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AQUATIC PLASTICS WASTE BIODEGRADATION USING PLASTIC DEGRADING MICROBES

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ABSTRACT

Plastic is a synthetic polymer that is highly used every year in almost every field of life. Aquatic plastic waste is plastic that scattered in the aquatic environment in the form of macroplastic or microplastic. Plastic production is expected to continue increasing from year to year. Due to the massive production and use of various plastic products, the accumulation of plastic waste in the environment is still increasing resulting in environmental pollution. Biodegradation is considered as the appropriate method to solve the problem. Plastics biodegradation involves various enzymes produced by plastic degrading microorganisms including algae, bacteria, and fungi. During biodegradation, plastics polymer will be converted into microbial biomass and gases through several steps including biodeterioration, biofragmentation, depolymerization, assimilation and mineralization. Thus, this process has less side effect on the environment.

Keywords: Algae, Bacteria, Fungi, Plastics Biodegradation

INTRODUCTION

Plastics come from the Greek language plasticos which means fit for molding and plastos means molded. Plastic is made or synthesized through several reactions. The first manmade plastic was Parkesine which was patented by Alexander Parkes in 1856, while synthetic plastic was first discovered in the 1900s. The first synthetic plastics were thermoplastics which were not yet stable and cannot be used for various purposes as today. Massive plastic production has begun after the second world war **(Barnes *et al*., 2009; Lusher *et al*., 2017)**. Plastics are widely used in daily life because these synthetic polymers are versatile **(Indumathi and Gayathri, 2016)**. Plastics composed of monomers **(Nkwachukwu *et al*., 2013; Archna *et al*., 2015)** are made from fossil fuels that are non-renewable sources. These synthetic polymers composed of carbon, hydrogen, nitrogen, sulfur, and other inorganic components are nonbiodegradable, strong, and resistant to moisture **(Kathiseran *et al*., 2003; Kumari *et al*., 2013; Asmita *et al*., 2015)**. Some of the plastic properties are acid resistant, solvents resistant, alkaline resistant, flexible, durable, and others **(Nkwachukwu *et al*., 2013; Archna *et al*., 2015)**.
In 2010, China and Indonesia were the two highest plastic waste producing countries in the world. China produced 27% of the total world plastic waste with 8.8 million tons of plastic waste per year. Meanwhile, the amount of plastic waste produced in Indonesia was 10% of the total plastic waste in the world. The amount was equal to 3.2 million tons per year **(Jambeck *et al*., 2015; Geyer *et al*., 2017; UNEP, 2018)**. Besides, single-use plastics are the huge sources of plastic waste in the world. North-East Asia was the largest single-use plastic producer in the world in 2014. North-East Asia produced 26% of the world's total plastic waste **(UNEP, 2018)**. Plastic production in Europe in 2016 reached 60 million tons, around 60% of those were used in the packaging industries **(PlasticEurope, 2017; Syranidou *et al*., 2019)**.
Polyethylene (PE) bags are the common form of widely used plastics that reach 500 million to 1 billion units each year. PE is produced around 12% of the total synthetic plastic each year **(Roy *et al*., 2008; Vatseldutt and Anbuselvi, 2014; Indumathi and Gayathri, 2016)**. PE is a synthetic plastic group of polyolefins that has long linear petroleum-based carbon bonds. The long carbon and hydrogen bonds lead this polymer to be resistant of degradation **(Krueger *et al*., 2015)**. Resistant properties possessed by plastic polymers make them suitable to be used for various things. On the other hand, those properties also make them difficult to be degraded in nature and accumulated voluminously in the environment. Not only polluting the terrestrial environment, but plastics that carried by the water flows will also be accumulated in the aquatic environment **(Shah *et al*., 2008; Sowmya *et al*., 2014)**.
The use of nonbiodegradable polymers as plastics causes environmental problems all over the world **(Indumathi and Gayathri, 2016)**. Plastics waste carried by the river reaches 1.15 to 2.41 million tons annually **(Lebreton *et al*., 2017; Syranidou *et al*., 2019)**. The pollution of plastics waste in the marine environment has threatened many living creatures. The plastics waste has threatened at least 267 species, including all mammals, sea turtles around 86%, and seabirds by 44% **(Coe and Rogers, 1997; Indumathi and Gayathri, 2016)**.
The common plastic waste treatment methods are landfill disposal, incineration, and recycling **(Al-Salem *et al*., 2009; Hopewell, 2009; Gan and Zhang, 2019)**. However, these methods are considered less effective **(Drzyzga and Prieto, 2018)**. Landfill plastic waste processing requires an enormous space **(Kumar *et al*., 2017)**. Meanwhile, incineration releases toxic gases into the environment **(Al-Salem *et al*., 2009; Hopewell, 2009; Gan and Zhang, 2019)**. Another method that could be used is biodegradation, which is considered to be more effective method. Biodegradation is conducted by using various kinds of plastic degrading microorganisms **(Okmoto *et al*., 2003; Agrawal and Singh, 2016)**, including bacteria and fungi **(Shah *et al*., 2008; Jacquin *et al*., 2019)** that catalyzed by various plastic degrading enzymes **(Starnecker *et al*., 1996; Rani *et al*., 2019)**. Plastics degrading microorganisms will utilize this recalcitrant polymer as their energy and carbon source **(Shah *et al*., 2008; Jacquin *et al*., 2019)**.

PLASTICS

Plastics are widely used synthetic products made from fossil fuel **(Kumar *et al*., 2007; Jumaah, 2017)**. Plastics consist of synthetic and semisynthetic polymers produced from coal, natural gas, crude oil, and organic products including cellulose, salt, and can also come from renewable components such as grain, corn, potato, palm, sugar beet and cane, starch, seaweed, and vegetable oil. Plastics can be divided into three groups based on the physical properties, which includes thermoplastics, thermosets, and elastomers **(Lusher *et al*., 2017)**. Thermoplastics are plastics that can be re-melted while thermosets are plastics that cannot be re-melted. Thermoplastics are including Polyethylene Terephthalate (PET), Polyethylene (PE), Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), Polystyrene (PS), Expanded Polyethylene (EPE), Expanded Polystyrene (EPS), Polyvinyl-chloride (PVC), Polycarbonate (PC), Polypropylene (PP), Polylactic acid (PLA) and Polyhydroxyalkanoates (PHA). Thermosets are including Polyurethane (PUR), Phenolic resins (PR), Epoxy resins (ER), Silicone, Vinyl esters, Acrylic resins (AR), Ureaformaldehyde (UF) resins **(UNEP, 2018)**. Meanwhile, elastomers are elastic polymers like rubber and neoprene **(Lusher *et al*., 2017)**.

PE has high molecular weight polymers, complex three-dimensional structures, and hydrophobic components **(Hadad *et al*., 2005; Shah *et al*., 2009)**. PET is a synthetic plastic that was first developed in 1941 which is commonly used as food containers, bottles, and others. HDPE is a synthetic plastic that has been produced since 1939 **(Dodbida and Fujita, 2004; Archna *et al*., 2015)**. LDPE which has been developed and produced since 1939 **(Dodbida and Fujita, 2004; Archna *et al*., 2015)** is commonly used as drink containers **(UNEP, 2018)**. PS has been produced since 1930 **(Dodbida and Fujita, 2004; Archna *et al*., 2015)**, widely used as disposable cups and wrapping tools **(Mukherjee and Chatterjee, 2014)**. Styrene monomers, the building unit of PS is a carcinogenic component that can increase the likelihood of leukemia and lymphoma and also disrupt epithelial ion channels **(McCharty *et al*., 2011; Asmita *et al*., 2015)**. PP is used as bottle caps, medicine bottles, car benches, batteries, disposable syringes, and carpets **(Mukherjee and Chatterjee, 2014)** since the 1950s **(Dodbida and Fujita, 2004; Archna *et al*., 2015)**.

Plastics contain many additives used to reinforce those polymers **(Lusher *et al*., 2017)**. Those components used to increase the resistance of plastics toward biotic and abiotic factors **(Hahladakis *et al*., 2018; Campanale *et al*., 2020)**. Additives that commonly used in plastic production are phthalates, bisphenol A (BPA), flame retardants (FRs), polybrominated diphenyl ethers (PBDEs), and nonylphenols **(Lusher *et al*., 2017)**. Commonly used Phthalates are Di-2- (ethylexyl) phthalate (DEHP), Dibutyl phthalate (DBP), and Diethyl phthalate (DEP) **(Net *et al*., 2015; Lusher *et al*., 2017)**. Phthalates make plastics more flexible and stronger **(Oehlmann *et al*., 2009; Lusher *et al*., 2017)** yet cause bronchitis and cancer **(UNEP, 2018).**

BPA is used as a monomeric building block in polycarbonate plastics and epoxy resins **(Erickson, 2008; Lusher *et al*., 2017)** as well as in PE, PP, and PVC **(PlasticsErurope, 2016; Lusher *et al*., 2017)**. BPA is a hazardous chemical that can bind to estrogen receptors α (Erα) and estrogen receptor β (ER β) interfering estrogen activity **(Kuipper *et al*., 1998; Lusher *et al*., 2017)**. Flame Retardants (FRs) are additional components used to reduce the flammability of plastic polymers. The widely used FRs that are including polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCD). Both types of FRs can interfere with the endocrine system and disrupt liver and kidney function **(Muirhead *et al*., 2006; Yogui and Sericano, 2009; Lusher *et al*., 2017)**. Nonylphenols ethoxylate (NPE) and Nonylphenols (NP) are used as stabilizers in food packaging and as antioxidants in several polymers including rubber, vinyl, polyolefins, polystyrenes, and PVC **(USEPA, 2010; Lusher *et al*., 2017)**.

Besides synthetic plastic, there are also bioplastics. Bioplastics are divided into biodegradable plastics, oxo-biodegradable, and bio-based plastics based on biodegradability. Biodegradable plastics are plastics that can be degraded by microorganisms into water and carbon dioxide or methane, such as poly(butylene succinate-*co*-butylene adipate) with various degree of crystallinity **(Baidurah *et al*., 2012, 2013)** and poly(3-hydroxybutyrate-*co*-3-hydroxyhexanoate) **(Baidurah *et al*., 2019)**. Oxo-biodegradable plastics are plastics that belong to the polyolefin group which contain a metal salt and will be fragmented into smaller fragments. Also, bio-based plastics are plastics that easily degraded by microorganisms because they are made of easily degraded materials **(Lusher *et al*., 2017)**. One example of biodegradable plastic is polycaprolactone (PCL). The plastic can be properly degraded using the cutinase enzyme produced by *Bacillus mojavensis* TH309 **(Adigüzel, 2020)** *and Bacillus* sp. KY0701 **(Adigüzel and Tunçer, 2017).** At the first stage of biodegradation, the rate of degradation was low. Then, the reaction rate was increased when the cutinase enzyme succeeded in covering the plastic surface **(Adigüzel, 2020).**

MICROPLASTICS

Plastics production in 2017 reached 348 million tons **(PlasticsEurope, 2018; Nguyen *et al*., 2020)** increased the amount of plastic waste accumulated in the environment. Plastic waste that is scattered on land will be carried by water currents to pollute the aquatic environment **(Shah *et al*., 2008; Devi *et al*., 2014)**. The massive use of plastic causes the high production of plastic waste in the world. Plastic waste polluting the environment consists of various types and sizes. Generally, plastic waste polluting the aquatic environment are microplastics. Microplastics are smaller plastic waste fragments. They are one of the factors affecting the balance of aquatic ecosystems due to their toxic compounds which endanger many aquatic organisms **(Mrowiec, 2017)**. It is estimated that the amount of microplastics waste that pollutes the aquatic environment will reach 250 million tons in 2025 **(Wright and Kelly, 2017; Mrowiec, 2017)**.

Microplastics are plastics that range from 0.1 μm to 5000 μm. Microplastics waste that can be found in marine water are in the form of fragments, fibers/filaments, beads/spheres, films/sheets, and pellets **(Lusher *et al*., 2017)**. There are two kinds of microplastic, namely primary microplastic and secondary microplastic. Primary microplastics are micro-sized plastic particles that are commonly used in various industries such as cosmetics. Meanwhile, secondary microplastics are microplastics produced from the fragmentation of macroplastic waste **(Essel *et al*., 2015).** Microplastics resulted from macroplastics that are degraded by UV light into small fragments **(Tokiwa and Calabia, 2007; Morohoshi *et al*., 2018)**. They also produced from many cosmetic products. Besides, microplastics are also widely produced as cleaning agents such as toothpaste and facial wash soap **(Thompson, 2015; Browne, 2019; Okunola *et al*., 2019)**. Microplastics contain two kinds of chemical components distinguished based on their origin which includes additives or material originated from plastics and chemical absorbed from the environment. They carry the plastic components themselves and also carry chemicals absorbed from the surrounding places **(Campanale *et al*., 2020).**

Plastic particles can be found in various parts of the ocean or waters. It depends on the relative density of plastic particles to the seawater. They can be found on the surface of the water and in the water column **(Harrison *et al*., 2011; Kaiser *et al*., 2017; Oberbeckmann and Labrenz, 2020).** Plastic types of polyolefines, PE, PP, and PS are the most common plastic groups found as microplastics on the surface of marine water **(Song *et al*., 2014; Song *et al*., 2015; Galgani *et al*., 2018)**. Not only can be found in the water column, but microplastics can also be found in 5000 m depth sea sediments in which there are around 2000 microplastic particles per m^2 **(Cauwenberghe *et al*., 2013; Fisher *et al*., 2015; Cauwenberghe *et al*., 2015)**. The existence of plastic waste in the aquatic environment is determined by its buoyancy. The larger plastic waste will have a higher buoyancy and scattered over the surface or water body. Meanwhile, smaller plastic waste such as fragments has lower buoyancy, therefore it's easily sinking in the sediment due to biofouling. Plastic waste that has been turned into microplastics will be accumulated in sediments **(Fazey and Ryan, 2016; Kalogerakis *et al*., 2017; Jacquin *et al*., 2019)**. Microplastics found in sediments can be in the form of fibers, fragments, and pellets **(Claessens *et al*., 2011; Manalu *et al*., 2017)**. For instance, microplastics found in the sediments in the Jakarta Bay of Indonesia were dominated by microplastics measuring between 100 μm to 500 μm. Whereas in water samples, microplastics were found to range from 20 μm to 40 μm **(Manalu *et al*., 2017)**.

Microplastics are one of the main factors contribute to environmental issues **(Oberbeckmann and Labrenz, 2020)**. Microplastics are easily ingested by aquatic organisms. A study conducted by **Avio *et al*. (2015)**, detected the presence of microplastics in the intestines of several fish species including *Sardina pilchardus*, *Squalus acanthias*, *Merluccius merluccius*, *Mullus barbatus*, and *Chelidonichthys lucerna*. Based on the research, it was known that 65% of the plastic contained in the gut of the fish was PE **(Mrowiec, 2017)**. The plastic contaminated fish is likely consumed by humans will result in bioaccumulation **(Oberbeckmann and Labrenz, 2020)**.

Not only polluting the aquatic environment and accumulated in the bodies of living organisms, but microplastics can also be colonized by pathogenic microbes. The interaction between pathogenic microbes to microplastics resulting in other problems such as increasing the antibiotic-resistance gene transfer by the pathogenic microbial community. Microplastics are also a carrier of antibiotic resistance genes. Microorganisms associated with microplastics had an increased transfer of trimethoprim resistant encoded plasmids (**Arias-Andres *et al*. 2018; Oberbeckmann and Labrenz 2020**).

The presence of microplastics in the aquatic environment is threatening the socio-economy system because they change the quality of the aquatic environment thus cause various problems across generations. Microplastics involved in the food chain leads to health problems for both animals and humans. Therefore various kinds of actions are needed to alleviate the problem. The most important initiative that can be implement is to improve the disposal system, practising the 3R principles which are reuse, reduce, and recycle, as well as public awareness is also needed **(Mrowiec, 2017)**. Meanwhile, the ability of microorganisms to degrade microplastics plays an important role in the management of the aquatic environment to reduce the effects caused by microplastics. The ability of microorganisms in degrading microplastics is strongly influenced by their ability to colonize many substrates, both natural and synthetic, or artificial substrates **(Oberbeckmann and Labrenz, 2020)**.

THE EFFECTS OF PLASTIC WASTE IN THE AQUATIC ENVIRONMENT

Plastic waste polluting the aquatic environment is a serious problem faced by the world. Hazardous substances contained in plastic waste have been reported to threaten thousands of species. It is estimated that in 2050 as many as 99% of seabirds will be exposed to plastic waste through ingestion. Moreover, toxic compounds consumed by various marine organisms cause bioaccumulation through food chains including humans **(UNEP, 2018)**. It is estimated that around 5-13 million tons of plastic pollute the aquatic environment. Approximately 1.5 – 4% of the world's plastics production will be accumulated in the marine environment **(Geyer *et al*., 2017; Drzyzga and Prieto, 2018)**.

Around 80% of plastic waste polluting the aquatic environment originated from the land. Hazardous substances from incompletely degraded plastic waste on the land will be washed away by the water flows **(Sheavly, 2005; Okunola *et al*., 2019)**. Also, plastic waste floating on the water flows can be colonized by many organisms. They will be transported to other places along with the movement of the plastic waste. They become invasive species in those new places that threaten the existence of native species **(Derraik, 2002; Hasnat *et al*., 2018)**. The accumulation of plastic waste in the aquatic environment encourages the pollution of other dangerous pollutants. Plastic waste leads to the accumulation of various contaminants including nonylphenol, PCBs, dichlorodiphenyldichloroethylene

(DDE), and phenanthrene **(Mato, 2001; Okunola *et al.*, 2019)**. The accumulation of those properties causes some reproduction system disorders such as hormone disorder and interfere sperm motility **(Halden, 2010; Okunola *et al.*, 2019).** Moreover, plastics waste accumulated in water bodies and waterways clogs waterways resulting in floods.

Plastics waste is often accidentally consumed by aquatic animals. Plastic waste entering the digestive tract of these animals will poison them. It was reported about 400,000 marine mammal deaths were related to plastic pollution. Further, aquatic organisms can also be accidentally entangled with plastic waste **(Daniel, 2004; Okunola *et al*., 2019)**. PC and PVC waste contains bisphenol A, a dangerous chemical component interfering with the reproductive system. PS and PVC also contain phthalates disturbing the male reproductive system. Plastics that contain styrene monomers can be dangerous to the body due to their carcinogen compounds. Components including dioxins, persistent organic pollutants (POPs), polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) found in almost all plastics also lead to various health problems **(Halden, 2010; Okunola *et al*., 2019)**.

Plastics waste is a vector of pathogenic microorganisms. An increase in plastic waste increases their presence in an aquatic environment. Plastics have been reported to increase *Vibrio* sp. communities, pathogenic bacteria causing infectious diseases **(Zettler *et al*., 2013; Jacquin *et al*., 2019)**. Plastic waste is also reported increasing the number of pathogenic Dinoflagellates including *Ostreopsis* sp. and *Coolia* sp. **(Masó *et al*., 2013; Dussud *et al*., 2018a; Jacquin *et al*., 2019)**. Moreover, various biogeochemical cycles that occur in the marine environment are also affected by the presence of plastic waste **(Hutchins and Fu, 2017)**. Therefore, biodegradation is needed to overcome this worldwide issue to save the aquatic environment **(Mandan and Arya, 2017)**.

PLASTICS BIODEGRADATION

Petroleum-derived synthetic polymers that pollute the environment might be degraded incompletely in a long time through various ways. Synthetic polymers degradation in nature occurs through physical degradation including abrasive forces, heating or cooling, freezing or thawing, and wetting/drying. They can also be degraded through photodegradation mediated by UV light. Furthermore, recalcitrant pollutants can also be degraded through chemical degradation including oxidation and or hydrolysis **(Duwez and Nysten; Klein *et al*., 2018)**. Degradation of plastic waste in the aquatic environment by various environmental factors associated with some microorganisms. The first stage or initial degradation phase can be through mechanical degradation, photodegradation initiated by UV light found in sunlight, oxidation, and hydrolysis, and assisted by various living things (biodegradation). This process produces smaller fragments of plastic or microplastics **(Klein *et al*., 2018)**. Incomplete plastic degradation caused by various environmental factors produces small-sized plastic waste, 1-5000 μm, which is known as microplastic which is furthermore transformed into nano plastic through a further mechanical degradation **(Lambert and Wagner, 2016; Klein *et al*., 2018)**. Nano plastic is a plastics fragment that is smaller than 1 mm in size. This kind of plastic is hard to identify directly in the water environment thus often ingested by aquatic organisms and carried in the food chain **(Valsesia *et al*., 2021).** Synthetic polymers can also be degraded by many microbial reactions including bacteria, fungi, and algae, with relatively long time required **(Duwez and Nysten; Klein *et al*., 2018)** involving some spesific enzymes such as esterase **(Adigüzel, 2020).** This process is called biodegradation **(Duwez and Nysten; Klein *et al*., 2018)**. Plastics can be used as energy sources for plastic degrading microorganisms. For example, PE degradation provides energy which is almost the same value as glucose. That polymer oxidation process produces energy from -422 kJ to -425 kJ per mole of O^2 while energy resulted from glucose oxidation is -479 Kj per mole O^2 **(Gewert *et al*., 2015; Krueger *et al*., 2015; Oberbeckmann and Labrenz, 2020)**.

The ability of a microorganism to utilize many substrates as nutritional sources is influenced by the ability of these microorganisms to grow on the substrates. The attachment of a microorganism to the surface of the substrate is influenced by the hydrophilic or hydrophobic (chemical properties) surface of the substrate. In general, bacteria with high hydophobicity will be more easily attached to the surface of the substrate that is also hydrophobic. Conversely, bacteria with low hydophobicity will more easily stick to the surface of the hydrophilic substrate as well. For example, PE is hydrophobic so that bacteria with more hydrophobic cell surfaces will more easily stick to the surface of the plastic **(Duddu *et al*. 2015)**.

Biodegradation is a process of converting polymers into gas and biomass mediated by various microorganisms including bacteria, fungi, and actinomycetes. They can utilize the polymers as their carbon energy sources **(Shah *et al*., 2008; Jacquin *et al*., 2019)**. Biodegradation catalyzes by many enzymes produced by microorganisms **(Starnecker *et al*., 1996; Rani *et al*., 2019)**. The enzymes released by these microorganisms break down plastic polymers into smaller and simpler parts, in the form of monomers and oligomers. Decomposed fragments will be absorbed by microbial cells and involved in the metabolism **(Usha *et al*., 2011; Soud *et al*., 2019)**.

Biodegradation occurs through aerobic and anaerobic metabolisms that produce gases **(Calil *et al*., 2006; Shah *et al*., 2009)**. The type of gases produced from the biodegradation process is determined by the polymer metabolic pathway based on the presence of oxygen **(Mohee *et al*., 2008; Jacquin et al., 2019)**. Within aerobic conditions, the process produces carbon dioxide, whereas in anaerobic conditions it produces methane as the final product **(Calil *et al*., 2006; Shah *et al*., 2009)**. Meanwhile, the level of biodegradability of a polymer can be observed through weight loss, tensile strength, changing in the elongation percentages, decreasing in the molecular weight of the polymer **(Devi *et al*., 2014)**, microscopic observation, changing in color and shape **(Tiwari *et al*., 2018)**. Meanwhile, the tensile strength values in plastics can be influenced by several factors, including the molecular structure of plastic polymers that affect the density of plastics, the chemical composition of the plastic constituent, and the temperature-resistance properties **(Khoironi *et al*., 2019)**.

Two important processes occured during biodegradation are oxidation and decarboxylation. The oxidation process of a polymer occurs in the presence of oxidizing agents such as molecular oxygen, singlet oxygen, atomic oxygen, and ozone. Polymers exposed to oxygen will form hydrogen peroxide which can initiate the auto-oxidation process. The auto-oxidation process of a polymer runs faster with an increase in temperature **(Tiwari *et al*., 2018)**. Decarboxylation is a chemical process that releases a carbonyl and produces CO_2 **(Booth, 1963; Tiwari *et al*., 2018)**.

Biodegradation occurred through several stages. Biodeterioration is the first stage of biodegradation of plastic polymers **(Dussud and Ghiglione, 2014; Jacquin *et al*., 2019)**. Biodeterioration is the process of changing the structure of plastic polymers carried out by plastic degrading microbes **(Helbling *et al*., 2006; Ipegoklu *et al*., 2007; Sharma *et al*., 2017)**. At this stage, microbes will cover the entire surface of the plastic to form biofilms both on the surface and in the plastic. Biodeterioration divided into physical biodeterioration and chemical biodeterioration **(Dussud and Ghiglione, 2014; Jacquin *et al*., 2019)**. Biofilms formed on the surface of the polymers enhance the biodeterioration process **(Kumar *et al*., 2017)**. In the form of biofilms, these microbial cells will produce extracellular polymeric substances (EPS), **(Bonhomme *et al*., 2003; Sharma *et al*., 2017)** consisting of polysaccharides, proteins, and nucleic acids **(Gilan and Sivan, 2013)**. These components produced by biofilms are useful to form holes in plastic polymers that lead the physical biodeterioration **(Bonhomme *et al*., 2003; Sharma *et al*., 2017)**. Biofilms also produce various acids **(Dussud and Ghiglione, 2014; Jacquin *et al*., 2019)** including nitrous acid, nitric acid or sulfuric acid, citric, fumaric, gluconic, glutaric, glyoxalyc, oxalic, and oxaloacetic **(Sharma *et al*., 2017**) that change the pH of the plastic, the pore structure and the plastic microstructure. The process is called chemical biodeterioration **(Dussud and Ghiglione, 2014; Jacquin *et al*., 2019)**.

Biofragmentation is a stage of biodegradation in which the enzymes produced by microorganisms play an essential role in degrading plastic polymers. Plastic degrading microorganisms release extracellular enzymes such as oxygenases, lipases, esterases, depolymerases, and other enzymes. These enzymes cover the surface of the plastic polymer which will reduce the molecular weight of the plastic polymer **(Dussud and Ghiglione, 2014; Jacquin *et al*., 2019)**.

Microbial cells can not absorb large plastic polymers easily. To overcome this problem, microorganisms release exoenzymes or free radicals to break down plastic polymers into smaller fragments. In carrying out the lysis process and chemical reactions, they require different electric potentials. However, highly stable plastic polymers have high electric potential stability. In addition to this, they use the oxygenases (**Lugauskas *et al*., 2003; Sharma *et al*., 2017)** which can add oxygen to the long carbon bonds (**Krueger *et al*., 2015)** of plastic polymers **(Lugauskas *et al*., 2003; Sharma *et al*., 2017)**. Monooxygenase and dioxygenases will be combined encouraging the formation of alcohol or peroxyl. The next transformation process will be catalyzed by esterase and lipase after the formation of the carboxylic group. After the formation amide, the next reaction will be catalyzed by endopeptidase **(Lugauskas *et al*., 2003; Sharma *et al*., 2017)**.

The depolymerization of plastic constituent polymers uses depolymerase enzymes. The results of these reactions can be in the form of oligomers, dimers, and monomers which structures are simpler than polymers. The three results will be further processed according to the presence of oxygen molecules in metabolism. Aerobic degradation of the three components produces microbial biomass, CO_2, and H_2O. Anaerobic degradation transforms the three components into microbial biomass, CO_2, H_2O, and CH_4 or H_2S **(Tiwari *et al*., 2018)**.

The next stage is assimilation. It is the process of absorbing plastic polymer fragments that have become smaller parts (monomers) into plastic degrading microbial cells. Molecules less than 600 daltons will be absorbed into the cell and used as carbon sources to form biomass **(Dussud and Ghiglione, 2014; Jacquin *et al*., 2019)**. For example, *Rhodococcus rhodochorus* assimilates soluble oxidized oligomers after 240 days **(Eyheraguibel *et al*., 2017: Jacquin *et al*., 2017)** assisted by Major Facilitator Superfamily (MFS) or Harboring ATP Binding Cassettes/ ABC **(Gravouil *et al*., 2017: Jacquin *et al*., 2019)**. The assimilation process takes place inside the cells in which the monomers will be metabolized into energy, biomass, and secondary metabolites **(Marjayandari and Shovitri, 2015)**. Inside the cell, oxidized carboxylic molecules formed from the initial degradation of the PE polymer will be transported to β-oxidation to form Acetyl CoA or Propionyl CoA. Then, Propionyl CoA will be carboxylated by Propionyl CoA carboxylase to form Succinyl CoA **(Gravouil *et al*., 2017: Jacquin *et al*., 2019)**. Acetyl CoA and Succinyl CoA will enter the tricarboxylic acid (TCA) cycle. These cycles produce important energy for the formation of microbial biomass formed through

replication **(Jacquin *et al*., 2019)**. Whereas components that cannot be assimilated will be released by microbial cells and will be used by other microorganisms **(Sharma *et al*., 2017)**.
The final step of biodegradation is mineralization. In this process, various gases are produced as a result of the metabolism of perfectly oxidized plastic monomers. The results of the metabolism are H_2O, CO_2, N_2, and CH_2 **(Dussud and Ghiglione, 2014; Jacquin *et al*., 2019)**. This process will be terminated when all carbon sources are converted to carbon dioxide and all biodegradable components are consumed by microorganisms **(Kyrikou and Briassoulis, 2007; Leja and Lewandowicz, 2010)**. This stage is strongly influenced by the ability of microorganisms to utilize those small fragments **(Klein *et al*., 2018)**.
Furthermore, several factors affecting the process of microplastic biodegradation in aquatic environments are the leaching of additional substances in plastic polymers that disrupt the plastic stability, biofouling, and other mechanical processes **(Jahnke *et al*., 2017; Oberbeckmann and Labrenz, 2020)**. Photodegradation, salts, and the ability of microorganisms to degrade plastic polymers are also influential factors **(Oberbeckmann and Labrenz, 2020)**. Plastic degradation is also influenced by humidity **(Bikiaris *et al*., 2013; Raspa *et al*., 2014)** and UV light. The initial stage of the biodegradation can be assisted by providing preliminary treatment such as UV irradiation and acids **(Devi *et al*., 2014)**. UV exposurement accelerates the process of biodegradation of plastics by microorganisms **(Albertson *et al*., 1994; Nandi and Joshi, 2013)**. It reduces complex chains of plastics, then oxidizes plastic polymers to form several groups of compounds including hydroperoxides, peroxides, alcohols, ketones, and some aldehydes **(Hasan, 2007; Nandi and Joshi, 2013)**.

ENZYMES INVOLVED IN PLASTIC BIODEGRADATION

Microorganisms such as *Pseudomonas* sp. can degrade various plastic polymers, including PE, PP, PS, PET, and others. In the biodegradation process, microbial cells will penetrate and colonize the plastic surface. These cells will secrete some enzymes that will hydrolyze or oxidize the plastic polymer resulting in the form of smaller plastic fragments, which will then be absorbed and assimilated by microbial cells and involved in their cell metabolism **(Wilkes and Aristilde, 2017).** One of the stages in the biodegradation process is polymer hydrolysis. The hydrolysis process will cause changes in plastic polymer morphology and composition. The plastic hydrolysis process is affected by several factors including pH, plastic morphology, and the molecular weight of the plastic itself **(Pantani and Gorrasi, 2018).** Hydrolysis is the biodegradation of polymers catalyzed by the hydrolase enzymes **(Ganesh *et al*., 2017).**
Some enzymes catalyzing polyethylene degradation are including amylase, manganese peroxidase, lignin peroxidase, and laccase. These enzymes can be produced by many microorganisms. *Pseudomonas aeruginosa*, *Bacillus* sp., and *Streptomyces griseus* produce amylase, laccase, lignin peroxidase, and manganese peroxidase. *Alcaligenes* sp. produces amylase. *Bacillus antharacis* produces amylase, laccase, and lignin peroxidase. *Rhodococcus ruber* produces laccase, lignin peroxidase, and manganese peroxidase. Those enzymes also found in some fungal strains, including *Aspergillus flavus*, *Aspergillus niger*, and *Fusarium graminearum* **(Ganesh *et al*., 2017)**. Laccase catalyzes intermediate product conversion resulted from the earlier breakdown process of plastic polymers **(Yoon *et al*., 2012; Muhonja *et al*., 2018)**. Laccase is generally used as self-defense in some microbes. They release the enzyme to overcome the phenol toxins produced from the biodegradation process or produced by other microorganisms. Therefore, it is potentially used in many industrial activities including the handling of industrial wastes including xenobiotics that pollute the environment **(Rama *et al*., 1998; Khalil *et al*., 2013)**. In polyethylene degradation, this enzyme catalyzes the oxidation process of polyethylene to form carboxylic acids. The acids will be brought to the reaction of fl-oxidation with coenzyme-A. Within this further reaction, two carbons contained in the acids will be converted to acetyl-CoA then be involved in the citric acid cycles inside microbial cells **(Khalil *et al*., 2013)**.
In PE biodegradation, monooxygenase catalyzes the degradation and conversion of PE into alcohol. Alcohol dehydrogenase converts it into aldehydes which will then be further converted into fatty acids catalyzed by aldehyde dehydrogenase. Fatty acids formed will be included in the β-oxidation inside plastic degrading microbial cells **(Gautam *et al*., 2008; Leja and Lewandowicz, 2010)**. Oxidation of fatty acids occurs in the mitochondria. However, fatty acids must be converted first into fatty acyl-CoA thioesters catalyzed by ATP-dependent acyl-CoA synthetase/thiokinase before entering the mitochondria **(Prakash, 2018)**.
Meanwhile, the enzyme involved in PET degradation is PETase, an aromatic polyesterase enzyme. Besides, the enzyme is also able to degrade polyethylene-2,5 furandicarboxylate (PEF), a substitute of PET **(Austin *et al*., 2018; Drzyzga and Prieto, 2018)**. PET degradation by *Ideonella sakaiensis* catalyzed by two correlated types of enzymes, they are PETase (PET-digesting enzyme) and MHETase, MHET-digesting enzyme **(Yoshida *et al*., 2016; Austin *et al*., 2018)**. PETase hydrolyzes PET into mono-(2-hydroxyethyl) terephthalate (MHET), terephthalic acid (TPA), and bis (2-hydroxyethyl) terephthalate or BHET **(Liebminger *et al*., 2007; Jacquin *et al*., 2019)**. Furthermore, MHET will be converted into TPA and ethylene glycol (EG) catalyzed by MHETase. TPA will be assimilated into microbial cells through TPA transporter **(Hosaka *et al*., 2013; Jacquin *et al*., 2019)** and catabolized by TPA 1,2-dioxygenase (TPADO) and 1,2-dihydroxy-3,5-cyclohexadiene-1,4-dicarboxylate dehydrogenase (DCDDH) into PCA or protocatechuic acid **(Yoshida *et al*., 2016; Jacquin *et al*., 2019)**. It is further converted by PCA 3,4 dioxygenase (PCA34) to form hemiacetal of 4-carboxy-2-hydroxy muconic. Moreover, the product will be catalyzed by dehydrogenase resulting in 2-pyrone-4,6 dicarboxylic acid. The formed 2-pyrone-4,6 dicarboxylic acid will be converted into pyruvate and oxaloacetate through the TCA cycles inside microbial cells **(Jacquin *et al*., 2019)**.
Styrene monomers are the building unit of PS polymers will be oxidized into styrene epoxide catalyzed by styrene monooxygenase. Styrene epoxide will be oxidized by styrene oxidase into phenylacetaldehyde which is then converted into phenylacetic acid through catabolization. It will be further converted into phenyl acetyl-CoA. The formed Phenylacetyl-CoA will be converted to acetyl-CoA and succinyl-CoA through the TCA cycles **(Luu *et al*., 2013)**. Several other essential enzymes also catalyze plastics biodegradation. Polyurethane degrading enzymes are including polyurethanase **(Mandan and Arya, 2017)** and serine hydrolase **(Russell *et al*., 2011; Lii *et al*., 2017)**. Polyester degrading enzyme breaks down and cuts polyester polymers into fragments. Enzymatic hydrolysis of polyester reduces that polymer's molar mass resulting in water-soluble intermediates that will be dissolved in water contained in the media **(Bikiaris, 2013; Râpa *et al*., 2014)**. Also, PHB depolymerase released by some bacteria such as *Azotobacter* and *Bacillus* catalyzes the degradation of PHB polymer **(Aburas, 2016)**.

BIOFILMS

Biofilms are microbial communities immersed in an extracellular matrix on the surface of a substrate. In the formation of biofilms, interactions occur between the same species and other microorganisms **(Liaqat *et al*., 2019)**. Plastics in the marine environment will be colonized by various inorganic and organic components including bacteria, Gammaproteobacteria, and Alphaproteobacteria **(Oberbeckmann *et al*., 2015; Jacquin *et al*., 2019)**. Microplastics serve community spaces for several microbes including fungi, which is used as fungal attaching media. The diversity of fungi colonizing microplastic surfaces depends on the type of plastics. Those fungi may be pathogenic and not indigenous because microplastics oscillate to various places in the aquatic environment **(Kettner *et al*., 2017)**.
The biofilms formation influenced by many factors. These factors are including structural and chemical surface chemistry, biological interactions, environmental conditions, movement, and transport between habits and biogeography. The structure and surface chemistry of plastics is determined by the type of polymer, absorbed and leaching chemicals, age/weathering, and particle size. Biological interactions are determined by colonizing microbes that act as pioneers, the successional stage, competition, and grazing/ingestion. Environmental factors are including temperature, oxygen, availability of nutrients, light, salinity, pressure, and the presence of other pollutants. Meanwhile, the movements and transport between habitats include buoyancy, flocculation, particle spiraling, flooding, and currents. While biogeography covers the geographic location of the place **(Harrison *et al*., 2018)**.
The colonization of several microorganisms on the plastic surface encourages the formation of biofilms **(Jacquin *et al*., 2019)**. The rate of biofilms formation on plastic surfaces varies according to the type of polymers and based on their biodegradable and non-biodegradable properties **(Webb *et al*., 2009; De Tender *et al*., 2017; Jacquin *et al*., 2019)**. Microorganisms found on the seabed and below the surface are including Bacteroides (Flavobacteriaceae) and Proteobacteria mainly from the Rhodobacteriaceae and Alcanivoraceae families **(Zettler *et al*., 2013; Bryant *et al*., 2016; De Tender *et al*., 2017; Dussud *et al*., 2018b; Jacquin *et al*., 2019)**. The most common microbial communities found on the sub-surface plastisphere are photoautotrophic microorganisms especially Cyanobacteria such as *Phormidium* and *Rivularia* **(Zettler *et al*., 2013; Bryant *et al*., 2016; Dussud *et al*., 2018a; Jacquin *et al*., 2019)**. Meanwhile, fungal biofilms formed on the plastic surfaces are dominated by Chitridiomycota, Cryptomycota **(Kettner *et al*., 2017: Jacquin *et al*., 2019)**, and Ascomycota **(Oberbeckmann *et al*., 2016; De Tender *et al*., 2017; Kettner *et al*., 2017; Jacquin *et al*., 2019)**. Meanwhile, the biofilm community predominating poly-(3-hydroxybutyrate-*co*-3-hydroxyhexanoate) (PHBH) polymers, is dominated by the Betaproteobacteria and Alphaproteobacteria **(Suyana *et al*., 1998; Morohoshi *et al*., 2018)**.
Biofilms formed on a substrate is beneficial yet detrimental **(Liaqat *et al*., 2019)**. The beneficial factor of the formation of biofilms is related to the plastics biodegradation. Biofilms formed on plastic surfaces play an essential role in the biodegradation process **(Gilan and Sivan, 2013; Morohoshi *et al*., 2018)**. The biofilms formation on plastic surfaces facilitates microbes to degrade those polymers. Biofilms act as initiators and increase the efficiency of enzymes released by microorganisms during the biodegradation process. The rate at when biofilm is formed on plastic surfaces determines the rate of the biodegradation process **(Indumathi and Gayathri, 2016)**.
Biofilms are formed through several stages. The first stage is the initial contact or attachment to the substrate surfaces, followed by micro-colony formation, maturation and architecture, and the detachment or dispersion of **biofilms (Sutherland, 2001; Jamal *et al*., 2018)**. Initial contact or attachment to the

substrate surface is the initial stage of biofilms formation. At this stage, the microbial cells try to attach themselves to the surface of a substrate with the help of pili and flagella. Also, they can stick to a surface due to physical impulses such as Van der Waal's forces and electrostatic interactions **(Maric and Vranes, 2007; Garreth *et al*., 2008; Jamal *et al*., 2018)**. Fimbriae, other proteins, lipopolysaccharide (LPS), extracellular polymeric substance (EPS), and flagella which are part of the cell surface are essential in the substrate colonization. Fimbriae, other proteins, and mycolic acids (Gram-positive bacteria) that are nonpolar components encourage the colonizing process of hydrophobic substrate surfaces. Meanwhile, EPS and lipopolysaccharide induce the colonization of hydrophilic substrates **(Donlan, 2002)**.

Micro-colony formation is the stage where syntrophic associations occur between many microorganisms. At this stage, there are at least three forms of interactions. First, fermentative bacteria use organic components presented in a substrate to produce alcohol and some acid compounds. Then acetogenic bacteria utilize these products and produce acetate and carbon dioxide. The last, the methanogen bacteria convert acetate, carbon dioxide, and hydrogen into methane to produce energy **(Davey and Oooloole, 2000; Jamal *et al*., 2018)**.

The next step is maturation and architecture that involve microbial interactions induced by signaling molecules to form quorum sensing **(Federle and Bassler, 2003; Jamal *et al*., 2018)**. The biofilms formation is closely related to quorum sensing, a system regulating microbes in producing and detecting communication signals of microbial density. The quorum system in Gram-negative bacteria is mostly acylhomoserine lactone (AHL), but in Gram-positive is autoinducing peptide (AIP). Meanwhile, autoinducer-2 (AL-2) is a quorum-sensing system found in both Gram-negative and Gram-positive bacteria (Liaqat *et al*., 2019). These interactions involve functional genes that are responsible for inducing signals between cells. For example, *Pseudomonas aeruginosa* involving lasR-lasI and rhlR-rhlI genes to form biofilms **(Davies *et al*., 1998; Donlan, 2002)**. Furthermore, biofilm maturation in *P.aeruginosa* involves five stages consisting of reversible adsorption, irreversible attachment, maturation 1, maturation II and dispersion **(Sauer *et al*., 2002; Marić and Vraneš, 2007)**. At the maturation stage, EPS is formed which functions to distribute nutrients and remove the microbial metabolic waste products **(Parsek and Singh, 2003; Jamal *et al*., 2018)**. EPS protects them from temperature, pH changes, UV rays, changes in salinity, nutritional deficiencies, antimicrobials, predators **(de Carvalho, 2018)**, and draining **(Flemming, 1993; Marić and Vraneš, 2007)**.

The number of microorganisms in biofilms is only about 5-35%. EPS is the main composition of biofilms **(Sun *et al*., 2005; Jamal *et al*., 2018)**. While water is the main component of EPS which is around 97%. Biofilms are also composed of protein which is about 2%, other components like polysaccharides around 1-2%, DNA less than 1%, RNA less than 1%, and various ions **(Sutherland, 2001; Lu and Collins, 2007; Jamal *et al*., 2018)**. Most EPS is both hydrophobic and hydrophilic. The formation of EPS is strongly influenced by the availability of nutrients such as carbon, nitrogen, potassium, and phosphate **(Sutherland, 2001; Donlan, 2002)**.

The final step is detachment or dispersion of biofilms. This stage is the stage in which the microbial cells detached from biofilms to colonize new areas. At this stage, microorganisms produce some enzymes to lyse the EPS matrix. For instance, *Escherichia coli* produces N-acetyl-heparosan lyase, *Pseudomonas aeruginosa* produces alginate lyase and *Streptococcus equi* produces hyalurodynase **(Sutherland, 1999; Jamal *et al*., 2018)**. The spread or dispersal of biofilms is also driven by physical impulses including erosion or shearing, sloughing. and abrasion **(Characklis, 1990; Donlan, 2002)**.

Biofilms formed on plastic surfaces produce some compounds increasing the rate of biodegradation and hydrophilicity of plastic polymers **(Fotopoulou *et al*., 2015; Ghosh *et al*., 2019)**. Within biofilms, they accumulate water to increase conductivity. Moreover, these microorganisms also release lipophilic pigments that are essential in destructing the plastic color **(Zettler *et al*., 2013; Ghosh *et al*., 2019)**. The formation of biofilms on plastic surfaces encourages the formation of various kinds of acids changing the pH of plastic polymers thus leading to chemical plastic deterioration causing changes in the polymer microstructure. These acids are including nitrous acid, nitric acid or sulfuric acid, citric, fumaric, gluconic, glutaric, glyoxalyc, oxalic. and oxaloacetic **(Sharma *et al*., 2017)**. Microorganisms also produce biosurfactants that encourage them to degrade many polymers including plastics **(Ghosh *et al*., 2019)**. The plastic surface damages associated with metabolites and extracellular enzymes released by bacteria **(Rosario and Baburaj, 2017)**.

PLASTIC DEGRADING MICROORGANISMS

Plastic degrading microorganisms can be found in several environments. They can be found around the mangrove rhizosphere, plastic contaminated soil, dumping site, and in marine water **(Indumathi and Gayathri, 2016)**. The use of well-designed plastic degrading microbial communities has the potential to overcome plastic waste in the future **(Drzyzga and Prieto, 2018)**. The plastic biodegradation rate can be enhanced by adding other required nutrients **(Rummel *et al*., 2017; Khoironi *et al*., 2019)**. Table 1 shows the summary of plastic degrading microorganisms with the degradation rate based on the spesific condition of experiment.

Table 1 Some Plastic Degrading Microorganisms

No.	Type of Plastics	Microbes (Bacteria, Fungi, Algae) and Strain Name	Biodegradaion Rate / Duration to be Degraded	Weight Reduction (%)	References
1.	PE	*Aspergillus terreus* MANGF1 / WL	60 Days	50	Sangale *et al.* (2019)
		Aspergillus sydowii PNPF15 / TF	60 Days	94	Sangale *et al.* (2019)
2.	PE Microplastics	*Zalerion maritimum*	14 Days	43	Paco *et al*. (2017)
3.	PE Bags	*Pseudomonas* sp.	1 Month	20.54	Kathiresan (2003)
		Staphylococcus sp.	1 Month	16.39	Kathiresan (2003)
		Moraxella sp.	1 Month	7.75	Kathiresan (2003)
		Micrococcus sp.	1 Month	6.61	Kathiresan (2003)
		Streptococcus sp.	1 Month	2.19	Kathiresan (2003)
		Aspergillus glaucus	1 Month	28.80	Kathiresan (2003)
		A. niger	1 Month	17.35	Kathiresan (2003)

Table 1 Some Plastic Degrading Microorganisms (Continued)

No.	Type of Plastics	Microbes (Bacteria, Fungi, Algae) and Strain Name	Biodegradaion Rate / Duration to be Degraded	Weight Reduction (%)	References
4.	PE Cups	*Pseudomonas* sp.	1 Month	3.97	Kathiresan (2003)
		Staphylococcus sp.	1 Month	0.56	Kathiresan (2003)
		Moraxella sp.	1 Month	8.16	Kathiresan (2003)
		Micrococcus sp.	1 Month	1.02	Kathiresan (2003)
		Streptococcus sp.	1 Month	1.07	Kathiresan (2003)
		A.glaucus	1 Month	7.26	Kathiresan (2003)
		A. niger	1 Month	5.54	Kathiresan (2003)
5.	PP	*Bacillus cereus*	40 Days	20	Helen *et al*., (2017)
		Sporosacrina globispora.	40 Days	11	Helen *et al*., (2017)
6.	LDPE	*A. niger*	1 Month	19.5	Alshehrei (2017)
		A. flavus	1 Month	16.2	Alshehrei (2017)
		A. terreus	1 Month	21.8	Alshehrei (2017)
		A. fumigatus	1 Month	20.5	Alshehrei (2017)
		Penicillium sp.	1 Month	43.3	Alshehrei (2017)
		Anabaena spiroides	1 Month	8.18	Kumar *et al*. (2017).
		Scededesmus dimorphus	1 Month	3.74	Kumar *et al*. (2017).
		Navicula pupula	1 Month	4.44	Kumar *et al*. (2017).

7.	Pyrene (PY)	*Oscillatoria* sp.	30 Days	95	Aldaby and Mawad (2018).
		Chlorella sp.	30 Days	78.7	Aldaby and Mawad (2018).

Plastic-Degrading Aquatic Bacteria

In the marine environment, the bacterial plastics colonization is quite fast. Within a few hours, they will cover the entire surface of the plastic to form biofilms and start breaking down the polymers **(Harrison *et al*., 2011; Urbanek *et al*., 2018)**. The number of plastic degrading bacteria is relatively high with 286 identified species. The bacterial phyla which are vital in plastic waste degradation are Proteobacteria, Actinobacteria, Firmicutes, Bacteroidetes, and Cyanobacteria. The class of Gammaproteobacteria which belong to the phylum of Proteobacteria were able to degrade different type of plastics including PE, PET, PP, PS, PVC, and PU. Meanwhile, the most abundant genus was *Pseudomonas* sp. **(Gambarini *et al*., 2021).** Furthermore, many studies reported some sources of plastic degrading bacteria, which include garbage soil, plastic polluted-soil, marine plastic waste sedimentation, mangrove sedimentation, digester sludge, and oil contaminated soil **(Asiandu[a] *et al*., 2021).**
Jiang *et al*. (2018), successfully revealed the microbial diversity assemblages on plastic particles in three locations including Lvsi Port, Chongming Island, and Xiangshan Bay. On Chongming Island, it was known that the family Erytrhrobacteraceae, Sphingomonadaceae, Comamonadaceae, Cyanobacteriaceae, and Blastocatellaceae dominated the region. Meanwhile, the family of Rhodobacteraceae, Erythrobacteraceae, Moraxellaceae Planococcaceae, and one another family dominated Lvsi Port. Xiangshan Bay was dominated by Cyanobacteria, Saprospiraceae, Pseudoalteromonadaceae, Flavobacteriaceae, and Erythrobacteraceae.
Sphingomonadaceae is a family of bacteria found as a broad microplastic colonizer. The ability of this bacterial family to colonize and form biofilms on microplastic surfaces is influenced by their ability to break down hydrocarbons and their ability to produce carotenoids. Because of their ability to break aromatic hydrocarbons, halogenated hydrocarbons including petroleum and pesticides, some members of the family are widely used in bioremediation efforts **(Rosenberg *et al*., 2014; Kertesz *et al*., 2017; Oberbeckmann and Labrenz, 2020)**. Carotenoids are useful to protect those bacteria from UV rays **(Matallana-Surget *et al*., 2012; Oberbeckmann and Labrenz, 2020)**.
Furthermore, Alphaproteobacteria and Gammaproteobacteria are two classes of bacteria that dominate the biofilm community on the plastic waste in the Pacific and Atlantic regions. Both of them are belong to the Proteobacteria phylum, the phylum that dominates the formation of biofilms on plastic surfaces **(Ogonowski *et al*., 2018; Syranidou *et al*., 2019)**. The order Rhodobacterales, Oceanospirillales, and Burkholderiales are the three most common bacterial orders found in the plastisphere community **(Didier *et al*., 2017; Jiang *et al*., 2018; Syranidou *et al*., 2019)**.
Communities formed on plastic surfaces can be divided into primary colonizers and secondary consumers. Both are formed according to the plastic biodegradation stage that takes place. Two genera originated from the pelagic community including Alcanivorax and Ochrobacterum are the most common genera with a relative abundance of 40% **(Godfrin *et al*., 2018; Syranidou *et al*., 2019)**. Meanwhile, biofilms formers found from the planktonic counterpart areas were *Bacillus* and *Pseudonocardia*, two genera of fossil-based polymer and biopolymers degraders **(Karamanlioglu *et al*., 2017; Auta *et al*., 2018; Syranidou *et al*., 2019)**.
Pinto *et al*. (2019), successfully reported a biofilm community formed on plastic surfaces soaked in seawater within one week, one month, and two months incubation with two different treatments including direct sunlight and dim light conditions. Based on that study, it was known that PVC was dominated by Alteromonadaceae, Cellvibrionaceae, and Oceanospirillaceae. Meanwhile, the surfaces of other plastic samples (LDPE, HDPE, PP) were dominated by Cyanobacteria and the Flavobacteriaceae and Oleiphilaceae families. After incubated for 1 month, the plastic surfaces were dominated by Hypomonadaceae, Flavobacteriaceae, Rhodobacteriaceae, Plantomycetaceae. LDPE and HDPE were dominated by the genera of Loktanella and Ruegeria. After 2 months, PVC was dominated by Hypomonadaceae. While, HDPE dominated by the Arenicillaceae family.
Vibrio crassostreae strain J2-9 isolated from the Bay of Brest, France, was tested for its ability to degrade microplastics obtained from dense-microbial-communities sea harbors. The study concluded that *V.crassostreae* is a secondary colonizer. Incubation of PS microparticles in the medium containing the bacteria for 6 days showed different microplastic structures. As a secondary colonizer, this bacterium needs other bacterial communities to support the plastic biodegradation process **(Foulon *et al*., 2016)**.
When plastics incubated with marine bacteria, carbonyl groups and double bonds will be found on the surface of the plastic **(Harshvardhan *et al*., 2013; Syranidou *et al*., 2019)**. The formation of double groups indicates that these bacteria eat carbonyl groups and transport them into unsaturated chains **(Esmaeili *et al*., 2013; Syranidou *et al*., 2019)**. The oxidized plastic polymers will be attacked by biofilms. The biofilms change the oxidized polymers into smaller parts such as oligomers which then absorbed by cells **(Eyheraguibel *et al*., 2017; Syranidou *et al*., 2019)**. Various metabolic pathways occur within the microbial communities around plastic waste. They do the adaptation to the environment, signaling molecules and interactions, and cell motility. Also, various metabolisms occur such as carbohydrate and amino acid metabolisms, membrane transport, energy metabolisms as well as metabolism and biodegradation of xenobiotic components **(Jiang *et al*., 2019)**.
The study of PE bags and plastic cups degradation was carried out by burying them in mangrove soil, *Rhizophora* sp. and or *Avicennia* sp. with a depth of 5 cm with intervals of 2, 4, 6, and 9 months. After incubated for 9 months, PE bags were decreased by 4.21% and plastic cups decreased by 0.25% weight. Based on the calculation of the number of microbes present in each sample, it was known that the bacteria contained in the sample were up to $79.67x10^4$ per gram, while the total density of fungi reached $55.33x10^2$. Based on the identification, the samples contained *Streptococcus*, *Staphylococcus*, *Micrococcus*, *Moraxella*, and *Pseudom onas* as well as two fungi species including *Aspergillus glaucus* and *A.niger* **(Kathiresan, 2003)**.
Plastic degrading bacteria isolated from plastic cups and PE bags buried in mangrove soils have great potential in degrading plastic waste. They are including *Pseudomonas* sp., *Staphylococcus* sp., *Moraxella* sp., *Micrococcus* sp., and *Streptococcus* sp. In shaking culture with an incubation period of 1 month, *Pseudomonas* sp. reduced the weight of PE bags by about 20.54% and plastic cups around 3.97%. *Staphylococcus* sp. reduced the weight of PE bags around 16.39% and plastic cups 0.56%. Meanwhile, PE bags were degraded by *Moraxella* sp. about 7.75% and plastic cups around 8.16%, *Micrococcus* sp. reduced PE bags about 6.61% and 1.02% for plastic cups. Within the same condition, *Streptococcus* sp. reduced PE bags about 2.19% and plastic cups 1.07% **(Kathiresan, 2003)**. **Helen *et al*., (2017)**, reported that two plastic degrading bacteria isolated from mangrove sediment, identified as *Bacillus cereus* and *Sporosacrina globispora*. Within 40 days, *B.cereus* reduced PP about 12%, while *S.globispora* reduced PP plastic for about 11%.
PE degrading bacteria also isolated from seawater using Zobella Marine Agar and Tryptone Soy Agar. The selected bacteria then inoculated into PE minimal salt medium. From the screening process, three strains of plastic degrading bacteria (SI, S2, and T3) were obtained with yellow-creamish colonies by **Devi *et al*. (2014)**. They were isolated in the synthetic nutrient media containing PE strips as carbon source incubated for 15 days. The media were supplemented with mineral oil 0.05% to accelerate the rate of bacterial colonization. The results of the BATH assay showed that the SI strain's OD was 11%, while S2 was 38% and T3 was 33%. S1 strain had a higher adhesion capacity to hydrocarbons than the other two strains which can be seen from the smallest OD value of all. These OD values indicate the level of adhesion of the three isolates to hydrocarbons. The more hydrophobic the cell surface the greater the affinity for hydrocarbon compounds. Based on the SAT analysis, it was known that the S1 strain had more hydrophobic cells compared to other strains. Biodegradation results showed that strain S1 was able to degrade 24% of PE with 40 microns in thickness and 20% for PE with 20 microns in thickness within one month **(Devi *et al*., 2014)**. Plastic degrading bacteria also successfully isolated from the marine environment by **Delacuvellerie *et al*., (2019)**. They obtained LDPE degrading isolates from plastisphere (floating and sediment plastics) of Mediterranean Sea. The bacterium was *Alcanivorax borkumensis*, which was able to decrease 3.5% plastic weight within 80 days.
Furthermore, *Bacillus cereus* and *Sporosarcina globispora* were isolated from the mangrove environment in Peninsular, Malaysia. Both of these bacteria can grow on media containing PP granules as a carbon source. Both strains reduced the weight of PP granules. *B.cereus* degraded 12% of the PP weight while *S. globispora* degraded about 11% within 40 days. The plastic degradation rate of *B.cereus* was 0.003 grams per day, while *S. globispora* was 0.002 grams per day **(Helen *et al*. 2017)**. Meanwhile, thirteen PCL plastic degrading bacterial isolates were identified by **Sekiguchi *et al*. (2010)**. They were *Moritella* sp., *Shewanella* sp., *Psychrobacter* sp., and *Pseudomonas* sp. They were isolated from deep-sea sediments of Kurile and Japan Trenches with a depth of up to 5000 m. They are important decomposition agents of aliphatic polyester waste at the bottom of waters with low temperatures and high pressure.

Plastic-Degrading Aquatic Fungi

In addition to be applied as biodegradation agents for plastic waste on the land, fungi can also be used as plastic biodegradation agents in the aquatic environment (**Kettner *et al*., 2017)** due to their relatively fast growth rate **(Asiandu[b] *et al*., 2021)**. Plastic samples incubated in the aquatic environment with 1-3 meters deep shows many fungi colonizing the plastics. In one PE plastic sample, there were 36 different fungi taxa, while in PS there were 51 different taxa (**Kettner *et al*., 2017).**. Additionally, there are about 150 species of plastic-degrading fungi within 11 phyla. The phyla are dominated with Ascomycota with the percentage of 27%, Basidiomycota 4.4%, and the phyla of Mucoromycota with the percentage of 3% **(Gambarini *et al*., 2021).** Some fungi dominate the microplastic of PE. The fungal community on microplastics was dominated by Chitrydiomycota with a relative abundance of 41%. The next dominant fungi community was Ascomycota with a percentage of 18%. Also known to be a member of Cryptomycota and some unclassified fungi about 15%. In the fungal community was also found 2% of the members of Basidiomycota. Meanwhile, the Ascomycota community had 43 different taxa, Basidiomycota had 22 different taxa and Chytridiomycota contained in the microplastic samples had 10 different taxa. Chytridium dominated PE with a percentage of 22% and PS about 19%. Both plastic samples were incubated in the marine environment along the Baltic Sea to River Warnow, Mecklenburg-Vorpommern, Germany, before being tested for the existence of the fungal community formed on the plastics **(Kettner et al., 2017).**

There were many fungal genera found on the PE and PS microplastics including *Cladosporium*, *Guignardia*, *Cochiliobolus*, *Didymella*, *Phoma*, *Penicillium*, *Geoglossum*, *Lecophagus*, *Trichoderma*, *Acremonium*, *Fusarium*, *Lecythophora*, *Seridium*, *Kazachstania*, *Saccharomyces*, *Pichia*, *Debaryomyces*, *Torulaspora*, *Nakaseomyces*, *Zygotorulaspora*, *Citeromyces*, *Clavispora*, *Cyberlindnera*, *Candida*, *Wichkerhamomyces*, *Hanseniaspora*, *Taphrina*, *Dioszgia*, *Cryptococcus*, *Holtermannia*, *Trichosporon*, *Guehomyces*, *Agaricus*, *Occultifur*, *Bensingtonia*, *Sporidobolus*, *Puccinia*, *Malassezia*, *Chytridium*, *Hyaloraphidium*, *Paramicrosporidium*, and *Mortierella* **(Kettner *et al*., 2017)**. Another plastics-degrading fungi are *Aspergillus* sp. and *Penicillium* sp. which degraded PP/PBAT **(de Oliveira *et al*., 2020**). Some classes reported as plastics-degrading fungi are Mortierellomycetes, Mucoromycetes, Tremellomycetes, Sordariomycetes, Dothideomycetes, Saccharomycetes, Agarycomycetes, Ustilaginomycetes, Leotiomycetes, and Eurotiomycetes **(Gambaraini *et al*., 2021).**

There were also several unclassified isolates including the phylum Ascomycota and Chytridiomycota, some members of the sub-phylum Pezyzomycotina, Pucciniomycotina, some members of the Sordariomycetes and Agaricomycetes classes, found on PE and PS. Moreover, several unclassified orders of Capnodiales, Dothideomycetes, Pleosporales, Helotiales, Chaetothyriales, Hypocreales, Diaporthales, Saccharomycetales, Taphrinales, Tremellales, Agaricales, Sporidiobolales, Chocothyroids, Chococytes, Chococytes, Chucocytes were also found on the microplastic samples. There were also several unclassified families including Trichocomaceae, Saccharomycetaceae, Metschnikowiaceae, Cystofilobasidiaceae, Auriculariaceae, Lachnocladiaceae, Dacrymycetaceae, Chytridiaceae, and Chytriomycetaceae. As well as several other unclassified isolates that form communities on the microplastic samples **(Kettner *et al*., 2017)**.

Paco *et al*. (2017), reported that the fungus found in the sea, *Zalerion maritimum,* can degrade PE **(Drzyzga and Prieto, 2018)**. It was tested for its ability to degrade PE microplastics. The growth of its biomass correlated with the rate of weight loss of the microplastics. Within 14 days it reduced microplastic by 43%. Plastic polymers contained in the test media were used as energy sources for the fungus. Based on FTIR-ATR analysis, it was known that *Z.maritimum* incubated in a medium that did not contain microplastic decreased lipidic and proteic contents **(Paço *et al*., 2017)**. The fungus used the components as its energy sources along with nutrition decreasing in the medium **(Prasad and Ghannoum, 1996; Paço *et al*., 2017)**. The limited nutrition in the medium encouraged the fungus to produce intracellular proteolytic enzymes to utilize the protein as its energy source **(McIntyre *et al*., 2000; Nitsche *et al*., 2012; Paço *et al*., 2017)**. Meanwhile, *Zalerion maritimum* incubated in a medium containing PE microplastics used the polymers as its energy **(Paço *et al*., 2017)**. Two plastic degrading fungi also isolated from plastic cups and PE bags buried in mangrove soils including *A. glaucus* and *A.niger* were tested for their degradation ability. In shaking culture with an incubation period of 1 month, *A.glaucus* reduced the weight of PE bags by 28.80% and plastic cups around 7.26%. Meanwhile, *A.niger* reduce PE bags about 17.35% and plastic cups by 5.54% **(Kathiresan, 2003)**.

Chaetomium globosum also reported as PE degrading fungi. The degradation ability of PE by this fungus catalyzed by laccase and manganese peroxidase. Manganese peroxidase activity was higher compared to laccase in the biodegradation of PE **(Sowmya *et al*., 2014)**. Based on the degradation activity analyzed by FTIR, it was known that after the autoclaved PE degraded by *Chaetomium globosum,* the used medium contained several components including carboxylic acids, aldehydes, alcohols, esters, and aromatic compounds. In PE plastic previously exposed to UV light, there were carboxylic acids, aldehydes, aromatic compounds, alcohols and esters, alkyl halides, and alkenes **(Sowmya *et al*., 2014)**. FTIR analysis detected functional groups from plastic degradation processes including ketones, aldehydes, carboxylic acids, and others **(Verma and Gupta, 2019)**.

Sangale *et al*. (2019), obtained two plastic degrading fungi isolated from the *Avicennia marina* rhizosphere. They were *Aspergillus terreus* MANGF1/WL and *Aspergillus sydowii* PNPF15/TF. Withing the 60-day incubation, *Aspergillus terreus* MANGF1/WL was able to reduce the plastic weight by 50% at pH 5.0. Whereas *Aspergillus sydowii* PNPF15 / TF degraded plastic samples about 94% within the same incubation time, at pH 3.5. Moreover, **Alshehrei (2017)** also obtained some LDPE plastic degrading fungi isolated from the Red Sea. They were *A. niger*, *A. flavus*, *A. terreus*, *A. fumigatus*, and *Penicillium* sp. with the degradation percentage of 19.5%, 16.2%, 21.8%, 20.5%, and 43.3%, respectively.

Some PUR plastic degrading fungi were isolated from plastic debris floating on the shoreline. The degradation ability of PUR plastics by these fungal isolates was tested using agar media containing the plastic polymers. PUR was spread evenly in the agar medium. The ability of plastic degradation was marked by the presence of a clear zone around the growing fungi colonies formed on the surface of the medium after incubated for 3 weeks. Fungi that were capable to form clear zones in the polyurethane containing medium were *Cladosporium cladosporioides*, *Xepiculopsis graminea*, *Penicillium griseofulvum*, and *Lepthosphaeria* sp. Among these four isolates, *C. cladosporoides* was known to have the highest polyurethane adhesion ability that could be seen from the clear zone formed more than the other isolates. Besides, several cultures of fungi collections were also tested for their ability to degrade PUR plastics. Some collection cultures degraded PUR were *Pestalotiopsis microspora*, *Agaricus bisporus*, and *Marasmius oreades* **(Brunner *et al*., 2018)**.

Plastic-Degrading Algae

Algae, microorganisms living in the aquatic environment could be used in plastic waste bioremediation to reduce the amount of plastic waste which pollutes the aquatic environment especially microplastics. Algae are living things that are scattered in various habitats. Algae can be found in rivers, lakes, ponds, swamps, and other habitats. Some algae species are also found in stems, soil, rocks, ice, and even snow. Some of them associated with other living creatures **(Pareek and Srivastava, 2008; Sharma *et al*., 2014)**.

Algae are potential environmental bioremediation agents. They can be used in reducing BOD and reducing the concentration of N and P in the aquatic environment. These organisms are also able to reduce coliforms in the aquatic environment as well as absorbing heavy metals. Besides being used as bioremediation agents, algal biomass can be used in producing biofuels, composting, producing methane and fine chemical, and food sources for various aquatic organisms **(Abdel-Raouf *et al*., 2012)**. Algae are also potentially used as plastics biodegradation agents. Some groups of algae found on the surface of PE bags obtained from solid domestic sewage disposal sites of Silchar Town, Assam, India. The algae were belonging to Cyanophyceae, Chlorophyceae and Bacillariophyceae. Some Cyanophyceae were *Anabaena* spp., *Aphanothece microscopica*, *Arthospira plantensis*, *Calothrix* spp., *Hydrocoleum* sp., *Lyngbia cinerescens*, *Nostoc* spp., *Oscillatoria* spp., *Phormidium* spp., and *Spirullina major*. The Chlorophyceae were consisting of *Chlorella* sp., *Closterium* spp., *Cosmarium* spp., *Oedogonium* sp., *Pitophora* sp., *Scenedesmus quadricauda*, *Stigeoclonium tenue*, and *Spirogyra* sp. Meanwhile, Bacillariophyceae were *Anomoeoneis* sp., *Fragilaria* sp., *Gyrosigma* sp., *Navicula* spp., *Nitzchia* spp., *Pinnularia* spp., and *Synedra tabulata* **(Sarmah and Rout, 2018).**

Some algae have been reported to be able to degrade Polycyclic Aromatic Hydrocarbons (PAHs). Cyanophyta and microalgae have three different pathways to overcome these harmful pollutants. Algae adsorb PAHs on the surface of their cells, they also adsorb these cancer-causing pollutants into their cells, and the third way is to transform these PAHs catalyzed by various enzymes. The transformation of PAHs catalyzed by various enzymes is considered as the most effective way to overcome these pollutants **(Semple *et al*., 1999; El-Sheekh *et al*., 2012; Aldaby and Mawad, 2018)**.

Two species of microalgae including *Oscillatoria* sp. and *Chlorella* sp. have been reported about their ability to degrade pyrene (PY), a hazardous additive of plastics. Within 30 days, *Oschillatoria* sp. degraded pyrene about 95%, and *Chlorella* sp. degraded it about 78.7% using BG 11 medium added with pyrene as much as 50 mg/L. Both algae were able to degrade 100% of pyrene in the concentrations of 10 and 30 mg/L **(Aldaby and Mawad, 2018)**. *Chlorella* did not use organic components as its carbon source but degraded these components during the detoxification process **(Subashchandrabose *et al*., 2017; Aldaby and Mawad, 2018)**. It produces higher carotenoid pigments along with a higher concentration of PY contained in the medium (**Aldaby and Mawad, 2018)**.

Suseela and Toppo (2007), found algal biofilms on the surface of PE plastic debris submerged underwater in the Uttar Pradesh area. The plastic which was colonized by the algae suffered damage, changed in physical strength, and disintegrated. The plastic damages were closely related to the biodegradation process by the algal communities **(Suseela and Toppo (2007).** Microalgae formed on microplastics sank them to the bottom of the aquatic environment. **Marc *et al*. (2015)**, studied the effect of *Chaetoceros neogracile* and *Rhodomonas salina* aggregates on the movement of microplastics in the columns or water bodies. The aggregates formed by *C.neogracile* on microplastic surfaces sank faster than other microalgae. Its aggregate was larger and thicker. It was known that the movement of microplastics colonized by these microalgae reached tens to hundreds of meters per day.

Microplastics ranging from 1 to 5 nm, **(Lee *et al*., 2013; Khoironi *et al*., 2019)** are appropriate as carbon sources for many microorganisms including microalgae. Microalgae form biofilms on plastic surfaces damaging the plastic surfaces (Khoironi *et al*., 2019). A total of 15 algal biofilm consisting of *Chaetophora*, *Cooleochaete scutata*, *Coleochaete soluta*, *Aphanochaete*, *Gloeotaenium*, *Oedogonium*, *Oocystis*, *Oscillatoria*, *Phormidium*, *Chroococcus*, *Aphanoteche*, *Fragillaria*, *Cocconis*, *Navicula* and *Cymbella* formed on the surface of polythene-type plastic submerged in water damaged the plastic polymer surfaces **(Suseela and Toppo, 2007)**. Cyanobacteria and green algae will produce exopolysaccharides (EPS) around their cells or filaments **(Kumar *et al*., 2018),** which facilitate their attachment to substrats **(Vinagre *et al*., 2020)**. The presence of EPS provides the ideal environment for microalgae and encourages the degradation of many polymers **(Ford and Mitchell, 1990; Suseela and Toppo, 2007)**.

Kumar *et al*. (2017), successfully isolated blue-green algae (Cyanophyceae), green algae (Chlorophyceae), and diatoms (Bacillariophyceae) from three different regions around Chennai, India. The green microalga successfully isolated was *Scededesmus dimorphus*, the blue-green alga was *Anabaena spiroides*, and the diatom was *Navicula pupula*. The isolation was carried out from polyethylene plastic bags discharged in freshwater on the edge of the town. They damaged the surface of polyethylene. **Sharma *et al*. (2014)**, obtained 10 algal species potentially degrade polythene plastics. They belonged to 7 orders and 9 families, identified as *Amphora ovalis*, *Chlorella vulgaris*, *Closterium costatum*, *Microcystis aeruginosa*, *Monaraphidium contortum*, *Navicula cuspidata*, *Oscillatoria tenuis*, *Phormidium tenue*, *Scendesmus acuminatus*, and *Selanestrum minutum*. Furthermore, **Khoironi *et al*. (2019)**, studied the ability of *Spirulina* sp. in degrading plastic polymers. It was incubated in the liquid media containing micro-sized PP and PET separately for 112 days of incubation. Based on the tensile strength analysis, PET plastic tensile value decreased about 0.9939 MPa/day. While PP tensile strength was decreased about 0.1977 MPa/day. While the Energy Dispersive X-ray spectroscopy (EDX) analysis showed that there was a carbon reduction in PET around 48.61% and 36.7% in PP. *Anabaena spiroides*, *Scededesmus dimorphus*, and *Navicula pupula* showed biomass growth on medium containing low-density polyethylene plastic sheets. Of the three microalgae, *Anabaena spiroides* had the highest biomass growth. This can be attributed to the fact that filamentous blue-green algae produced more sticky biofilms than the other two types of microalgae. The percentage of plastic degradation carried out by *Anabaena spiroides* was 8.18%. Whereas *Scededesmus dimorphus* was 3.74% and *Navicula pupula* was 4.44% **(Kumar *et al*., 2017)**.

There is coordination between many microbes in the process of breaking down and degrading plastic polymers. Algal biofilms on the plastic surfaces trigger the plastic biodegradation process. Environmental factors also involved in the biodegradation of plastic polymers as UV light initiates the biodegradation process. The presence of other microorganisms such as bacteria will increase the biodegradation rate of the polymers **(Seneviranlne *et al*., 2006; Suseela and Toppo, 2007)**.

THE COMPARISON OF PLASTICS BIODEGRADATION RATE BY MICROORGANISMS

Based on the data compiled in table 1 above, it can be seen that biodegradation of plastic waste can be carried out by microorganisms including bacteria, fungi, and algae. These microorganisms can reduce the weight of plastic samples tested under certain conditions. Based on these data, fungi have an effective biodegradation rate of plastic waste. The highest biodegradation of PE plastic was carried out by *Aspergillus sydowii* PNPF15/TF with a weight reduction of 94% within 60 days **(Sangale *et al*. 2019).** The marine fungus *Zalerion maritimum* was also able to reduce the weight of PE microplastic by 43% within 14 days **(Paco *et al*., 2017).** Fungal ability to degrade plastics is inseparable from its relatively fast growth rate **(Asiandu[b] *et al*., 2021).**

The biodegradation rate of PE bags carried out by fungi was also higher than bacteria. The fungus *Aspergillus glaucus* was able to reduce the weight of the plastic sample by 28%. Meanwhile, the highest reduction rate of plastic by bacteria was *Pseudomonas* sp. with a plastic weight reduction of 20.54%. However, the reduction rate of plastic PE cups was higher in the bacteria *Moraxella* sp. compared to fungi **(Kathiresan, 2003).** In plastic biodegradation, bacteria convert plastic polymers into dimers and oligomers which will be used by them as energy and carbon sources for their cell growth **(Chaurasia, 2020).**

Meanwhile, the optimum biodegradation of LDPE was carried out by fungi and algae. Also, the biodegradation of PY can be carried out effectively by algae **(Aldaby and Mawad, 2018).** Algae will colonize the plastic surface **(Chia *et al*., 2020)** and produce enzymes that will weaken the bonds in plastic polymers **(Bhuyar, 2018).** Algae will use plastic polymers as their carbon sources and then further convert them into the algal cell biomass, CO_2 and H_2O. The algal biomass can be used in biorefinery for various goals such as biofuel production **(Chia *et al*., 2020).**

GENES INVOLVED IN PLASTIC BIODEGRADATION

Several studies have reported the involvement of functional genes in plastic biodegradation. AlkB gene as in *Brevibacillus borstelensis*, *Pseudomonas putida*, and *Bacillus cereus*, codes the expression of functional enzymes that are important in plastic polymers biodegradation **(Muhonja *et al*., 2018)**. AlkB gene codes alkane hydroxylase enzymes catalyzing the oxidation process of polymers into alcohol. Then further oxidized by dehydrogenases to form fatty acids. They will be transported into the Krebs cycles **(Yoon *et al*., 2012; Muhonja *et al*., 2018)**.

Rani *et al*. (2019), reported several bacteria capable of producing the alkB gene, an important gene in plastic biodegradation. They were *Pseudomonas putida*, *Pseudomonas fluorescence*, and *Streptomyces* sp. **(Rani *et al*., 2019)**. Meanwhile, *Escherichia coli* BL21 which was introduced by the alkB gene was also able to degrade plastic polymers as much as 19.3% **(Yoon *et al*., 2012; Jacquin *et al*., 2019)**.

Also, Alkaline hydroxylase genes play a vital role in *Pseudomonas* sp. E4 for degrading PE about 28.6% within 80 days. *Pseudomonas* spp. have an inducible operon system initiating the formation of certain enzymes that are useful in unusual carbon sources metabolisms **(Sriningsih and Shovitri, 2015)**. Moreover, the osmY gene takes part in PUR degradation. The gene encodes the Y protein that can fuse with PUR esterase and drives the enzyme out of the cell **(Bokinsky *et al*., 2011; Kang *et al*., 2011; Ghosh *et al*., 2019)**.

CONCLUSION

Plastic waste accumulation is one of the serious environmental issues in the world. Plastic waste pollution in the aquatic environment threatens many marine organisms as well as causes bioaccumulation. This problem should be resolved immediately. Some conventional methods in overcoming this problem have been carried out, such as landfills and incineration. However, this method still releases side effects for the environment. Biodegradation is considered an appropriate method of handling plastic waste. Biodegradation is carried out using plastic degrading microbes such as bacteria, fungi, and algae. They can produce various enzymes catalyzing the breakdown of plastic polymers into simpler fragments. The fragments can be assimilated as their carbon and energy sources as well as decreasing the amount of plastic waste polluting the environment. Still, there are great opportunities for research on the optimization of various kinds of plastic-degrading microorganisms and their applications on a large scale.

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