomed. Res. Int., 2018: 5862437. https://doi.org/10.1155/2018/5862437.

Kopecká, R., Kubínová, I., Sovová, K., Mravcová, L., Vítěz, T. and Vítězová, M. 2022. Microbial degradation of virgin polyethylene by bacteria isolated from a landfill site. SN Appl. Sci., 4(11): 1-12. https://doi.org/10.1007/s42452-022-05182-x.

Lamichhane, G., Acharya, A., Marahatha, R., Modi, B., Paudel, R., Adhikari, A., Raut, B.K., Aryal, S. and Parajuli, N. 2022. Microplastics in environment: global concern, challenges, and controlling measures. Int. J. Environ. Sci. Technol., 20: 4673-4694.. https://doi.org/10.1007/s13762-022-04261-1.

Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo, A.C., Pilditch, T.D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J.and Palardy, J.E. 2020. Evaluating scenarios toward zero plastic pollution. Science, 369(6509): 1455-1461. https://doi.org/10.1126/SCIENCE.ABA9475.

Li, Z., Wei, R., Gao, M., Ren, Y., Yu, B., Nie, K., Xu, H. and Liu, L. 2020. Biodegradation of low-density polyethylene by *Microbulbifer hydrolyticus* IRE-31. J. Environ. Manage., 263: 110402. https://doi.org/10.1016/j.jenvman.2020.110402.

Maraveas, C. 2020. Environmental sustainability of plastic in agriculture. Agriculture, 10(8): 310. https://doi.org/10.3390/agriculture10080310.

Maroof, L., Khan, I., Hassan, H., Azam, S. and Khan, W. 2022. Microbial degradation of low-density polyethylene by Exiguobacterium sp. strains LM-IK2 isolated from plastic dumped soil. World J. Microbiol. Biotechnol., 38(11): 1-9. https://doi.org/10.1007/s11274-022-03389-z.

Mercy, F.T., Alam, A.K.M.R. and Akbor, M.A. 2023. Abundance and characteristics of microplastics in major urban wetlands of Dhaka, Bangladesh. Heliyon, 9(4): e14587. https://doi.org/10.1016/j.heliyon.2023.e14587.

Mistretta, M. C., Mantia, F. P. La, Titone, V., Botta, L., Pedeferri, M. and Morreale, M. 2020. Effect of ultraviolet and moisture action on biodegradable polymers and their blend. J. Appl. Biomater. Funct. Mater., 18: 1-8. https://doi.org/10.1177/2280800020926653.

Mohanrasu, K., Premnath, N., Prakash, G.S., Sudhakar, M., Boobalan, T. and Arun, A. 2018. Exploring multi potential uses of marine bacteria; an integrated approach for PHB production, PAHs and polyethylene biodegradation. J. Photochem. Photobiol. B: Biol., 185: 55-65. https://doi.org/10.1016/j.jphotobiol.2018.05.014.

Montazer, Z., Habibi-Najafi, M.B., Mohebbi, M. and Oromiehei, A. 2018. Microbial degradation of UV-pretreated low-density polyethylene films by novel polyethylene-degrading bacteria isolated from plastic-dump soil. J. Polym. Environ., 26(9): 3613-3625. https://doi.org/10.1007/s10924-018-1245-0.

Muhonja, C.N., Makonde, H., Magoma, G. and Imbuga, M. 2018. Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi- Kenya. PLoS One, 13(7): 1-17. https://doi.org/10.1371/journal.pone.0198446.

Mytum, H. and Meek, J. 2021. The iron age in the plastic age: Anthropocene signatures at Castell Henllys. Antiquity, 95(379): 198-214. https://doi.org/10.15184/aqy.2020.237

Nadeem, H., Alia, KB., Muneer, F., Rasul, I., Siddique, M.H., Azeem, F. and Zubair, M. 2021. Isolation and identification of low-density polyethylene degrading novel bacterial strains. Arch. Microbiol., 203(9): 5417-5423. https://doi.org/10.1007/s00203-021-02521-1.

Nademo, Z.M., Shibeshi, N.T. and Gemeda, M.T. 2023. Isolation and screening of low-density polyethylene (LDPE) bags degrading bacteria from Addis Ababa municipal solid waste disposal site "Koshe." Ann. Microbiol., 73(1): 1-11. https://doi.org/10.1186/s13213-023-01711-0.

Nag, M., Lahiri, D., Dutta, B., Jadav, G. and Ray, R. R. 2021. Biodegradation of used polyethylene bags by a new marine strain of Alcaligenes faecalis LNDR-1. Environ. Sci. Pollut. Res., 28(30): 41365-41379. https://doi.org/10.1007/s11356-021-13704-0.

Namgay, T. 2020. Nation's waste on the scale: The first Bhutan waste inventory report. Stat. J. IAOS, 36(4): 915-924. https://doi.org/10.3233/SJI-200742.

Nourollahi, A., Sedighi-Khavidak, S., Mokhtari, M., Eslami, G. and Shiranian, M. 2019. Isolation and identification of low-density polyethylene (LDPE) biodegrading bacteria from waste landfill in Yazd. Int. J. Environ. Stud., 76(2): 236-250. https://doi.org/10.1080/00207233.2018.1551986.

Novotný, Č., Malachová, K., Adamus, G., Kwiecień, M., Lotti, N., Soccio, M., Verney, V. and Fava, F. 2018. Deterioration of irradiation/high-temperature pretreated, linear low-density polyethylene (LLDPE) by *Bacillus amyloliquefaciens*. Int. Biodeterior. Biodegrad., 132: 259-267. https://doi.org/10.1016/j.ibiod.2018.04.014.

Peng, B. Y., Li, Y., Fan, R., Chen, Z., Chen, J., Brandon, A. M., Criddle, C. S., Zhang, Y. and Wu, W. M. 2020. Biodegradation of low-density polyethylene and polystyrene in superworms, larvae of *Zophobas atratus* (Coleoptera: Tenebrionidae): Broad and limited extent depolymerization. Environ. Pollut., 266: 115206. https://doi.org/10.1016/j.envpol.2020.115206.

Plastics Europe. 2021. Plastics the Fact 2021. An analysis of European plastics production, demand and waste data. https://plasticseurope.org/.

Priya, A., Dutta, K. and Daverey, A. 2022. A comprehensive biotechnological and molecular insight into plastic degradation by microbial community. J. Chem. Technol. Biotechnol., 97(2): 381-390. https://doi.org/10.1002/jctb.6675.

Proshad, R., Kormoker, T., Islam, M.S., Haque, M.A., Rahman, M.M. and Mithu, M.M.R. 2018. Toxic effects of plastic on human health and environment : Consequences of health risk assessment in Bangladesh. Int. J. Health, 6(1): 1-5. https://doi.org/10.14419/ijh.v6i1.8655.

Rahman, A., Sarkar, A., Yadav, O.P., Achari, G. and Slobodnik, J. 2021. Potential human health risks due to environmental exposure to nano- and microplastics and knowledge gaps: A scoping review. Sci. Total Environ., 757: 143872. https://doi.org/10.1016/j.scitotenv.2020.143872.

Rani, A., Singh, P. and Kumar, R. 2020. Microbial deterioration of high-density polyethylene by selected microorganisms. J. Appl. Biol. Biotechnol., 8(6): 64-66. https://doi.org/10.7324/JABB.2020.80611.

Renzi, M. and Blašković, A. 2018. Litter and microplastics features in table salts from marine origin: Italian versus Croatian brands. Mar. Pollut. Bull., 135: 62-68. https://doi.org/10.1016/j.marpolbul.2018.06.065.

Rubio, L., Marcos, R. and Hernández, A. 2020. Potential adverse health effects of ingested micro- and nanoplastics on humans. Lessons learned from in vivo and in vitro mammalian models. J. Toxicol. Environ. Health - Part B Crit. Rev., 23(2): 51-68. https://doi.org/10.1080/10937404.2019.1700598.

Saritha, B., Sindgi, S.A. and Remadevi, O.K. 2021. Plastic degrading microbes: A Review. Microbiol. Res. J. Int., 22: 28. https://doi.org/10.9734/mrji/2021/v31i630324.

Sarmah, P. and Rout, J. 2018. Efficient biodegradation of low-density polyethylene by cyanobacteria isolated from submerged polyethylene surface in domestic sewage water. Environ. Sci. Pollut. Res., 25(33): 33508-33520. https://doi.org/10.1007/s11356-018-3079-7.

Sarmah, P. and Rout, J. 2019. Cyanobacterial degradation of low-density polyethylene (LDPE) by *Nostoc carneum* isolated from submerged polyethylene surface in domestic sewage water. Energy Ecol. Environ., 4(5): 240-252. https://doi.org/10.1007/s40974-019-00133-6.

Schwabl, P., Koppel, S., Konigshofer, P., Bucsics, T., Trauner, M., Reiberger, T. and Liebmann, B. 2019. Detection of various microplastics in human stool: A prospective case series. Ann. Intern. Med., 171(7): 453-457. https://doi.org/10.7326/M19-0618.

Shao, H., Chen, M., Fei, X., Zhang, R., Zhong, Y., Ni, W., Tao, X., He, X., Zhang, E., Yong, B. and Tan, X. 2019. Complete genome sequence and characterization of a polyethylene biodegradation strain, *Streptomyces albogriseolus* LBX-2. Microorganisms, 7(10): 379. https://doi.org/10.3390/microorganisms7100379.

Shrestha, J.K., Joshi, D.R., Regmi, P. and Badahit, G. 2019. Isolation and identification of low-density polyethylene (LDPE) degrading *Bacillus* spp. from a soil of landfill site. Acta Sci. Microbiol., 2(4): 30-34. https://www.researchgate.net/publication/331702789.

Sintim, H.Y., Bandopadhyay, S., English, M.E., Bary, A.I., Debruyn, J.M., Schaeffer, S.M., Miles, C.A., Reganold, J.P., and Flury, M. 2019. Agriculture, ecosystems and environment impacts of biodegradable plastic mulches on soil health. Agric. Ecosyst. Environ., 273: 36-49. https://doi.org/10.1016/j.agee.2018.12.002.

Šišková, A. O., Peer, P., Andicsová, A. E., Jordanov, I. and Rychter, P. 2021. Circulatory management of polymer waste: Recycling into fine fibers and their applications. Materials, 14(16): 4694. https://doi.org/10.3390/ma14164694.

Skariyachan, S., Manjunatha, V., Sultana, S., Jois, C., Bai, V. and Vasist, K.S. 2016. Novel bacterial consortia isolated from plastic garbage processing areas demonstrated enhanced degradation for low density polyethylene. Environ. Sci. Pollut. Res., 23(18): 18307-18319. https://doi.org/10.1007/s11356-016-7000-y.

Soleimani, Z., Gharavi, S., Soudi, M. and Moosavi-Nejad, Z. 2021. A survey of intact low-density polyethylene film biodegradation by terrestrial *Actinobacterial* species. Int. Microbiol., 24(1): 65-73. https://doi.org/10.1007/s10123-020-00142-0.

Souza, P.M.S., Coelho, F.M., Sommaggio, L.R.D., Marin-Morales, M. A. and Morales, A.R. 2019. Disintegration and biodegradation in soil of pbat mulch films: Influence of the stabilization systems based on carbon black/hindered amine light stabilizer and carbon black/vitamin E. J. Polym. Environ., 27(7): 1584-1594. https://doi.org/10.1007/s10924-019-01455-6.

Sullivan, C., Thomas, P., Stuart, B., Sullivan, C., Thomas, P. and Stuart, B. 2018. An atomic force microscopy investigation of plastic wrapping materials of forensic relevance buried in soil environments. Aust. J. Forensic Sci., 51(5): 596-605. https://doi.org/10.1080/00450618.2018.1450893.

Syranidou, E., Karkanorachaki, K., Amorotti, F., Repouskou, E., Kroll, K., Kolvenbach, B., Corvini, P.F.X., Fava, F. and Kalogerakis, N. 2017. Development of tailored indigenous marine consortia for the degradation of naturally weathered polyethylene films. PLoS One, 12(8): e0183984. https://doi.org/10.1371/journal.pone.0183984.

Szlachetka, O., Witkowska-Dobrev, J., Baryła, A. and Dohojda, M. 2021. Low-density polyethylene (LDPE) building films – tensile properties and surface morphology. J. Build. Eng., 44: 103386. https://doi.org/10.1016/j.jobe.2021.103386.

Taghavi, N., Udugama, I.A., Zhuang, W.Q. and Baroutian, S. 2021. Challenges in biodegradation of non-degradable thermoplastic waste: From environmental impact to operational readiness. Biotechnol. Adv., 49: 107731. https://doi.org/10.1016/j.biotechadv.2021.107731.

Tamoor, M., Samak, N. A., Jia, Y., Mushtaq, M. U., Sher, H., Bibi, M. and Xing, J. 2021. Potential use of microbial enzymes for the conversion of plastic waste into value-added products: A viable solution. Front. Microbiol., 12: 777727. https://doi.org/10.3389/fmicb.2021.777727.

Tareen, A., Saeed, S., Iqbal, A., Batool, R. and Jamil, N. 2022. Biodeterioration of microplastics: A promising step towards plastics waste management. Polymers, 14(11): 2275. https://doi.org/10.3390/polym14112275.

Teboul, E., Orihel, D.M., Provencher, J.F., Drever, M.C., Wilson, L. and Harrison, A.L. 2021. Chemical identification of microplastics ingested by red phalaropes (*Phalaropus fulicarius*) using Fourier transform infrared spectroscopy. Mar. Pollut. Bull., 171: 112640. https://doi.org/10.1016/j.marpolbul.2021.112640.

Tharayil, A., Banerjee, S. and Kar, K. K. 2019. Dynamic mechanical properties of zinc oxide reinforced linear low-density polyethylene composites. Mater. Res. Express, 6(5): 2-30. https://doi.org/https://doi.org/10.1088/2053-1591/aaff8b.

Tu, C., Chen, T., Zhou, Q., Liu, Y., Wei, J., Waniek, J. J. and Luo, Y. 2020. Biofilm formation and its influences on the properties of microplastics as affected by exposure time and depth in the seawater. Sci. Total Environ., 734: 139237. https://doi.org/10.1016/j.scitotenv.2020.139237.

Urbanek, A.K., Rymowicz, W. and Miro, A.M. 2018. Degradation of plastics and plastic-degrading bacteria in cold marine habitats. Appl. Microbiol. Biotechnol., 102(18): 7669-7678. https://doi.org/10.1007/s00253-018-9195-y.

Varyan, I., Tyubaeva, P., Kolesnikova, N. and Popov, A. 2022. Biodegradable polymer materials based on polyethylene and natural rubber: Acquiring, investigation, properties. Polymers, 14(12): 2457. https://doi.org/10.3390/polym14122457.

Venkatesan, R., Santhamoorthy, M., Alagumalai, K., Haldhar, R., Raorane, C. J., Raj, V. and Kim, S. C. 2022. Novel approach in biodegradation of synthetic thermoplastic polymers: An overview. Polymers, 14(20): 4271. https://doi.org/10.3390/polym14204271.

Wang, Y., Lee, Y., Chiu, I. and Lin, Y. 2020. Potent impact of plastic nanomaterials and micromaterials on the food chain and human health. Int. J. Mol. Sci., 21(5): 1757. https://doi.org/10.3390/ijms21051727.

Waqas, M., Haris, M., Asim, N., Islam, H., Abdullah, A., Khan, A., Khattak, H., Waqas, M. and Ali, S. 2021. Biodegradable potential of *Bacillus amyloliquefaciens* and *Bacillus safensis* using low density polyethylene thermoplastic (LDPE) substrate. Eur. J. Environ. Public Health, 5(2): em0069. https://doi.org/10.21601/ejeph/9370.

Windheim, J., Colombo, L., Battajni, N.C., Russo, L., Cagnotto, A., Diomede, L., Bigini, P., Vismara, E., Fiumara, F., Gabbrielli, S., Gautieri, A., Mazzuoli-Weber, G., Salmona, M. and Colnaghi, L. 2022. Micro- and nanoplastics' effects on protein folding and amyloidosis. Int. J. Mol. Sci., 23(18): 10329. https://doi.org/10.3390/ijms231810329.

Worm, B., Lotze, H. K., Jubinville, I., Wilcox, C. and Jambeck, J. 2017. Plastic as a persistent marine pollutant. Annu. Rev. Environ. Resour., 42: 1-26. https://doi.org/10.1146/annurev-environ-102016-060700

Ya, H., Jiang, B., Xing, Y., Zhang, T., Lv, M. and Wang, X. 2021. Recent advances on ecological effects of microplastics on soil environment. Sci. Total Environ., 798: 149338. https://doi.org/10.1016/j.scitotenv.2021.149338.

Zadjelovic, V., Gibson, M.I., Dorador, C. and Christie-Oleza, J.A. 2020. Genome of *Alcanivorax* sp. 24: A hydrocarbon degrading bacterium isolated from marine plastic debris. Mar. Genomics, 49: 0–1. https://doi.org/10.1016/j.margen.2019.05.001.

Zarus, G.M., Muianga, C., Hunter, C.M. and Pappas, R.S. 2021. A review of data for quantifying human exposures to micro and nanoplastics and potential health risks. Sci. Total Environ., 756: 144010. https://doi.org/10.1016/j.scitotenv.2020.144010.

Zhang, S., Han, B., Sun, Y. and Wang, F. 2020. Microplastics influence the adsorption and desorption characteristics of Cd in an agricultural soil. J. Hazard. Mater., 388: 121775. https://doi.org/10.1016/j.jhazmat.2019.121775.

Zhang, Y., Pedersen, J.N., Eser, B.E. and Guo, Z. 2022. Biodegradation of polyethylene and polystyrene: From microbial deterioration to enzyme discovery. Biotechnol. Adv., 60: 107991. https://doi.org/10.1016/j.biotechadv.2022.107991.

Zhao, S., Pei, L., Li, H., Zhang, X., Hu, W., Zhao, G. and Wang, Z. 2020. Enhanced comprehensive properties of polybenzoxazine via tailored hydrogen bonds. Polymer, 201: 122647. https://doi.org/10.1016/j.polymer.2020.122647.