

Microbial Biofilm of Plastic in Tropical Marine Environment and their Potential for Bioremediation of Plastic Waste

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ABSTRACT

Plastic debris has become a global problem due to its widespread distribution and accumulation in the marine environment. Indigenous bacteria in the marine environment are able to quickly contaminate plastic surface and assemble to form successional plastisphere-specific bacterial. The formation of microbial biofilms on the plastic surface can indirectly initiate the degradation of plastic polymers. The environmental conditions of the tropical region make the growth of microbial biofilms become faster. However, the study on the biodiversity of microorganisms in marine plastic debris is limited to the northern hemisphere, which includes subtropical and temperate regions. This review provides current studies of biodiversity and community structure of plastisphere in tropical environments, including bacteria and microalgae, and their potential to degrade the plastic polymer. A systematic literature search has been conducted using Scopus with different combinations of keywords. In addition, Google Scholar databases were also used to find more studies on some specific topics, including plastic degrading organisms. The climate-associated areas have been grouped according to the latitude of the study site into tropical, subtropical, and temperate latitudes. The microorganisms analyzed in this review are only bacteria, actinobacteria, and microalgae.

Keywords: biofilm, microorganism, plastic debris, tropical, marine environment, biodegradation.

INTRODUCTION

In modern society, plastic debris, both macro and micro-plastic, is extensively spread and accumulated in the marine environment and has become a global concern (Barnes et al., 2009; Van Cauwenberghe et al., 2015). Cosmetic microbeads, synthetic fibers from clothes, and many other products are micro-form fragments that directly propagate microplastics in the environment (Hwang et al., 2020). In 2016, more than 300 million metric tons of plastics had been produced including waste generation, and it has significantly risen worldwide (Geyer et al., 2017). In the environment, plastic debris degrades down to microplastic which high potentially enters the food chain directly and contaminates it through the degradation of chemical compounds (F. Galgani et al., 2015; Walther et al., 2018). In Indonesia, approximately 0.52 kg

of plastic waste was generated by each person per year, and more than 80% of that total failed to be managed. Plastic debris has an 11% proportion of the total, whilst the well-managed plastic waste corresponds to about 10% (Jambeck et al., 2015). Along 50 km of coastline with more than 180 million inhabitants, approximately 5.4 million metric tons of plastic debris was generated, of which unmanaged waste is about 60%; consequently, more than 1 million metric tons ultimately became marine debris (Syakti et al., 2017).

It was widely recognized that plastic debris poses a risk to marine life and human health (Iñiguez et al., 2017). Therefore, this issue has been included in national and international policies and legislation such as stated in SDGs 14 by United Nation-related life underwaters the aims to “by 2025, prevent and significantly reduce marine pollution of all kinds, particularly

from land-based activities, including marine debris and nutrient pollution” (Zafeiridou et al., 2018). In the marine environment, plastic will break down into smaller microplastic fragments (less than 5 mm in diameter) due to physical and chemical processes such as ultraviolet radiation, oxidation, and mechanical forces (Galgani et al., 2018). Microplastics are ubiquitous and ingested by an extensive range of organisms due to their sizes, possibly endangering the ecosystem and public health (Maes et al., 2017).

When plastic debris accumulates in the marine environment, it will serve as a new habitat for various microorganisms. It provides a durable substrate that can be colonized by microorganisms and supports the growth of microbial biofilms. The ecosystem that has evolved to live in plastic environments is known as the *plastisphere*. *Plastisphere* is formed by the association of microorganisms with organic and inorganic substances. Indigenous bacteria in the marine environment able to quickly contaminate microplastics and assemble successional *plastisphere*-specific bacteria (Galgani et al., 2018). The film layer formed on plastic debris can affect the surface of the material properties and influence the colonizing microorganisms, which begin when microbes first attach to the plastic debris substrate (Rummel et al., 2017). After forming the aforementioned, an adhesion of other microorganisms can be provided by first coating. Extracellular polymeric substances (EPS) produced by microorganisms will facilitate cell adhesion to surfaces, bind other organic compounds in the environment, facilitate the metabolism of microorganisms using their extracellular enzymes and provide physical and mechanical stability (Flemming & Wingender, 2010; L. Galgani et al., 2018). It forms a more complex biofilm (Lobelle & Cunliffe, 2011). In addition, microalgae such as *Diatomae*, *Cyanobacteria*, and *Coccolithophores* groups are the fastest and earliest microbial groups to attach and form colonies on plastic substrates (Casabianca et al., 2019; Eich et al., 2015).

The microorganisms colonizing plastics were co-influenced by multiple factors, such as environmental factors, including nutrient and exposure duration, polymer types, biogeographical, and seasonal variability exposure (Amaral-Zettler et al., 2015; Jiang et al., 2018; McCormick et al., 2014; Oberbeckmann et al., 2018). Their research showed that geographical location has a more significant influence on the formation of microbial biofilms. Microbial biofilm formation

is faster in tropical waters than in subtropical waters (Schlundt et al., 2020). It was known that the tropical region has the greatest level of biodiversity. Understanding the biodiversity of indigenous microorganisms attached to the plastic in the tropical region will certainly be a useful database for the development of several things, including the efforts to overcome the massive plastic pollution. However, the number of studies in tropical regions is lesser than in other regions. The study on the biodiversity of microorganisms in marine plastic debris is limited to the northern hemisphere, including subtropical and temperate areas (Roager & Sonnenschein, 2019). In this review, the current status about the studies of biodiversity and community structure of *plastisphere* in a tropical environment, including bacteria and microalgae, and their potential to degrade plastic polymer, was provided.

METHODS

The literature research was performed using Scopus with different combinations of the following keywords: plastic, macroplastic, microplastic, microorganism, bacteria, actinobacteria, plankton, *plastisphere*, biofilm, biofouling, degradation, marine, ocean, and coastal. In addition, the Google Scholar databases were also used to find more studies on some specific topics, including plastic-degrading organisms. The literature research was concluded on September 17th, 2021. The studies published after this date are not included in the reference list. Review articles were excluded and only research studies were included. Duplicate articles generated due to different keyword combinations were removed. The climate-associated areas were grouped according to the latitude of the study site into tropical (0–23.5°N or S), subtropical (23.5–40°N or S), and temperate latitudes (>40°N or S). The organisms analyzed in this review are only bacteria, actinobacteria and microalgae, whereas fungi are not included. Furthermore, the articles that contain the tropical region were analyzed.

PLASTISPHERE

Plastic will become a new habitat for microorganisms, known as *plastisphere* (Zettler et al., 2013). The plastic in marine waters will be exposed to UV radiation, heat, oxidation,

biodegradation, and mechanical disruption. This process causes the plastic to be cut into smaller sizes, either macro, micro, or even nanoplastic. Due to the air and ocean current conditions, plastics will be suitable substrates for the microbial community. The macroplastic waste in the waters is a durable substrate and provides an attachment site for various kinds of micro and macro-organisms in the seas. Indigenous bacteria in aquatic habitats will be able to attach and form a biofilm layer within about one week after plastic materials, such as PET (polyethylene terephthalate), PVC (polyvinyl chloride), and PS (polystyrene), submerged in water. In addition, the microalgae from the Diatom, Cyanobacteria, and Coccolithophores groups are among the fastest and earliest microbial groups to attach and form colonies on plastic substrates covered by microbial biofilms (Casabianca et al., 2019; Eich et al., 2015).

Biofilm microbial growth can cause damage to the plastic surface and initiate the polymer degradation process (Rummel et al., 2017). The plastic degradation process is a complex process involving a consortium of microorganisms in the biofilm. Biofilm composition on the plastic surface are influenced by several factors, including the type of plastic polymer, nutrition, geographic location, and environmental exposure (Amaral-Zettler et al., 2015; Jiang et al., 2018; McCormick et al., 2014; Oberbeckmann et al., 2018). Schlundt et al. 2020 showed that geographical location has a greater impact on the formation of microbial biofilms. Microbial biofilms formation is faster in tropical than sub-tropical waters (Schlundt et al., 2020).

BIODIVERSITY OF PLASTISPHERE IN TROPICAL ENVIRONMENT

Bacteria

Bacteria are the initiators of microorganisms and the most dominant organism in the plastisphere. The search of a literature study using the Scopus machine showed that 69 articles focused on microorganisms' biodiversity in plastic surfaces for both macro and microplastics during the last ten years. It is known that the tropical region has the greatest level of biodiversity. However, the number of papers on microorganisms' biodiversity in plastic surfaces is still low. Among these articles, 43.5% concern the studies on the biodiversity of microorganisms that colonize on

plastic in the temperate zone, followed by 42% percent in the subtropics and 14.5% in the tropical region. Although, the effect of latitude is still controversial in the diversity of microorganisms (Amend et al., 2013; Fuhrman et al., 2008; Ladau et al., 2013; Pommier et al., 2007; Raes et al., 2018). A study on the patterns of species richness along the latitudinal gradient from tropical waters of the US Virgin Islands (12.0°N) to the temperate waters off Cap Cod (41.5°N) found that tropical areas have a greater bacterial richness than temperate areas (Amaral-Zettler et al., 2015). However, the number of studies about the microbial biodiversity of plastisphere in tropical regions is the least, compared to other regions. A study of microbial biodiversity on a plastic surface in the tropical environment based on the natural existing biofilm and in situ experiment including one-time collection or time series sample collection was found (Table 1). SEM microscopy analysis of the surface of a naturally existing microbial biofilm in the Victoria Bay area of Brazil revealed that the plastisphere is inhabited by a variety of microorganisms, including bacteria, bacterial spores, filamentous fungus, and even diatom remains (Baptista Neto et al., 2019). Bacteria are the initiators of microorganisms and the most dominant organism in the plastisphere. The plastic with larger sizes can become new habitats for these organisms including cyanobacteria, diatoms, bryozoans, polychaetes and barnacles (Abed et al., 2020; Muthukrishnan et al., 2019; Schlundt et al., 2020).

Proteobacteria, Bacteroidetes, and Firmicutes were the dominant phyla found on microplastic surfaces on sandy beaches along the coast of Singapore. However, there are very significant differences in the dominant genera. The environmental factor influences the differences of dominant genera in these microplastics. The virgin area was dominated by *Brachymonas*, *Pseudomonas*, and *Sphingobium*, whereas *Arcobacter*, *Albimonas*, and *Bacteroides* dominated the moderately populated area. In the areas with a high impact of anthropogenic activities, the dominant bacteria are *Erythrobacter*, *Cohaesibacter*, and *Hyphomonas*. Interestingly, the number of dominant bacteria in pristine and moderate areas was only about 5–6% for each genus. Still, the *Erythrobacter* genera appeared in very high numbers, reaching 21% of the inhabitants of the plastisphere. *Erythrobacter* is known as a hydrocarbon-degrading bacteria (Curren & Leong, 2019). Generally, plastics are

derived from petroleum products and have a long carbon chain structure. Therefore, the attachment of *Erythrobacter* on the plastic surface is closely related to the structure of the plastic.

Bacterial biofilm formation consists of several stages, including attachment, initiated when bacteria extrude extracellular polymeric substances (EPS); early-stage biofilm which is indicated by microorganisms that are already irreversibly attached; and mature biofilm (Renner & Weibel, 2011). In contrast to the existing natural biofilms, microbial biodiversity at the same stage of biofilm formation can be identified and compared using in situ experiments. However, from several studies on biofilm formation using in situ experiment, it can be concluded that there are different community structures and formation rates between temperate and tropical zones. (Rajeev et al., 2019) stated that the dominance of primary colonizers at early-stage biofilms formation in the tropical zone is different from the temperate zone. These results are still in line with the indications of an early-stage biofilm that Proteobacteria dominate. The 72 hours-old biofilm from Kundakulam, India, has a Gammaproteobacteria as a dominant primary colonizer. In comparison, some studies in the temperate zone concluded that the Rhodobacteraceae family of Alphaproteobacteria dominates at the early phase of bacterial

biofilm formation (Dang et al., 2008; Jones et al., 2007; Schlundt et al., 2020). Schlundt et al. 2020 also mentioned that the biofilm of plastic in the tropical ocean has a high diverse bacterial community. Early-stage biofilm formation is not only dominated by Rhodobacteraceae but also other genera from Alpha and Gammaproteobacteria. The complexity of microbial community in tropical zone is followed by the attachment of organic material and EPS production that occur faster compared to other zones. In situ experiments using nine different plastic types were conducted in the Zhangziang mangrove area for three months. All taxa of bacteria in the mangrove rhizosphere were also found on plastic surfaces. However, plastic biofilms have higher diversity with more taxa of bacteria. The capability of the plastic to adsorb organic and inorganic compounds facilitates the metabolism of microorganisms in the plastisphere and creates similar conditions with sediment only 2–3 cm apart. (Xie et al., 2021) showed that biofilms succession in plastic surfaces is influenced by the surrounding environment and the chemotaxis ability of bacteria. Bacterial growth on the surface of polymers such as acrylonitrile butadiene styrene (ABS), polycarbonate, and polyethylene terephthalate is more influenced by environmental factors than the type of plastic. The first month in the initial phase of

Table 1. Study in microorganism community of plastisphere in the tropical marine environment

Geographical location	Habitat	Sampling methods	Plastic size	Plastic-type	References
Zhanjiang Mangrove National Nature Reserve	Mangrove rhizosphere	In situ experiment (30 and 90 days)	Microplastic (1-3 mm)	LDPE, PS, EPS, PP, PC, PA6, PVC, PET, ABS	(Xie et al., 2021)
Kudankulam, South Coast of India	Coastal	In situ experiment (3 days)	Macroplastic	PVC	(Rajeev et al., 2019)
Singapore	Beach	Natural collection	Microplastic	n/a	(Curren & Leong, 2019)
Tropical atlantic	Deep sea	Natural collection	Macroplastic	PE, PA, PVC	(Woodall Id et al., 2018)
Marina Shangri La, Muscat Oman	Enclosed bay	In situ experiment (20 and 80 days)	Macroplastic	OXO-PE, PE, PET	(Abed et al., 2020)
Coastal ocean surface of the Tropical Atlantic Ocean	Ocean	In situ experiment (7 and 14 days)	Microplastic	Polyethylene	(Schlundt et al., 2020)
Sea of Oman	Coastal	In situ experiment (30 days)	Macroplastic	PET, PE	(Muthukrishnan et al., 2019)
Tropical waters of the US Virgin Islands (12.0°N) to the temperate waters off Cape Cod (41.5°N)	Coastal and open ocean	Natural collection	Microplastic	n/a	(Amaral-Zettler et al., 2015)
Vitória Bay estuarine system (SVB), SE Brazil	Estuarine sediment	Natural collection	Microplastic	n/a	(Baptista Neto et al., 2019)
Guanabara Bay, Brazil	Mangrove, river, beach	Natural collection	Macroplastic	PE, PP, PET	(Silva et al., 2019)

biofilm formation showed that the dominance of microorganisms in the same kind of plastic was different according to the immersion location. On the other hand, Abed et al. 2020 showed that bacterial communities were replaced by specialists (plastic-specific) after biofilm maturation (>80 days) at Marina Shangri La, Muscat Oman. It was also indicated by the decrease in shared OTUs between several plastics.

Several studies have also shown that pathogenic bacteria can be associated with plastic debris. A predominance of Vibrionales was found in PS, PE, and PET polymers in Zhangjiang China (Xie et al., 2021). Meanwhile, Curren and Leong (2019) stated that a study on the coast of Singapore showed that the genus *Vibrio* in smaller percentage (less than 0.2%) was found in microplastics at any kind of beaches (pristine, moderate, and heavily populated). Silva et al. (2019) reported that 59 strains of the genus *Vibrio* were found inhabiting the plastisphere belonging to *V. mimicus*, *V. vulnificus*, and *V. cholerae*. Interestingly, no species of *V. Parahaemoliticus* was found, which is a *Vibrio* species in marine habitats. Meanwhile, Xie et al. (2021) identified *Vibrio parahaemolyticus* and *Escherichia-Shigella* in plastic surfaces collected from the mangrove areas in China. Spirochetes pathogenic bacteria were also found in polystyrene and PA6 surface (Xie et al., 2021).

The growth of microorganisms in plastic polymers is able to initiate the degradation of plastic polymers, affecting the density, buoyancy, and sinking rate of plastics (Rummel et al., 2017). Tropical mangrove areas being polluted by plastic debris can be a habitat for plastic-degrading microorganisms. Incubation of plastic material in the mangrove area for three months contributed a pitting on the plastic surface, i.e., low-density polyethylene, polyamide 6, and polyvinyl chloride. These results indicate a plastic degradation process carried out by microorganisms. Hydrocarbon degrading bacteria are known to be the dominant bacteria in the two types of plastic (Xie et al., 2021). The plastic type seems to affect the formation of bacterial biofilm shown by the dominance of *Erythrobacter* on the surface of polyamide 6 polymer (Xie et al., 2021), the occurrence of genera *Alteromonas* and *Zoogloea* that were only detected on the OXO-PE polymer (Abed et al., 2020), and highest relative abundance of Actinobacteria i.e. *Aciditerrimonas*, *Streptomyces* and *Ilumatobacter* on PET (Abed et al., 2020; Muthukrishnan et al., 2019). This polymer is composed

of aminocaproic acid, which has a carbonyl functional group. *Erythrobacter* is known to be a bacterium that can utilize the carbonyl group for its metabolism (Xie et al., 2021). Therefore, the attachment of these genera on the plastic surface is closely related to the plastic structure. In addition, hydrocarbon-degrading bacteria were also detected dominantly in the areas with the highest microplastic pollution along the Singapore coast (Curren & Leong, 2019). Generally, plastics are derived from petroleum products and have a long carbon chain structure. It increases the potential use of hydrocarbon-degrading bacteria to overcome the massive plastic pollution.

Benthic microalgae and invertebrates

Plastic debris provides a new surface for the growth of biofilm producers, such as bacteria and microalgae, which supported the growth of benthic invertebrates and later on formed a community consisting of both phototrophic and heterotrophic organisms (Eich et al., 2015). Diatoms were one of the first colonizer and also the most commonly abundant microalgae on the plastic debris in the ocean (Amaral-Zettler et al., 2020; Carson et al., 2013; Eich et al., 2015; Muthukrishnan et al., 2019; Reisser et al., 2014). As photoautotrophs, the diatoms tend to colonize the marine plastic debris that is exposed to the sunlight (Amaral-Zettler et al., 2020). Among the diatoms group, pennate diatoms, particularly of the genera *Mastogloia*, *Haslea*, *Frustulia*, *Diploneis*, *Ardissonea*, *Fragilaria*, *Protoraphis*, and *Thalassionema* were commonly found and abundant on the plastic debris in the Northeast Pacific Ocean (Carson et al., 2013). Similarly, a study on the plastic debris in the coastal areas around Australia found other diatom genera, such as *Nitzschia*, *Licmophora*, *Grammatophora*, *Amphora*, *Thalassionema*, *Microtabella*, *Achnanthes*, *Cocconeis*, *Navicula*, *Minidiscus*, and *Cymbella*, with the *Nitzschia* spp. as the most common and abundant genus living on the Australian plastic debris (Reisser et al., 2014). Similar diatoms genera were also reported on the marine plastic debris sampled from the coastal area of Northwest Mediterranean Sea (Masó et al., 2016). Aside of diatoms, calcareous coccolithophores species, such as *Calcidiscus leptoporus*, *Emiliania luxleyi*, *Coccolithus pelagicus*, *Calciosolenia* sp., *Gephyrocapsa oceanica*, *Umbellosphaera*

tenuis, and *Umbilicosphaera hulburtiana*, were also reported on the plastic debris from Southern Australian coast (Reisser et al., 2014). On the other hand, several benthic dinoflagellates genera, such as *Coolia*, *Ostreopsis*, *Prorocentrum*, and *Alexandrium* (*Alexandrium taylori*), were reported from plastic debris in the coast of Costa Brava, northeastern Spain (Masó et al., 2003) and Northwest Mediterranean Sea (Masó et al., 2016). Additionally, filamentous cyanobacteria are often present on the surface of marine plastic debris, although some studies, such as (Masó et al., 2003), (Reisser et al., 2014), (Masó et al., 2016), and (Schlundt et al., 2020), did not perform any taxonomic identification on this particular group. Even so, Zettler et al. (2013) reported the presence of Operational Taxonomic Unit (OTU) of two filamentous cyanobacteria genera from plastic debris, which were *Phormidium* and *Rivularia* in their research in North Atlantic Sub-tropical Gyre. Similarly, a study by (Bryant et al., 2016) on the marine plastic sampled from North Pacific Sub-tropical Gyre between Hawaiian Islands and California coast reported three filamentous cyanobacteria genera, which were *Phormidium*, *Rivularia*, and *Leptolyngbya*. A more detailed list of microalgae taxa reported colonizing the surface of marine plastic debris both in the coastal and oceanic systems are shown in Table 2.

On the other hand, benthic invertebrates, such as species from the taxa group of bryozoans, lepadomorph barnacles (*Lepas*), marine insect (*Halobates*), Asellote isopods, and marine worms were reported on drifted plastic debris sampled around the coastal waters of Australia (Reisser et al., 2014). A study on the rafting invertebrates on the marine plastic debris by Goldstein et al. (2014) in the Eastern and Western Pacific listed 11 phyla consisting of 95 identified taxa; the most abundant invertebrates were from the phylum Arthropoda, Mollusca, and Cnidaria. About 70 invertebrates taxa in Goldstein et al. (2014) study were known as common rafting invertebrates, such as barnacles (*Lepas*) and membraniporid bryozoans. On the other hand, about 40 invertebrates taxa on the plastic debris in the Eastern and Western Pacific were suspension feeders, about 20 taxa were omnivores, and the rest were grazer, predator, borer, and parasites (ecto- and endoparasite) (Goldstein et al., 2014). Several other predatory ciliates, such as choanoflagellates, *Ephelota*, and other suctorian ciliates, were reported as part of the plastisphere

community in the oligotrophic oceanic ecosystem (Amaral-Zettler et al., 2020).

POTENTIAL CANDIDATE FOR BIOREMEDIATION

Substrate availability, surface characteristics, substrate form, and polymer molecular weight all contribute to the complex biodegradation process. Chemical, physical, or biological degradation can occur naturally. Microorganisms will act as effective bioremediation agents, contribute to the biological degradation process (Ammala et al., 2011; Harrison et al., 2018). There have been several studies on the use of microorganisms as bioremediation agents for plastic degradation. In bioremediation, microorganisms such as bacteria, actinomycetes, microalgae, and fungi, play a significant role. Plastic polymer, specifically petroleum-based plastic, show great promise for decomposition into monomers using bioremediation (Montazer et al., 2020). Microorganisms can biodegrade plastics and alter their physical qualities. In order to lessen plastic pollution in the environment, genetic engineering of microorganisms can enhance the enzymes produced by microorganisms to increase their ability to break down plastic waste into carbon dioxide.

Bacteria

Plastic waste is generally found in the areas where the population is quite dense, such as in coastal areas. Beaches have a high population density; thus, the abundance of plastic waste will also be high because it is influenced by the anthropogenic pressure. Proteobacteria and Bacteroides are two types of bacteria found in bacterial communities, and their distinctions vary by location. In previous studies, the characteristics of the bacterial community on the surface of marine microplastics revealed the same types of microorganisms (Amaral-Zettler et al., 2015; Oberbeckmann et al., 2016). *Erythrobacter* is more abundant in the areas with high levels of pollution. Plastic waste has been found to carry harmful bacteria such as *Vibrio* (Oberbeckmann et al., 2014) and *Pseudomonas* (Curren & Leong, 2019). When plastic debris enters the water, it immediately develops a biofilm on the surface. Biofilms are made up of individual or consortia microbial species that are capable of degrading

Table 2. Reported microalgae genera on drifted marine plastic debris from the taxa group of diatoms, dinoflagellates, coccolithophores and filamentous cyanobacteria

Genus	Geographical region/location	References
Diatoms		
Achnanthes	North Western Mediterranean Sea; Coastal Australia	Maso et al., 2016; Reisser et al., 2014
Amphora	North Western Mediterranean Sea; Coastal Australia; Sea of Oman	Maso et al., 2016; Reisser et al., 2014; Muthukrishnan et al. 2019
Ardissonea	North East Pacific Ocean	Carson et al., 2013;
Ceratoneis	North Western Mediterranean Sea	Maso et al., 2016;
Chaetoceros	Coastal Australia; North Atlantic Sub-tropical Gyre	Reisser et al., 2014; Zettler et al., 2013
Cocconeis	North Western Mediterranean Sea; Coastal Australia	Maso et al., 2016; Reisser et al., 2014
Cyclotella	North Western Mediterranean Sea; Coastal Australia	Maso et al., 2016; Reisser et al., 2014
Cymbella	Coastal Australia	Reisser et al., 2014;
Diploneis	North Western Mediterranean Sea; North East Pacific Ocean	Maso et al., 2016; Carson et al., 2013;
Fragilaria	North East Pacific Ocean	Carson et al., 2013;
Fragilariopsis	North Western Mediterranean Sea	Maso et al., 2016;
Frustulia	North East Pacific Ocean	Carson et al., 2013;
Grammatophora	Coastal Australia	Reisser et al., 2014;
Haslea	North East Pacific Ocean; Coastal Australia	Carson et al., 2013; Reisser et al., 2014
Licmophora	North Western Mediterranean Sea; Coastal Australia; Sea of Oman	Maso et al., 2016; Reisser et al., 2014; Muthukrishnan et al. 2019
Mastogloia	North Western Mediterranean Sea; North East Pacific Ocean; Coastal Australia; Sea of Oman	Maso et al., 2016; Carson et al., 2013; Reisser et al., 2014; Muthukrishnan et al. 2019
Microtabella	Coastal Australia	Reisser et al., 2014;
Minidiscus	Coastal Australia	Reisser et al., 2014;
Navicula	North Western Mediterranean Sea; Coastal Australia; North Atlantic Sub-tropical Gyre; Sea of Oman	Maso et al., 2016; Reisser et al., 2014; Zettler et al., 2013; Muthukrishnan et al. 2019
Nitzschia	Coastal Australia; North Atlantic Sub-tropical Gyre; Sea of Oman	Reisser et al., 2014; Zettler et al., 2013; Muthukrishnan et al. 2019
Pleurosigma	Coastal Australia	Reisser et al., 2014;
Protoraphis	North East Pacific Ocean	Carson et al., 2013;
Sellaphora	Coastal Australia; North Atlantic Sub-tropical Gyre	Reisser et al., 2014; Zettler et al., 2013
Stauroneis	Coastal Australia; North Atlantic Sub-tropical Gyre	Reisser et al., 2014; Zettler et al., 2013
Striatella	North Western Mediterranean Sea	Maso et al., 2016;
Thalassionema	North Western Mediterranean Sea; Coastal Australia	Maso et al., 2016; Reisser et al., 2014
Thalassiosira	North Western Mediterranean Sea; Coastal Australia	Maso et al., 2016; Reisser et al., 2014
Thalassiothrix	North Western Mediterranean Sea	Maso et al., 2016;
Dinoflagellates		
Alexandrium	Coastal Australia; Northeast Spain	Reisser et al., 2014; Maso et al., 2003
Ceratium	Coastal Australia; North Western Mediterranean Sea	Reisser et al., 2014; Maso et al., 2016
Coolia	Northeast Spain; North Western Mediterranean Sea	Maso et al., 2003; Maso et al., 2016
Dinophysis	North Western Mediterranean Sea	Maso et al., 2016
Heterocapsa	North Western Mediterranean Sea	Maso et al., 2016
Ostreopsis	Northeast Spain	Maso et al., 2003;
Pentapharsodinium	North Western Mediterranean Sea	Maso et al., 2016
Prorocentrum	Northeast Spain; North Western Mediterranean Sea	Maso et al., 2003; Maso et al., 2016
Coccolithophores		
Calcidiscus	North Western Mediterranean Sea; Coastal Australia	Maso et al., 2016; Reisser et al., 2014
Calciosolenia	Coastal Australia	Reisser et al., 2014
Calyptrosphaera	North Western Mediterranean Sea	Maso et al., 2016
Coccolithus	Coastal Australia	Reisser et al., 2014
Coronosphaera	North Western Mediterranean Sea	Maso et al., 2016
Emiliania	North Western Mediterranean Sea; Coastal Australia	Maso et al., 2016; Reisser et al., 2014
Gephyrocapsa	Coastal Australia	Reisser et al., 2014
Helicosphaera	North Western Mediterranean Sea	Maso et al., 2016
Rhabdosphaera	North Western Mediterranean Sea	Maso et al., 2016
Scyphosphaera	North Western Mediterranean Sea	Maso et al., 2016
Syracolithus	North Western Mediterranean Sea	Maso et al., 2016
Syracosphaera	North Western Mediterranean Sea	Maso et al., 2016
Umbellosphaera	Coastal Australia	Reisser et al., 2014
Umbilicosphaera	North Western Mediterranean Sea; Coastal Australia	Maso et al., 2016; Reisser et al., 2014
Zygosphaera	North Western Mediterranean Sea	Maso et al., 2016
Filamentous Cyanobacteria		
Leptolyngbya	North Pacific Sub-tropical Gyre	Bryant et al., 2016
Phormidium	North Atlantic Sub-tropical Gyre; North Pacific Sub-tropical Gyre	Zettler et al., 2013; Bryant et al., 2016
Rivularia	North Atlantic Sub-tropical Gyre; North Pacific Sub-tropical Gyre	Zettler et al., 2013; Bryant et al., 2016

polymers (Debroas et al., 2017). According to Curren & Leong (2019), plastic waste samples contain 35 dominating species. Rhodobacterales, Oceanospirillales, and Burkholderiales are some of the most common orders of bacteria in the plastisphere. Primary colonizers and secondary consumers are thought to account for the majority of biofilm in inhabitants; nevertheless, species within this varied community could play a

key role in the plastic degrading pathway. Many studies have been conducted in order to identify the greatest bacterial candidates for degrading plastics. However, the research on marine bacteria that can break down microplastics effectively is still limited, particularly in the tropics. In this review, the Publish or Perish program is used to conduct a review of the studies on the bacteria that can degrade plastics, particularly in the

Table 3. Study of biodegradable plastic from marine bacteria in tropical and subtropical areas

Location	Bacteria	Type of plastic	Result	Cites
Tropical				
Sea water of Bay of Bengal near Puri, India	<i>Alicalgens faecalis</i>	Polyethylene bags (BP: black plastic; WP: white plastic)	It was found that LNDR-1 (<i>Alcaligenes faecalis</i>) had a better decay rate of $15.25 \pm 1\%$ and $21.72 \pm 2.1\%$ for black and white plastic bags respectively in 10 weeks without prior oxidation as compared to <i>S. marcescens</i> .	(Nag et al., 2021)
Tamil Nadu, India	<i>Bacillus</i> spp. and <i>Pseudomonas</i> spp	HDPE	The identification of efficient HDPE degrading isolates confirms that most of the bacterial isolates belong to the genus <i>Bacillus</i> spp. and <i>Pseudomonas</i> spp.	(Sangeetha et al., 2019)
Dumpsites of Gulf of Mannar	<i>Arthrobacter</i> sp. and <i>Pseudomonas</i> sp.	HDPE	After 30 days of incubation, <i>Arthrobacter</i> sp. lost nearly 12% of its weight, while <i>Pseudomonas</i> sp. lost 15% of its weight.	(Balasubramanian et al., 2010)
Magrove area in Malayasia	<i>Rhodococcus</i> sp. and <i>Bacillus</i> sp.	Polypropelene	The weight loss was 6.4% by <i>Rhodococcus</i> sp. strain 36 and 4.0% by <i>Bacillus</i> sp. strain 27 after 40 days of incubation	(Auta et al., 2018)
Mangrove area in Peninsular Malaysia	Consortia bacteria from mangrove sediment	Polyethylene, polyethylene terephthalate, polypropylene, polystyrene	38 species was isolated from mangrove sediment reduced polyethylene (27.9%); polyethylene terephthalate (24%), polypropylene (19.5%), polystyrene (15%)	(Syamimi, 2018)
Subtropics				
The Soyang river and the shores of Busan and Jeju Island	<i>Bacillus</i> sp. JY14	Polyhydroxybutyrate	Approximately 98% PHB degradation within two weeks	(Cho et al., 2021)
Intertidal of Zhanziang Bay, China	<i>Mycolicibacterium phocaicum</i>	Di-(2-ethylhexyl) phthalate (DEHP)	<i>Mycolicibacterium phocaicum</i> could rapidly degrade DEHP and achieve complete degradation of DEHP (50 mg/L) in 48 H, when Tween 80 was added as solubilizing agent	(Ren et al., 2021)
Mediterranean Sea	<i>Alcanivorax borkumensis</i>	Low Density PolyEthylene (LDPE), PolyEthylene Terephthalate (PET) and PolyStyrene (PS)	<i>Alcanovorax borkumensis</i> had ability to form thick biofilms specifically on LDPE and to degrade this petroleum-based plastic. After 96 h and 144 h a significantly higher percentage of biofilm associated bacteria was observed on LDPE, 68.5% and 68.1% respectively.	(Delacuvellerie et al., 2019)
Dameisha coastline, China	<i>Rhodococcus ruber</i>	Di-(2-ethylhexyl) phthalate (DEHP)	Strain <i>Rhodococcus ruber</i> completely degraded 100 mg/L DEHP within three days (pH 7.0, 30 °C); Furthermore, <i>Rhodococcus ruber</i> metabolized initial concentrations of DEHP ranging from 0.5 to 1000 mg/L. Especially, YC-YT1 degraded up to 60% of the 0.5 mg/L initial DEHP concentration	(Yang et al., 2018)
Microcosm in lab experiment	Marine consortia bacteria	Low-density polyethylene (LLDPE)	The acclimated consortia (indigenous and bioaugmented) reduced more efficiently the weight of PE films in comparison to non-acclimated bacteria	(Syranidou et al., 2017)
Coastal seawater, Suruga Bay, Japan	<i>Shewanella</i> spp.	A poly[(R)-3-hydroxybutyrate] [P(3HB)]	The isolate was able to grow at temperature 30-37°C; however, the optimum isolate for degradation of P(3HB) was 15°C	(Sung et al., 2016)
Sediment samples of the coast India	<i>Vibrio parahaemolyticus</i> and <i>Vibrio alginolyticus</i>	Polyvinyl alcohol-low linear density polyethylene (PVA-LLDPE)	Results indicated that relatively 20 % decrease in tensile strength of the film could be achieved with 25 and 30 % blend of PVA in the PVALLDPE plastic film compared to other ratios	(Raghul et al., 2014)
Coastal seawater, Okinoshima Park, Chiba,	<i>Pseudomonas pachastrellae</i>	Polyester poly(ε-caprolactone) (PCL)	<i>Pseudomonas pachastrellae</i> JCM12285T ; Strain TKCM 64 degraded PCL film at a rate of 1.39 ± 0.09 mg cm ⁻² .day ⁻¹ .	(Suzuki et al., 2018)

tropics; from the data obtained, only a few studies have been conducted, as shown in Table 3. Several research results were discovered on the marine bacteria originating from the tropics in degrading microplastics, including *Alicagens faecalis* (Nag et al., 2021), *Bacillus* spp, *Pseudomonas* spp (Auta et al., 2018; Balasubramanian et al., 2010; Sangeetha et al., 2019), *Arthrobacter* sp. (Syamimi, 2018).

The community of plastic waste-degrading bacteria in the tropics has some similarities to those occurring in the subtropics. The bacteria from the genera *Bacillus*, *Pseudomonas*, and *Rhodococcus* are found in tropical and subtropical regions (Auta et al., 2018; Balasubramanian et al., 2010; Cho et al., 2021; Sangeetha et al., 2019; Suzuki et al., 2018; Yang et al., 2018). This can be the basis for the candidate bacteria that can degrade plastic waste. After 30 days of incubation, the bacteria from the genus *Pseudomonas* sp. can reduce the weight of HDPE by 15%, according to Balasubramanian, et al. (2010). Meanwhile, bacteria *Bacillus* sp. isolated from tropical mangrove sediments can reduce the weight of Polypropylene granules by 4% (Auta et al., 2018). *Bacillus* sp. from the subtropics might breakdown Polyhydroxybutyrate (PHB) about 98% after two weeks, according to Cho, et al. (2021). This indicates that the bacteria belonging to the *Pseudomonas* sp. genus are present and *Bacillus* sp. are the best microorganisms for degrading microplastics, particularly in the tropics.

Actinobacteria

Among plastic polymer biodegraders, the most active taxa are fungi and actinobacteria (Tosin et al., 2012). Actinobacteria, often known as actinomycetes, are Gram-positive bacteria that have a high GC content. These bacteria can be found in a variety of ecological habitats, including soils, freshwater, and marine environments (Valan et al., 2012). Actinobacteria, one of many microorganisms, has been found attached to the marine environment plastic waste surface but seldom reported from tropical areas. On the basis of the literature study conducted, from 61 articles, sorted by 12 articles, only one article reported the presence of plastics-degrader actinobacteria in tropical environments. In contrast, most were reported from temperate regions.

Most actinobacteria are known as bioactive compounds producers, such as anticancer, antimicrobial, antifungal, and others, but recently those

microorganisms have also been found to degrade complex polymers (Goodfellow, 1983; Sharma et al., 2014). Besides being known as a producer of many secondary metabolites, the marine actinobacteria are also reported for the degradation of oil spills, chlorobenzenes, aliphatic and polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), phenols, n-alkanes, heavy metal compounds, and plastic materials (Rathore et al., 2021). The actinobacteria are also reported to biodegrade various pollutants, such as pesticides, plastics, rubber, heavy metal, and other organic matters (Diez, 2010; Tseng et al., 2007). Actinobacteria are known to decompose a large number of biomolecules (lignin, cellulose, and hemicellulose) and to metabolize recalcitrant polymers such as long-chain n-alkanes (Lo Piccolo et al., 2011), xenobiotics (Borozan, 2013), pesticides (Alvarez et al., 2017), and rubber (Shivlata & Satyanarayana, 2015).

The predominant genera of Actinobacteria in the degradation and bioremediation were reported by Rathore et al. (2021). They are *Rhodococcus*, *Nocardiosis*, *Streptomyces*, *Gordonia*, *Dietzia*, *Actinopolyspora*, *Amycolicococcus*, *Micrococcus*, *Arthrobacter*, *Salinispora*, *Micromonospora*, *Actinomadura*, *Streptosporangium*, *Streptomonospora*, *Prauserella*, *Pseudonocardia*, *Aeromicrobium*, *Marinactinospora*, and *Microbacterium*. The *Rhodococcus* sp. seem the most reported actinobacteria-degrading microplastics. The actinobacterium *Rhodococcus ruber*, for example, is reported as a plastic degrader (Andrady, 2011) and produces biofilm, which helps to improve degradation (Auta et al., 2018). Other *Rhodococcus* such as polyethylene (PE)-degrader actinobacteria by *Rhodococcus ruber* strain C208 (Sivan et al., 2006), *Rhodococcus rhodochrous* ATCC 29672 (Bonhomme et al., 2003), polystyrene (PS) - degrader *Rhodococcus ruber* (Mor & Sivan, 2008), and polypropylene (PP) - degrader *Rhodococcus* sp. strain 36 (Auta et al., 2018). The other actinobacteria have also been reported as plastics degraders, such as PE-degrader *Micrococcus* sp. (Kathiresan, 2003) and consortia of bacteria including actinobacteria (Nowak et al., 2011). *Microbacterium paraoxydans* was declared as polyethylene (PE)-degrader with nitric acid pretreatment (Rajandas et al., 2012). Hydrocarbon-degrading bacteria, such as *Alcanivorax*, *Marinobacter*, and *Arenibacter*, have been found to be potential agents in plastic degradation, with *Alcanivorax borkumensis* chosen as a significant player in LDPE degradation (Delacuvellerie et al., 2019).

The use of actinobacteria in plastics waste bioremediation has raised the hopes that the plastic problem will be solved in the future (Oliveira et al., 2020). The improvement was such that the *Rhodococcus ruber* of marine origin is reported to degrade plastic waste significantly. This organism can degrade 8% of dry weight of plastic waste within 30 days under in vitro conditions (Andrady, 2011). The use of *Rhodococcus ruber* strain C208, the initial signs of degradation appeared after only 16 days. *R. ruber* degraded 7.5 percent of the initial weight of the microplastic in only two months and could use PE as the sole carbon source (Sivan et al., 2006). *Amycolatopsis orientalis* expressed an extracellular PLA-degrading enzyme with high degrading activity, which resulted in the total degradation of the PLA powder within 8 hours. Additionally, the *Kibdelosporangium aridum* strain showed a high capacity for biodegradation, degrading almost 97 percent of the initial polymer. This strain formed several small pits across the PLA surface (Jarerat et al., 2003).

Some of the actinobacteria mentioned above are marine-derived actinomycetes. These revealed high polymer degradation, as well as polymer structural and chemical changes. Therefore, the marine actinomycete counterparts appear to be quite effective in using polymers as a sole carbon source, especially for PLA degradation (Oliveira et al., 2020). Most of the papers reported actinobacteria from the temperate zone, but only some studies informed plastics-degrader actinobacteria from a tropical area. Auta *et al.* (2018) investigated the growth response and mechanism of degradation of polypropylene (PP) by *Bacillus* sp. and *Rhodococcus* sp. isolated from mangrove sediments in Peninsular Malaysia. These bacteria and actinobacteria strains were able to thrive on PP microplastic, as indicated by the polymer mass reduction. After 40 days of incubation, *Rhodococcus* sp. lost 6.4 percent of its weight while *Bacillus* sp. lost 4.0 percent of its weight. Harshvardhan & Jha, (2013) reported sixty marine bacteria isolated from pelagic waters of the Arabian Sea coast, India, were screened for their ability to degrade low-density polyethylene; among them, *Kocuria palustris* M16, *Bacillus pumilus* M27 and *Bacillus subtilis* H1584 were positive and able to grow in a medium containing polythene as the sole carbon source.

Benthic microalgae

Marine microalgal taxa, particularly diatoms and cyanobacteria, are one of the first organisms that colonize a new substrate such as plastic debris. Those microalgae help the formation of biofilm by secreting polysaccharide substances that form Transparent Exopolymer Particles (TEPs) under turbulent conditions which help stabilize the biofilm and allow the diatoms or cyanobacteria cells to stick to the surface of the plastic debris (Casabianca et al., 2020; Ryabushko et al., 2021). However, whether the microalgae contribute directly towards the degradation of the plastic debris itself or not is still debatable. The microalgae were thought to contribute indirectly by promoting the growth of plastic degrading bacteria. The biofilm that formed with the help of microalgae and their metabolic waste could provide an additional substrate and nutrients for the bacteria that are capable of degrading some components of plastic, particularly the hydrocarbon compounds (Amaral-Zettler et al., 2020; Zettler et al., 2013). Meanwhile, the existence of bacteria on the biofilm could help provide essential nutrients and growth factors, such as vitamin B12, to the associated phototrophic microalgae (Amaral-Zettler et al., 2021). On the other hand, the biofilm that produced by microalgae and bacteria could prevent the plastic breakdown via reduced exposure to ultraviolet (UV) radiation (Masó et al., 2016; Schlundt et al., 2020). The additional weight of microalgae and other biofouling organisms also decreases the buoyancy and causes the plastic debris to sink faster to the aphotic zone and to the bottom of the ocean, which also reduces the degradation rate of the plastic itself (Eich et al., 2015; Smith et al., 2021).

CONCLUSIONS

The number of studies on microbial biodiversity of plastisphere in the tropical marine region is the least compared to the other regions. However, several studies have shown higher diversity and faster biofilm formation in tropical areas. The potential of microorganisms on plastic surfaces has not been studied further, although several studies have shown indications of the potential microorganisms as plastic degrading agents. The discovery of plastic degrading microorganisms

in the tropical areas is also still very rare. Future research needs to focus on using the omics approach to understand gene or enzyme secretion by microorganisms in a biofilm of plastic to find their function. In addition, the isolation of microorganisms and analysis of their potential as plastic degrading from tropical marine environments is an essential part of further research.

Acknowledgements

The study was fully funded by LIPI's CORE-MAP-CTI 2021–2022 (17/A/DK/2021).

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