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REVIEW ARTICLE

Marine Microbes and Plastic Debris: Research Status and Opportunities in the Philippines

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Marine plastics have been shown to affect all organisms across the trophic levels including the microbial communities, influencing their community assembly, composition, metabolic processes, and ecosystem functions. Thus, studying plastic-microbe interactions in the marine environment is important in understanding its implications alongside the growing issue of plastic pollution. The Philippines, despite being suggested as the third-largest contributor to marine plastic debris, currently does not have any existing national research programs on basic plastics research, resulting in our limited understanding of the extent and implications in the country. This paper then reviews the current status and knowledge of the plastic-microbe association focusing on how plastic surfaces serve as a new environment for marine microbes, how this system could become dispersal mechanisms of unwanted microorganisms, and how microbes possibly contribute to the biodegradation of plastics in the marine environment. These also translate to possible research opportunities for Filipino scientists to work on the topic.

Keywords: biodegradation, dangerous hitchhikers, microbes, microbial succession, plastic pollution, plastics

INTRODUCTION

Most studies on marine plastics and their implications on the environment are mainly focused on macroplastics (plastic pieces > 20 mm) and their effects on macroorganisms. However, plastics affect all trophic levels including the microorganisms (Worm *et al*. 2017), which are at the base of oceanic food webs. In fact, microbes are the first and the last group of organisms that interact with plastics. To date, only a few studies have been dedicated to understanding such interactions and associations [see Jacquin *et al.* (2019) and references therein], resulting in our limited understanding of the true extent and gravity of plastics pollution.

Due to their ubiquity and position at the base of the food web, microbes are also at the frontline of any changes occurring in the environment. Their widespread distribution and abundance in our oceans allow microbes to directly get into contact with the plastics immediately after being released into the sea, affecting the fate of the material (Rummel *et al.* 2017). The majority of macro- and microplastics are released from the terrestrial environment (*i.e.* dumpsites, residential areas, landfills), which are then transported through rivers and stormwater runoffs, and get deposited in beaches and other marine habitats (Schwarz *et al.* 2019). Other sources include ghost nets and other fisheries materials, shipping and transportation, and atmospheric outfall (Hardesty *et*

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al. 2017). The hydrophobic nature of plastic surfaces stimulates the rapid formation of the microbial biofilm, which then drives the succession of microorganisms (Reisser *et al.* 2014; Oberbeckmann *et al.* 2014). While out at sea and being exposed to the elements, degradation of the plastic material leads to physical fragmentation that produces smaller plastic segments called microplastics (Andrady 2015; Barnes *et al.* 2009). These floating plastics are either beached on the coastlines, ingested by marine life, or suspended in the surface of the ocean, and accumulating in gyres (Thevenon 2014; Eriksen *et al.* 2014; Hardesty *et al.* 2017). These are considered sinks for marine plastic debris. Microbes accumulate on the surfaces of floating plastic fragments resulting in changes in its buoyancy and are then vertically transported down the seafloor (Kooi *et al.* 2017) and the deep sea (Woodall *et al.* 2014), serving as other sinks for plastics (Schwarz *et al.* 2019). In the sediments, they undergo immediate deposition and colonization of sediment microbes (Harrison *et al.* 2014) – further undergoing physical deterioration, biodegradation, and/or permanent sequestration (Quero and Luna 2017), or get resuspended and ingested by marine organisms (Hardesty *et al.* 2017). Such environments could provide insights on the general fate of plastics in nature, and how its remineralization will affect ecosystem processes and even nutrient recycling. Ecologically, limited studies suggest that plastics could interfere with the community assembly, composition, and microbial metabolic processes, which would have direct implications for their ecosystem functions (Zettler *et al.* 2013). Surface colonization of highly buoyant materials could also become an efficient dispersal mechanism for pathogenic, harmful, and invasive species, allowing them to benefit from the micro-environment that forms in the plastic surface (*i.e.* biofilm) while waiting for the optimum condition to proliferate and eventually invade a new environment (Masó *et al.* 2003; Zettler *et al.* 2013). Biofilm-coated microplastics could also serve as a cue for grazing or predation (Vosshage *et al.* 2018) and, thus, facilitate plastics ingestion and transfer to higher trophic levels. In all of these scenarios, microbial organisms are undeniably playing a significant role. Thus, understanding the ecology and biology of the plastic-microbe interaction in the marine environment could also provide insights into the many uncertainties surrounding the issue of plastic pollution.

In the Philippines, several aspects of the ecology of plastics remain unexplored despite the country being the third-leading global potential contributor to marine plastics pollution (Jambeck *et al.* 2015). This has significant implications for our understanding of the full extent of the effects and consequences of this environmental issue on our marine resources and even public health. Since microbial organisms react rapidly to such changes, understanding their responses to plastics may then reveal insights on how biological communities are being affected by this looming ecological disaster. However, currently, there are no existing national full-blown research programs or scientific research framework dedicated to basic studies on plastics in the Philippine marine environments (Abreo 2018). Also, the current Harmonized National Research and Development Agenda (HNRDA) of the Department of Science and Technology (DOST 2017) does not specifically include plastics research in its marine science research priorities until 2022. The National Academy of Science and Technology during their 41st annual scientific meeting called on in their resolution that single-use non-biodegradable plastics should be phased out (NAST 2019). Further, limited published studies in the country were mainly on large marine vertebrate and mollusk ingestion, toxicology, or biodegradation in terrestrial and extreme environments (Table 1). Although these could be reflective of current shortcomings, it also provides several opportunities for Filipino scientists. Thus, here, we provide a brief review of the current status and knowledge of plastics-microbes associations focusing on the attachment and transport of microorganisms and their possible contribution to the eventual biodegradation of plastics. We also suggested research directions that may be of interest to local researchers. Lastly, we discussed possible directions to help us move forward and develop management strategies for plastics pollution.

KEY ISSUES

Plastics Surface as a New Microenvironment

Microbes in the environment often colonize surfaces via the production of a polymeric matrix or extracellular polymeric substance, which may either enhance the attachment of other microorganisms or the adsorption of nutrients (Donlan 2002). In the marine environment, plastic debris presents a novel substrate for the attachment of microorganisms. Microbes colonize the plastic's surface as early as several hours to a week upon its release (Dang and Lovell 2000; Lobelle and Cunliffe 2011), and later creating an environment different from the surrounding waters. The said microenvironment is now commonly referred to as the 'plastisphere' (Zettler *et al.* 2013). This also makes the microbial organisms the first biological groups that get into contact with plastic wastes. Dang and Lovell (2000) found bacteria affiliated with *Alteromonas* and *Rhodobacter* as primary and secondary colonizers on polyvinyl alcohol and polyurethane plastics. *Alteromonas*, under the class Gammaproteobacteria, are commonly associated with biofilm-forming (Dang and Lovell 2000) as well as hydrocarbonoclastic bacteria (Dussud

Table 1. Summary of plastics related research in the Philippines.

Environment	Organism	Interaction	References
Marine	Beaked whale (*Mesoplodon hotaula*)	Plastic ingestion	Abreo *et al.* 2016a
Marine	Green turtle (*Chelonia mydas*)	Plastic ingestion	Abreo *et al.* 2016b
Marine	Gastropod (*Nassarius pullus)*	Effect on foraging activity	Aloy *et al.* 2011
Marine	Mussel (*Mytilus galloprovincialis*)	Toxicological	Avio *et al.* 2015
Freshwater (hyperalkaline spring)	*Bacillus krulwichiae*, *B. pseudofirmus,* *Prolinoborus fasciculus*, and *Bacillus* sp.	Biodegradation	Dela Torre *et al.* 2018
Marine	Whale shark (*Rhincodon typus*)	Plastic ingestion	Abreo *et al.* 2019
Marine	Asian green mussel *(Perna viridis)*	Plastic ingestion	Argamino and Janairo 2016
Terrestrial (dumpsite)	Bacteria (*Kocuria kristinae, Dermacoccus nishinomiyaensis, Pseudomonas stutzeri, Acinetobacter haemolyticus*)	Biodegradation	Bolo *et al.* 2015
Terrestrial (forest)	Fungi (*Xylaria* sp.)	Biofilm formation, colonization, biodegradation	Abecia *et al.* 2019

et al. 2018). Similarly, *Rhodobacter* under the class Alphaproteobacteria is also surface-associated taxa (Dang and Lovell 2000). In the study of Dussud *et al.* (2018), they found hydrocarbonoclastic Gammaproteobacteria such as *Alcanivrax* sp., *Aestuariicella hydrocarbonica*, and *Marinobacter* sp. as the dominant early colonizers on different plastic substrates. Oberbeckmann and co-authors (2016) also found similar species in addition to biofilm formers such as Saprospiraceae, Flavobacteriaceae, and Oscillatoriaceae. Further, they observed eukaryotic microorganisms attached to the biofilm with diatoms being the most abundant. Similarly, Reisser and colleagues (2014) showed using scanning electron micrographs (SEMs) that diatoms and other protists such as coccoliths and dinoflagellates were also abundantly thriving on plastic biofilm after the establishment of bacterial biofilms. Multicellular microorganisms such as bryozoans and isopods were also observed as those last to attach (Reisser *et al.* 2014). This demonstrates a clear succession of the attaching organisms, starting with the primo colonizers hydrocarbonoclasts to the multicellular eukaryotes.

These patterns of microbial attachment and succession in the plastisphere seemed universal. Aged plastic samples collected from Manila Bay (*i.e.* Baseco; Navotas; Las Piñas-Parañaque Critical Habitat and Ecotourism Area; and Ternate, Cavite) and Bolinao, Pangasinan, for example, showed high diversities of attached microorganisms. Preliminary observations revealed the presence of diatoms (Figure 1A–E), dinoflagellates (Figure 2A–C), and other unknown flagellates (Figure 1C). Diatoms were observed to be the most abundant with some even undergoing active cellular division (Figure 1B), potentially indicating a favorable condition in the plastisphere for their proliferation. Previous studies and the initial surveys we conducted demonstrate that plastics are becoming a new environment that could modify the microbial communities in the marine environment, but its implications remain little understood.

Plastics as a Dispersal Mechanism of Unwanted Organisms

The ability of the attaching microorganisms to thrive in plastic surfaces and create a microenvironment would have significant implications on their dispersal and distribution. The recent increase in plastic debris entering the oceans has provided different marine organisms, including microorganisms, with new substrates that are longer-lasting, more pervasive, and travel slowly (Barnes and Milner 2005; Gall and Thompson 2015; Worm *et al.* 2017). Physical processes such as winds, tides, currents, and storms can facilitate the dispersal of these debris and, along with it, are the attached organisms. Further, the availability of potential nutrient sources from leachates and microbial biofilms on plastics increase the survival of attaching species, which can also increase the potential for transport of non-native species, changing their natural distribution (Barnes and Milner 2005; Hammer *et al.* 2012; Reisser *et al*. 2014; Gall and Thompson 2015).

Among the species found in the plastisphere were pathogenic bacteria and harmful algal blooms (HABs)-causing organisms, here referred to as 'dangerous hitchhikers' (Masó *et al*. 2003; Zettler *et al.* 2013; Kirstein *et al.* 2016). For example, active vegetative cells and cysts of potentially toxic microalgal species such as *Alexandrium* sp., *Ostreopsis* sp., *Coolia* sp., and

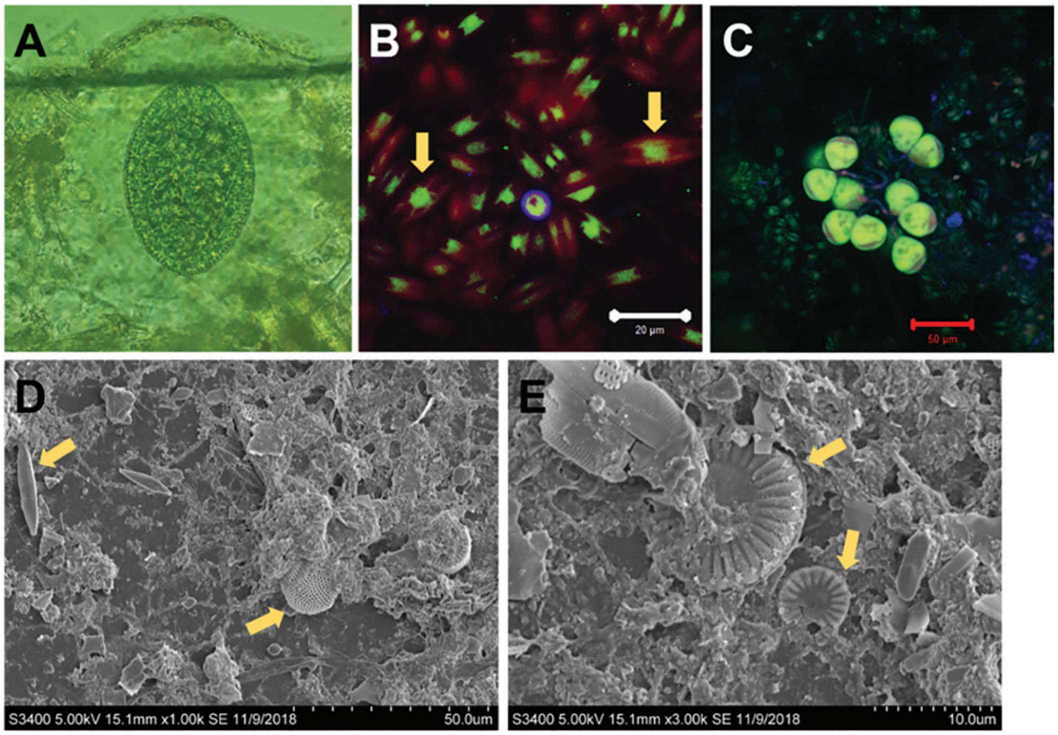

Figure 1. Microorganisms associated with floating plastic debris. A: *Cocconeis* sp. taken using a light microscope (100x); B–C: CLSM micrographs of the plastisphere were visualized using Calcofluor White M2R stain (0.15% final concentration; emission: 360–443 nm) for beta-polysaccharides, SYBR Safe DNA Gel Stain (100x final concentration; emission: 485–498 nm) for the nucleic acids, and autofluorescence (emission: 580–650nm) for lipids; green fluorescence: genetic material, red fluorescence: plastids and lipids, blue fluorescence: theca and other beta-polysaccharides; B: diatoms and dinoflagellate on plastic surface where yellow arrows indicate dividing diatoms; C: unknown flagellates on plastic surface; D–E: SEM micrograph showing diatoms on plastic surface (yellow arrows); samples were serially dehydrated in increasing ethanol concentrations (up to 100%), then mounted on aluminum stubs with carbon tape, and sputter-coated with 20–30 nm layer of gold-palladium.

Ceratium sp. were found on surfaces of floating plastic fragments in several studies in the Mediterranean Sea and Atlantic and Pacific Oceans (Masó *et al.* 2003; Zettler *et al.* 2013). Similarly, potentially human pathogenic bacteria such as *Vibrio* spp. has been consistently documented to survive on plastic fragments in coastal and even oceanic environments (Zettler *et al.* 2013; Kirstein *et al.* 2016). Further, some pathogenic strains from polystyrene samples were confirmed to already exhibit multiple antibiotic resistances (Lagana *et al.* 2019). This may be due to the widespread use of antibiotics for aquatic health management, which has led to an increase in antibiotic resistance in aquaculture species (Santos and Ramos 2018). For example, susceptibility profiles of *V. parahaemolyticus* and *V. vulnificus* isolates from water, sediment, and aquatic sources across countries also showed strong resistance to ampicillin, penicillin, and tetracycline (Elmahdi *et al.* 2016).

Transport of plastic debris from water bodies with high plastics pollution may then contribute to the introduction and invasion of dangerous hitchhikers to new environments (Masó *et al.* 2003). In the Philippines, Manila Bay is known to be heavily polluted by plastics, serving as a catch basin of its contributory riverine systems. The Pasig River alone is estimated to contribute 3.21 x 10^4 MT of plastic per year to the embayment, making it one of the biggest point sources of plastics pollution in the west coast of Luzon (Abreo 2018). This semi-enclosed embayment also has one of the longest histories of HABs occurrence with *Pyrodinium bahamense* as the main toxic species, capable of producing paralytic shellfish poisoning-causing saxitoxin (Corrales and Crisostomo 1996; Chang *et al.* 2009). Other HABs species such as *Noctiluca* sp., *Gymnodinium* sp., and *Alexandrium* sp. have also been reported (Fukuyo *et al*. 1993; Gentien *et al.* 1997; Azanza and Miranda 2001; Azanza *et al.* 2013). Indeed, floating plastic debris collected from Manila Bay showed the presence of *Gymnodinium* and *Protoperidinium* cells in the plastisphere (Figure 2A–C). This demonstrates not only the presence of the HABs species but also their ability to attach and possibly disperse through plastics.

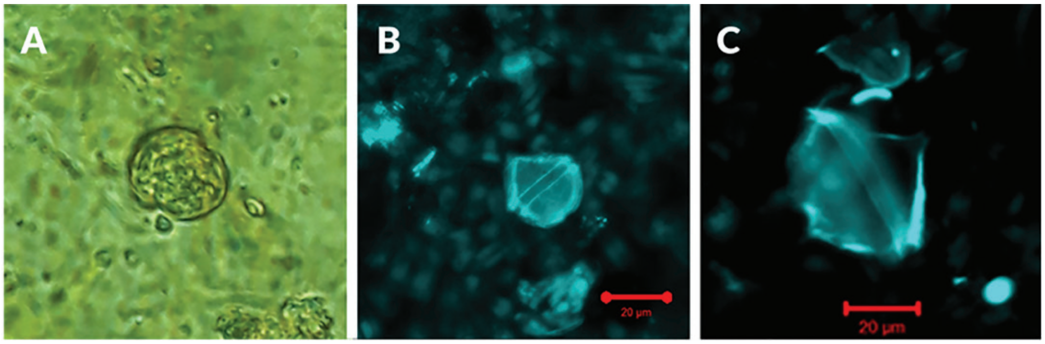

Figure 2. Micrographs showing different potentially harmful algae. A: *Gymnodinium* sp. taken using light microscopy (100x); B–C: confocal laser scanning micrograph of theca of different *Protoperidinium* cells stained using Calcofluor White Stain (0.15% final concentration; emission: 360–443 nm).

It remains unknown however if the plastisphere would be capable to sustain their growth once it reaches oligotrophic waters (*i.e.* open oceans) during transport.

The highly eutrophic waters of Manila Bay have also been reported to favor high abundances of fecal coliforms and other potentially pathogenic bacteria (Siringan *et al*. 2008; Chang *et al.* 2009; Fukuyo *et al*. 2011). Similarly, a local study on milkfish and tilapia samples from the Bacoor embayment of Manila Bay found that several bacterial strains from the fishes exhibited resistance to antibiotics such as ampicillin, tetracycline, and polymyxin B (Langaoen *et al*. 2018). Accumulation and transport of plastic debris in the embayment may then increase the spread of antibiotic resistance among pathogens through resistance gene-carrying bacteria. Although limited in the number of samples, a report showed the prevalence of microplastics in the guts of mussels harvested from Bacoor Bay, Cavite (Argamino and Janairo 2016). These ingested microplastics could also harbor pathogenic species, and their ingestion by shellfish raises questions on the state of food safety and, consequently, the public health risks associated with it.

These initial findings have significant implications for Philippine fisheries as the country continues to be one of the world's worst ocean polluters while also having a population reliant on the sea for livelihood and sustenance. Potential dispersion of harmful algae through plastic debris may increase the occurrence of HABs or invasive species, affecting the ecosystems of other pristine environments. For example, the recent expedition to the Kalayaan Island Group in the West Philippine Sea during the PROTECT WPS Expedition reported the accumulation of polyethylene terephthalate (PET) bottles in some of the sandbars near Panata Island (Figure 3). The physical appearance of the plastics and the presence of dried biofilms on the surface of the bottles suggest that these materials have drifted with ocean current for long periods of time before being deposited in the sandbars. Labels also indicate that the bottles originated from different countries in Southeast Asia such as Vietnam, Philippines, Malaysia, Thailand, and even Hong Kong and mainland China. These emphasize that plastic pollution could reach places far from metropolitan cities and human settlements, making it a transboundary and multinational problem that should be addressed by all countries in the region.

Figure 3. Photos showing presence of some plastic bottles in Kota Island near Panata during the PROTECT WPS Expedition. Most of these were PET bottles that had labels belonging to Vietnam, China, Philippines, and Thailand. Photo courtesy of Mr. Kevin Labrador.

Microbial Biodegradation and Its Ecological Implications

Plastics when released at sea invariably break down through means of abiotic (photodegradation, oxidation, and hydrolysis) and biotic degradation through microorganisms (Andrady 2015; Nithin and Goel 2017). So far, only microorganisms (bacteria and fungi) are known to be capable of degrading plastics by utilizing plastic polymers as carbon and energy sources, resulting in the conversion of organic carbon into gases and biomass (Shah *et al.* 2008). Biodegradation of plastic is a stepwise process that starts with the biodeterioration or physical breakdown of the plastic matrix by colony- and biofilm growth on the surface. This is followed by bio-fragmentation wherein bacterial enzymes released on the plastic surface convert polymers to oligomers and monomers, which can then be assimilated by the bacterial cells. Complete degradation ends with remineralization via bacterial metabolism and excretion of completely oxidized metabolites to CO_2, H_2O, and CH_4 (Mueller 2006; Lucas *et al.* 2008; Dussud and Ghiglione 2014). The ability of the microorganisms to assimilate carbon from plastics into their biomass (Zumstein *et al.* 2018) suggests that plastics can be a source of energy for some microbes. Heterotrophic microbial communities play a large role in cycling marine organic matter through the 'microbial loop' (Azam 1998), which is the trophic pathway that utilizes dissolved organic carbon (DOC) not readily utilizable to most marine organisms at higher trophic levels. Microbes incorporate DOC into their biomass, which is subsequently consumed by phagotrophic protozoa. Protozoans, in turn, are consumed by zooplankton, which is preyed upon by organisms in higher trophic levels, thereby facilitating nutrient cycling and transfer of energy across the marine food web. Plastics as alternative substrates for the growth of microbes at the base of the food web would have implications for some of the biogeochemical cycles in the marine environment. A study by Romera-Castillo *et al*. (2018) showed that plastics contribute to the oceanic DOC pool via leaching. Their results provided a global estimate of up to 23,000 MT of potential DOC leachates from marine plastics annually. The plastic-derived DOC can be utilized by marine microbes for growth, thereby directly influencing microbial activity and carbon cycling in the oceans. By serving as an alternative carbon source for the microbes, plastics could then possibly compete with the atmospheric CO_2 as the carbon source, affecting global carbon sequestration and storage. Moreover, microbial assimilation of carbon from plastic polymer results in the release of CO_2 as end products after aerobic metabolism (Starnecker and Menner 1996). Hence, with the magnitude of marine plastic pollution and the consequent interactions of marine microbes to plastics, microbial plastic biodegradation could potentially affect global ecological and biogeochemical cycles. This aspect, however, remains theoretical, and quantitative demonstration of such processes and phenomena is yet to be done.

Several studies have also been done on the biodegradation of plastics by microbes in the Philippines but mostly involving isolated strains or enriched cultures from terrestrial, freshwater, or extreme environments. For example, a fungal isolate – *Xylaria* sp., from a plastic bag in forest soil of Mount Makiling, Laguna – formed surface biofilms, colonized, and degraded polystyrene (Abecia *et al.* 2019). Isolates from a dumpsite in Payatas, Quezon City were also reported for their degradation activity against polyethylene glycol and low-density polyethylene (LDPE) plastics (Bolo *et al.* 2015), while bacterial isolates from an alkaline spring in Botolan, Zambales degraded LDPE (Dela Torre *et al.* 2018). In these studies, microbial colonization and biofilm formation on plastic surfaces were observed to be followed by a decrease in weight or changes in the surface structure of the plastics, indicating possible loss due to biodegradation (Harshvardhan and Jha 2013; Dela Torre *et al*. 2018). The presence of new functional groups as detected by Fourier transform-infrared spectroscopy indicates oxidation of low molecular weight compounds and conversion of crystalline structures of the polymer into an amorphous structure as a result of biodegradation. SEMs of polyethylene (PE) strips colonized by the fungal isolates showed cracks, holes, and crevices on the polymer surface, which indicate biodeterioration – the initial step in polymer biodegradation (ter Halle *et al.* 2017; Silva *et al.* 2018; Abecia *et al.* 2019). Assimilation studies can be conducted to correlate fungal colonization and the destruction of polymer surface to polystyrene utilization. Also, the production of substantial amounts of CO_2 after incubation for one week was attributed to the metabolic activity of the plastic-degrading microorganisms (Guillet *et al.* 1974). Biodegradation can, therefore, be measured in terms of CO_2 release since it represents the ability of the isolates to convert the carbon backbone of the polymer to metabolic end products.

The high biodiversity of microorganisms in the marine environment may offer a high potential for strains capable of remineralizing plastics (Bryant *et al.* 2016). Putative xenobiotic biodegradation genes were found in microbes attached to plastics in the North Pacific Gyre (Bryant *et al.* 2016), with the potential biodegrading genes being more prevalent in polluted sites (Quero and Luna 2017). This suggests that the biodegradation potential for plastic debris is present in marine microbial assemblages, and their abundance is related to the magnitude of plastic pollution within a site.

Our preliminary studies on the different aged plastics using confocal laser scanning microscopy also revealed significant changes in the topology of their surfaces. Specifically, new and unexposed PE plastics had relatively more homogenous surface topology (Figure 4a) compared with that of the UV-exposed (Figure 4b), indicating that physical degradation occurred even just with UV exposure. Interestingly, an old PE plastic found floating in Manila Bay and coated with thick biofilm (Figure 4c) had deeper crevices and a more heterogeneous surface. This indicates the possible contribution of microorganisms in the deterioration and eventual possible biodegradation of the plastic material. However, to date, no thorough studies have been done on the presence of plastic-biodegrading microorganisms in Philippine marine environments despite high abundance and accumulation of plastics in different embayments such as Manila Bay, Cebu, and Davao Gulf. These embayments serve as catch basins for wastes in metropolitan areas and their surrounding provinces, serving as a natural laboratory to study the role of microbes in plastics biodegradation. Understanding naturally occurring processes may also provide insights on how to possibly handle plastics pollution and, thus, could ultimately result in societal benefits.

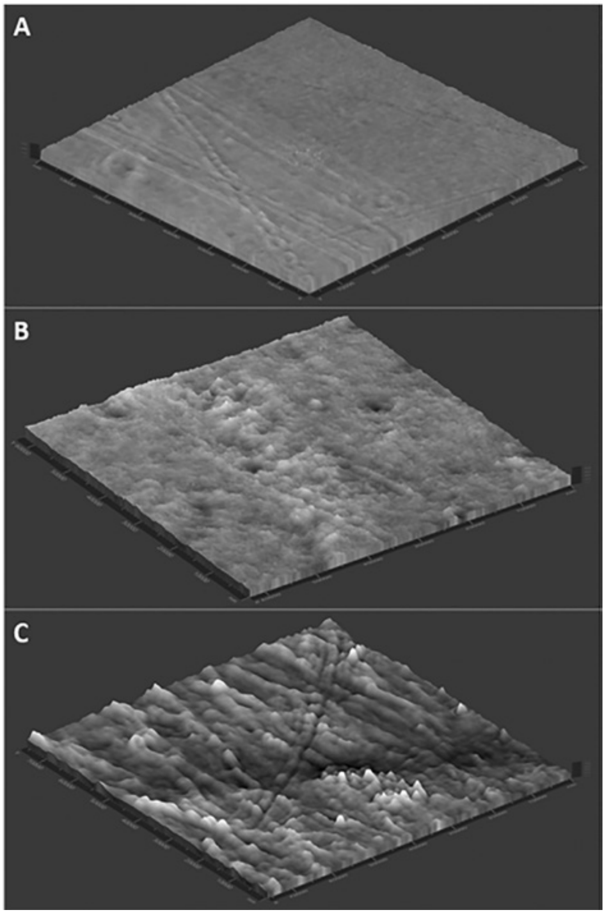

Figure 4. Differential interference contrast images of the plastic surface were captured using the photomultiplier tube function of the confocal laser scanning microscope and images were rendered using the 2.5D function showing the changes in the surface topology of the new or virgin PE plastic (A), UV-exposed PE (B), and biofilm-coated PE plastic from Manila Bay (C).

Opportunities and Research Directions

Studies on plastics-microbes interactions are still developing (Sivan *et al.* 2006; Yoshida *et al.* 2016; Quero and Luna 2017) and opening new opportunities for research. One aspect that gains attention is learning the natural management of plastic waste. Research is already being done on the use of plastic waste as a possible substrate for biotechnology applications (Wierckx *et al.* 2015) and has gained much attention as a sustainable method to remedy plastics-related problems. Biodegrading activity – for example, if present – could be further harnessed as a possible bioremediation approach for plastics pollution (Gouma *et al.* 2014). Some bacterial species have already shown to be good models for metabolizing plastic (Howard and Blake 1995) and, as previously discussed, screening bacterial communities in plastics-enriched environments could ultimately yield more enzymes that break down different types of plastics. The bacterium *Ideonella sakaiensis* – for example, isolated near a PET-recycling facility in Sakai, Japan (Yoshida *et al.* 2016; Chen 2016) – was able to fully degrade PET by feeding on the hydrocarbon polymer as its source of energy and carbon (Quaglia 2017). The enzymes produced by the bacterium evolved to solely hydrolyze PET and ultimately break it down into its monomeric units terephthalic acid and ethylene glycol (Yoshida *et al.* 2016; Quaglia 2017). It has now been modified and being explored to potentially be used to degrade plastics at an industrial scale. Given the diversity of plastics material, studies should also look into the biodegrading capabilities of microorganisms on different plastic types and not only focus on the common ones such as PET, LDPE, and HDPE (high-density polyethylene terephthalate) (Orr *et al.* 2004; Yoshida *et al.* 2016; Kumar and Vannan 2018). However, the application of biodegrading bacteria as a bioremediation approach to plastics pollution is still very far from realization and applicability since the search for highly active strains is still continuing. This makes natural laboratories (*e.g.* Manila Bay) and other extreme environments as rich and undermined resources for such bioactivity. Further, the underlying molecular mechanisms involved in plastics biodegradation remains to be elucidated and entails a clear understanding of the environmental impacts of these techniques to the ecosystem (Iwamoto and Nasu 2001).

More ecology-oriented studies can also have monitoring and policy implications. For example, understanding of the diversity of microorganisms and their modes of attachment can be used as indicators in tracking pollution and ecotoxicology. Combining this with satellite imagery and remote sensing will contribute not only to the understanding of plastics dispersal but also of its associated unwanted species or dangerous hitchhikers. This would be a direct response to the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection of the United Nation's action-oriented recommendation of "identifying the main sources and categories of plastics and microplastics entering the oceans" and "assessing the importance of plastics and microplastics as a vector for the transfer of organisms" (www.gesamp.org). Understanding of the fundamental ecology of biofilm formation in plastic surfaces may also generate insights on how biofouling can also be prevented, which would have many and profound industrial applications. Meanwhile, quantifying the contribution of microorganisms in plastics biodegradation will also allow us to estimate their inputs into the release of greenhouse gases such as CO_2 and CH_4. The inclusion of microbes and plastics-derived carbon in climate and CO_2 models will provide more accurate predictions and estimates of changes related to climate change scenarios. These studies will yield information on the extent of plastic pollution and possible future directions for mitigation and management. Given the status of plastic pollution and research in the country, together with the preliminary findings and ongoing research on plastics in the marine environment, it is imperative that we specifically include plastics as a research priority in the HNRDA of the DOST within the next few years.

Science-based decision-making is a fundamental and crucial factor in combating such environmental problems. In the last Intergovernmental Oceanographic Commission Western Pacific Meeting held in Manila in April 2019, the technical working group on microplastics reported that the Philippines is a country "with limited capacity and has no national program that started yet" to scientifically and systematically understand the extent of plastics pollution. This, however, is not true since many laboratories and research groups have been working on the different aspects of plastics pollution across disciplines and environments, albeit unconsolidated. The first step that needs to be done then is to create a platform that will provide a venue for different stakeholders to talk and discuss plastics. Recently, a think tank network of researchers was formed under the umbrella name "Plastics Research Network Philippines," with the aim to consolidate efforts and facilitate the creation of a national scientific research framework to complement the national plan of action being prepared by the Department of Environment and Natural Resources (DENR). These highlight the need to support both basic and applied research, which will help in crafting new policies and management strategies to address plastics pollution.

The Philippines, being at the center of marine biodiversity, is already vulnerable to many environmental issues such as nutrient pollution, extreme weather events, illegal fishing practices, poaching, and climate-related changes that continue to degrade its marine environment. The issue of plastics as an emerging threat adds to this long list of problems. Unlike other problems, however, plastics pollution is reversible but would need participation from all stakeholders – from its production to its consumption and its management and reuse, from knowledge to action, and from the scientific community to the larger public. Action, however, needs to start now.

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