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Review article

Plastic pollution and degradation pathways: A review on the treatment technologies

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ABSTRACT

In recent years, the production of plastic has been estimated to reach 300 million tonnes, and nearly the same amount has been dumped into the waters. This waste material causes long-term damage to the ecosystem, economic sectors, and aquatic environments. Fragmentation of plastics to microplastics has been detected in the world's oceans, which causes a serious global impact. It is found that most of this debris ends up in water environments. Hence, this research aims to review the microbial degradation of microplastic, especially in water bodies and coastal areas. Aerobic bacteria will oxidize and decompose the microplastic from this environment to produce nutrients. Furthermore, plants such as microalgae can employ this nutrient as an energy source, which is the byproduct of microplastic. This paper highlights the reduction of plastics in the environment, typically by ultraviolet reduction, mechanical abrasion processes, and utilization by microorganisms and microalgae. Further discussion on the utilization of microplastics in the current technologies comprised of mechanical, chemical, and biological methods focusing more on the microalgae and microbial pathways via fuel cells has been elaborated. It can be denoted in the fuel cell system, the microalgae are placed in the bio-cathode section, and the anode chamber consists of the colony of microorganisms. Hence, electric current from the fuel cell can be generated to produce clean energy. Thus, the investigation on the emerging technologies via fuel cell systems and the potential use of microplastic pollutants for consumption has been discussed in the paper. The biochemical changes of microplastic and the interaction of microalgae and bacteria towards the degradation pathways of microplastic are also being observed in this review.

1. Introduction

Generally, plastics in microplastic have caused health hazards to wildlife and the aquatic environment. However, plastic production and usage have increased, which has reached over 300 million tonnes in 2014 [1]. Plastic is derived from petroleum sources, including polyvinyl chloride (PVC), nylon, polyethylene (PE) and polypropylene (PP). These materials are the most successful product

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of our times, delivering unprecedented functionality and value to our lives. Several sources of the plastic polymer include low-density polyethylene (LDPE), and polyacrylates are also common [2]. However, the increasing plastic pollution from marine litter, beach debris, tourism activities, and synthetic polymer in our seas and oceans has become a critical concern [3].

This hazardous problem seriously threatens the marine environment, which impacts the entire ecosystem, including oceans, lakes, seas, rivers, coastal areas, and Polar Regions [4]. The process of mechanical abrasion and photochemical oxidation in the environment has led to plastic fragmentation, which resulted in micro-sized persistent plastic pieces (microplastic). This microplastic is a plastic particle of 5 mm or smaller [5]. The hazardous effect of microplastics has been detected in the food chain of marine biota, which has impacted the biology and ecology of these organisms [6]. Since the 1940s, we have revolutionized the use of plastic products for our daily basis usage. Moreover, we have made more plastic in the last ten years than in the past century. Plastic is made from natural resources and petrochemical compounds from beneath the earth. Normally, it will combine with additives such as fillers, dyes, and plasticizers [7]. Several plastic products that have been produced are still being used.

1.1. Category of plastic

Chemical composition, synthesis techniques and other characteristics can all be used to categorize plastics. One way to categorize plastics is by their polymer type, which includes LDPE (low-density polyethylene), acrylics, polyesters, silicones, polyurethanes, and halogenated plastics [8]. Another way to categorize plastics is by their recycling codes, which facilitate the recycling of post-consumer plastics. A proportion of this plastic waste is in the form of small particles known as microplastics (MPs). There are two categories of microplastics: primary and secondary [9]. Microplastics are microscopic plastic particles that come from the breakdown of bigger plastics and the development of commercial products. Microplastics are less than 5 mm and come from primary or secondary microplastics. Primary microplastics are smaller fragments made for industrial or commercial purposes, such as plastic fibres used in synthetic textiles, plastic pellets for utilization in industrial manufacturing, and microbeads found in personal care items. Primary MPs are plastic pellets or particles manufactured to produce cosmetic products and abrasives. It has been found that secondary microplastics are created if bigger plastic items are exposed to natural weathering processes after being released into the environment [10].

1.2. Type of plastic waste

Nowadays, many home products are plastics, such as water bottles, detergent bottles, milk jugs and plastic grocery bags. Nevertheless, more of it is no longer used and becomes waste due to the durability of the plastics. Some plastic products can be recycled, but we throw them away as waste. Ultimately, plastic from land, rivers, lakes, and coastal regions will find its way through the canal into the ocean.

From Table 1 type 1 and 2 plastic are widely recycled, but other than these two types are rarely recycled. It is important to encourage people to recycle plastic items. For instance, Plastic Bank, founded by David Katz and Shaun Frankson, motivates people to

Table 1
Common types of plastic waste [11].

Types of plastic	Common products	Recyclable	ID code
Polyethylene Terephthalate (PETE @PET)	Water bottles, cups, jars, trays	Yes	1 PETE
High-Density Polyethylene (HDPE)	Detergent bottles, grocery bag	Yes	2 HDPE
Polyvinyl Chloride (PVC)	Cleaning supply jugs, sheeting, automotive product bottles	No	3 PVC
Low-Density Polyethylene (LDPE)	Bread bags, paper towels, tissue overwrap, trash bags	Yes	4 LDPE
Polypropylene (PP)	Juice bottles, straws, hangers, shipping bags	Yes	5 PP
Polystyrene or Styrofoam (PS)	Food packing containers, CD cases, cartons, toys, costume jewellery	No	6 PS
Miscellaneous plastics (includes polycarbonate, polylactide, acrylic, acrylonitrile butadiene, styrene, fibreglass, and nylon)	Polycarbonate, nylon, ABS, acrylic, safety glasses, CDs, headlight lenses	No	7 OTHER

recycle plastic by exchanging it for money or goods [12].

All this plastic, once submerged in the sea, with less pressure and low UV radiation, leads to a slow rate of fragmentation [7]. Our oceans are driven by five major circular currents known as a gyre. They collect waste from rivers and coastline into the gyre and lastly will accumulate at the centre of the gyres. They become marine litter and disturb marine biota ecosystems.

MP debris comes from the land, ocean, recreational boats, and fishing gear. Low-trophic fauna will either ingest this debris or contaminate the sediments [13]. Tourism activity also contributes to the accumulation of MP debris due to improper littering practices. Plastic pollution also affects the local economies by decreasing the number of tourists in those places and losing tourism revenue [14]. Next, it will also disturb the boat's navigation when entangled in the steering systems [13]. Furthermore, the accumulation of debris will change the oceanic gyres, beaches, and benthic zones. It will lead to lower light intensity in the ocean and oxygen depletion and affect flora and fauna.

Hence, in this paper, the overview of plastic pollution has been discussed for its degradation pathway in the environment and by microorganisms, together with the emerging technologies of mechanical, chemical, and biological methods in combating these problems. Moreover, the focused employing microorganisms and microalgae in fuel cells has also been discussed, as there are several potentials for adapting these technologies for future utilization of microplastic pollutants.

2. Plastic pollution

2.1. Plastic pollution in the air

The search results reveal that plastic contamination can affect air pollution. Incineration of plastic trash results in the emission of hazardous substances into the atmosphere, such as microplastics, bisphenols, and phthalates [15]. The substances have been associated with the emergence of asthma, endocrine function alteration, and cancer [16]. The incineration of plastic trash is a prevalent practice, with approximately 40% of plastic garbage on a global scale being subjected to combustion [17]. This phenomenon can further increase dust occurrences and degrade air quality in densely populated regions [18].

Microplastics, characterized as minuscule plastic particles, have the potential to be ingested and are found in both indoor and outdoor atmospheric environments. The production and accumulation of plastic in the environment continue to increase, posing a possible exacerbation of the issue of airborne plastic pollution [19]. Plastic pollution can exert substantial effects on atmospheric conditions and human well-being, necessitating enhanced waste management strategies to mitigate the accumulation of plastic trash in natural surroundings.

2.2. Plastic pollution to the water

Annually, 14 million tons of plastic is deposited into the ocean, constituting approximately 80% of the marine debris discovered across various aquatic environments, ranging from surface waters to sediments in the deep sea [20].

The primary contributors to plastic debris in the ocean are derived from terrestrial sources. These include urban and stormwater runoff, sewer overflows, littering, insufficient waste disposal and management practices, industrial activities, tire abrasion, building activities, and illegal dumping [21]. Plastic pollution in marine environments has profound consequences for marine organisms and ecosystems, resulting in many detrimental effects such as suffocation, entanglement, laceration, infections, and internal damage [22]. Plastic trash lacks decomposition capability, leading to its persistence over an extended period, causing significant disruptions to marine ecosystems.

Plastic pollution has emerged as a significant global predicament, characterized by billions of pounds of plastic in vast aggregations, constituting approximately 40% of the earth's oceanic expanse [23].

2.3. Plastic pollution to the soil

The improper disposal of plastic garbage has the potential to introduce detrimental chemicals into the adjacent soil, subsequently infiltrating groundwater and other nearby water bodies, as well as the surrounding ecology. The presence of microplastics, small plastic particles, has the potential to impact soil organisms by influencing their well-being and soil-related activities [24]. In the presence of microplastics in the soil, earthworms exhibit altered burrowing behaviours, impacting their overall fitness and soil quality.

The presence of plastics in soils is a widespread issue that is commonly associated with the practice of intensive agriculture. Plastic garbage is often found across continents, from Asia and North America to Africa [25]. The presence of plastic pollution inside soil has the potential to exert adverse effects on both plant performance and soil parameters. An illustration of the impact of microplastics can be observed in their ability to alter soil conditions and subsequently influence the performance of plants [26].

The global accumulation of plastics utilized in agricultural practices is a matter of concern, as it can have significant implications for soil health, biodiversity, and productivity in the agricultural sector. Microplastics, including those incorporated in certain fertilizers, can affect human health when transmitted to individuals via the food chain [27].

2.4. Potential health hazards of plastic to human

The potential health risks associated with exposure to toxic chemicals and microplastics are significant throughout the entire lifecycle of plastic, as they can lead to various diseases, disabilities, and premature mortality. These risks can arise via inhalation, ingestion, or direct skin contact [28]. The presence of harmful chemical compounds and contaminants within plastics has been associated with potential carcinogenic effects and alterations in hormone action, which may subsequently adversely impact reproductive health, growth, and cognitive function.

The incineration of plastic garbage can potentially emit harmful substances, including hydrogen chloride, dioxin, cadmium, and fine particulate matter. These emissions have been linked to respiratory complications and health concerns [29,30]. More than 170 chemicals are employed in hydraulic fracturing, also known as fracking, which produces primary raw materials for plastic. These chemicals have been found to have established adverse effects on human health, such as the potential to induce cancer, neurological diseases, and developmental issues.

Exposure to plastic particles and their chemicals has induced several adverse biological responses, including inflammation, genotoxicity, oxidative stress, apoptosis, and necrosis. These biological effects have been related to many bad health outcomes, from cardiovascular disease to childhood cancer [31]. Children have heightened susceptibility to the detrimental impacts of plastic, as seen by the association between plastic chemicals and various health outcomes such as diminished cognitive abilities, respiratory ailments, and increased risk of obesity.

2.5. *Potential health hazards of plastic to biota*

Plastic can be recycled, but only a fraction of it is recovered. Most of this material is thrown away into the environment, coating our land and oceans like a disease. It becomes a health hazard to marine wildlife and humans. Plastic is made from natural resources such as oil, petroleum, and coal. When plastic is thrown away, the natural resources and energy that went into making this plastic in the first place are going to waste. If we recycle these plastics, we are saving these resources and our environment, as plastics are well known for their durability. Today, considerable research on biota is attracted to plastic floating or submerged in the water. It is also called hangers-on or hitch-hiking due to its characteristics and sinking plastics despite their buoyancy properties [32].

Plastic litter will harm mammals, fish, and invertebrates physically. Plastic litter will become ingested, entangled, asphyxiated, or create a blockage to the respiration or digestive system and become toxic to marine wildlife [7]. In the documentary *A Plastic Ocean*, a whale dies because of malnourishment due to its digestive system being blocked with 6 square meters of plastic [33]. When plastics break down into smaller particles, namely microplastic, they will be ingested by a wider organism. Microplastics have bigger surface-to-volume proportions, conceivably encouraging contaminant exchange and have been demonstrated to be ingested by many organisms [34].

Over time, the sun’s ultraviolet light, ocean wave’s action and salt concentration would make the plastic brittle and turn into smaller pieces of microplastics. Then, the chemicals from industry and agricultural leaching will attach to the surface of the MPs, making them highly toxic. In some aquatic sites, there are more MPs than plankton, leading to the MPs being eaten by marine life instead of plankton. Marine turtles have become one of the sufferers who have faced a higher rate of ingestion of plastic debris. MP debris will block the passage in female eggs and reduce this species’ quality of life and reproductive ability. It will also decrease their mobility and reduce their alertness for predator avoidance. Next, it will alter or disturb the food chain when nourishment, such as plankton, decreases. At the same time, seabirds will also be affected by the ingestion of MP debris, reducing body weight and reproductive capacity [13].

Humans love to eat seafood, but nowadays, many kinds of seafood are contaminated with MP debris and can pose a health risk when consumed. Plastic is a polymer made up of repeating sub-units. This plastic production consists of toxic monomers, which can lead to cancer and affect the human reproductive system. Plastic components can also harm human well-being—for instance, BPA, PCB, and phthalates [35]. BPA or Bisphenol A helps to harden the plastic containers typically used in food canning. BPA can act as an agent for estrogenic activity (EA) that mimics human oestrogen when ingested [13]. Exposure to ultraviolet (UV) light radiation will also increase the release of EA from resins.

Moreover, it can be denoted that oestrogen plays an important role in developing female secondary sexual characteristics and the maturation of sperm. High levels of oestrogen will increase the risk of breast and ovarian cancer. On the other hand, phthalates are typically used for plasticizers and polyvinyl chloride (PVC) fragrances. Phthalates tend to interfere with testosterone and affect sperm motility. Then, PCB or polychlorinated biphenyls are typically in all types of plastic. The PCB will interfere with thyroid function.

3. Plastic degradation pathways

3.1. *Degradation of plastic in the environment*

3.1.1. *Degradation by ultraviolet*

Ultraviolet (UV) light has the potential to induce the breakdown of plastic materials via a process known as photooxidative degradation. This phenomenon leads to the fragmentation of polymer chains, the generation of free radicals, and a subsequent reduction in molecular weight, ultimately resulting in plastic degradation [36]. The absorption of UV light by plastics can result in the excitation of photons, generating free radicals and subsequently causing deterioration. Nevertheless, it is important to note that not all types of plastics can effectively absorb ultraviolet (UV) radiation.

Several additives, such as blockers, stabilizers, or absorbers, can mitigate the effects of UV deterioration in plastics. Additionally, the incorporation of titanium dioxide has offered advantageous properties in this regard [37]. Benzophenones and various other organic compounds can absorb ultraviolet (UV) radiation and re-emit it as thermal energy, mitigating its potential impact. Certain types of plastics exhibit varying degrees of susceptibility to ultraviolet (UV) deterioration. Polymer degradation generated by ultraviolet (UV) radiation can be observed in the outdoor installation of PVC pipes, which tend to undergo yellowing and chalking. Similarly, the fading of colours in textiles serves as another illustration of UV-induced polymer degradation.

The potential for UV radiation to induce degradation, resulting in physical and chemical alterations, is significant for individuals involved in designing and utilizing diverse materials specifically meant for outdoor use and prolonged exposure to sunlight [38]. Bonds that undergo dissociation through exposure to ultraviolet (UV) radiation are also susceptible to undergoing reactions with oxygen that is readily present.

Researchers have discovered that the inclusion of sugar units in polymers enhances their degradability under UV radiation exposure [39]. The polymer structure can undergo photochemical breakdown due to the photochemical action induced by various forms of UV radiation. Plastic films are subject to surface deterioration and the subsequent release of microplastics when exposed to solar ultraviolet radiation (UVR) and mechanical abrasion (MA) during their use or disposal in the environment [40].

It is crucial to understand the fragmentation process of plastic into microplastic to determine the pollution to the environment [41]. In nature, physical factors such as abrasive pressures, heating or cooling, freezing or thawing, and wetting/drying cause the plastic to degrade [42]. Two processes enhance the fragmentation of plastic debris: photochemical oxidation and mechanical abrasion. Surface weathering of plastic happens when exposed to sunlight, making plastic brittle [41]. Additionally, recalcitrant contaminants can be degraded chemically through oxidation or hydrolysis [43]. Plastic that enters the ocean or the land will be exposed to ultraviolet light. Then, it became fragmented into microplastic. This process is known as photochemical oxidization. As plastic fragments reduce their sizes, microplastics will gradually increase in the environment (see Figure 1).

There are six types of plastic which are typically used and later will enter the environment. They are divided into two groups which are C-C backbone consisting of polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and heteroatoms in a backbone such as polyethylene terephthalate (PET) and polyurethane (PU) [34]. Ultraviolet (UV) exposure initiates the degradation of this plastic and leads to chain scission of the molecule. The chain scission makes the molecule into a smaller fragment with low molecular weight, leading to further plastic degradation by microbes [44]. The degradation pathway of plastics generally happens in three steps: the initiation step by sunlight or thermal heat energy, where the free radical is produced. The propagation step is where the free radical reacts with oxygen, and the termination step is where inert is produced. The unsaturated double bonds in the C-C backbone chain will engage light energy to initiate the degradation process. In PET and PU, the ester bond in the backbone undergoes photo-degradation, forming a carboxylic acid end group and a vinyl end group [34]. Furthermore, the plastic degradation rate depends on plastic's susceptibility to light, the surface area to volume ratio, temperature, and their molecular formula [45].

However, this result only tells us the potential lifetime of a few types of plastic in the ocean, called photoreactive plastics, that can easily be removed from the ocean. Besides these few plastics, it may take more time for their removal from the ocean [45].

3.1.2. Degradation by mechanical abrasion

Next, mechanical abrasion happens when plastic collides with rock or sand and makes them erode. It usually happens at the beach as wind and waves transport plastic there. From the previous study in the laboratory condition, results showed that polyethylene (PE) and polypropylene (PP) are improbable to be weathered by mechanical abrasion with sand compared to expanded polystyrene (EPS).

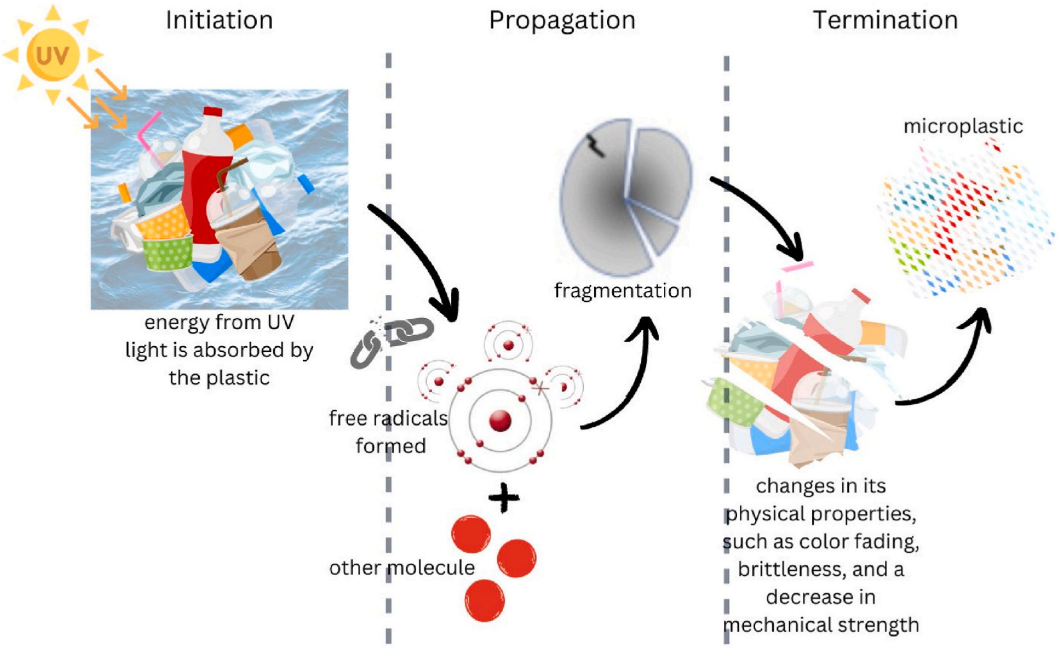

Fig. 1. The degradation pathway of plastic to microplastic in nature [34,44,45].

EPS is sensitive to frictional forces but absorbs shock and insulates heat [46]. In the sea, exposure to sunlight will decrease due to the shading of water and sea depth. This situation leads to a longer degradation rate of plastic in this environment [47].

In reducing the plastic waste problem, numerous research studies have been performed. Physical and chemical approaches to degrading plastic waste, such as ultraviolet (UV) treatment, physical stress, hydrolysis and ammonolysis, have been implemented [48]. However, this approach has some obstacles, such as high temperatures that need to be used, and typically, most of the byproducts are toxic to nature [49]. Moreover, most of this procedure was done in the laboratory environment as a substitute for the natural condition. UV treatment is the key step in plastic degradation as it starts the chain scission, which makes the material into smaller fragments [48]. However, as UV radiation degrades plastic, additives in the plastic also degrade, releasing other substances that may affect the environment [34]. Physical stress is like mechanical abrasion by sand towards the plastic litter. However, not all types of plastic can be degraded by mechanical abrasion [41]. Hydrolysis occurs when the water content is high to make chain cleavage [50]. The presence of acid will enhance the process of hydrolysis, and the ester bond in PU will produce carboxylic acid, creating an autocatalytic process [34]. The essential drawback of PET hydrolysis is the system's high corrosiveness and the high number of inorganic salts produced [51]. Ammonolysis is a prominent method for chemically recycling polyesters and polycarbonate under hydrothermal conditions [52].

3.1.3. *Degradation by microorganisms*

Biodegradation converts plastic polymers into gas and biomass using various microorganisms, including bacteria and fungi. The capacity of these microorganisms to grow on the substrates influences how well they can use the variety of substrates as food sources. The substrate's hydrophilic or hydrophobic surface affects a microbe's adhesion to the surface. This plastic-degrading microorganism will get energy from the biodegradation of plastics. A previous study showed that PE degradation could provide energy up to −425 kJ/mol of O_2, almost the same as glucose at −479 kJ/mol [42].

Moreover, the general overview of the potential pathway of microplastic biodegradation are subject to the attachment and colonization, where microorganisms, such as bacteria, algae, and fungi, colonize the surface of microplastic particles. They adhere to the microplastic through various mechanisms, including the secretion of extracellular enzymes. The enzymes target and cleave the chemical bonds in the microplastic polymer, initiating the degradation process [53].

Surface degradation, enzymatic activity breaks down the surface of the microplastic particles, leading to the formation of smaller fragments. It can result in the release of microplastic-associated chemicals and the exposure of fresh surfaces. Microorganisms may internalize the degraded microplastic fragments by engulfing them or through other mechanisms. Once inside the microbial cells, further enzymatic degradation and metabolism can occur (see Figure 2).

For the process of assimilation and metabolism, the microbes utilize the breakdown products of microplastic degradation as a carbon and energy source for growth and metabolism. The smaller molecules are incorporated into the microbial cell's metabolic pathways. As microorganisms metabolize the microplastic fragments, they produce metabolic byproducts, such as carbon dioxide (CO_2), water (H_2O), and microbial biomass. These byproducts are released into the environment [52].

Previous research also shows that the microorganisms' chemical properties, whether hydrophilic or hydrophobic to the substrate (plastic polymer), affect the rate of biodegradation [42]. When the microorganisms attach to the microplastic, it will promote the formation of different chemical bonds or degrade the existing bond [55]. It can be denoted that polyethene (PE) is hydrophobic. Therefore, the bacteria with more hydrophobic cell surfaces will attach to the plastic's exterior more easily.

In every microorganism, a specific enzyme will be produced during the biodegradation process. The enzyme will accelerate the decomposition process in breaking down plastic polymer into monomers and oligomers [42]. Research by Tsiota et al. (2018) [56] shows that different initial weights of PE could be reduced after being introduced to different communities of microorganisms. From their research, after two months, the initial weight reduced to 8% for the Agios community and 18% for the Souda community. This biodegradation process will release gas and oxygen as their product. Oxidation and decarboxylation are two major processes during the biodegradation of plastic polymer. The oxidation process needs oxygen gas, while the decarboxylation process releases the carbonyl group and produces CO_2 [42].

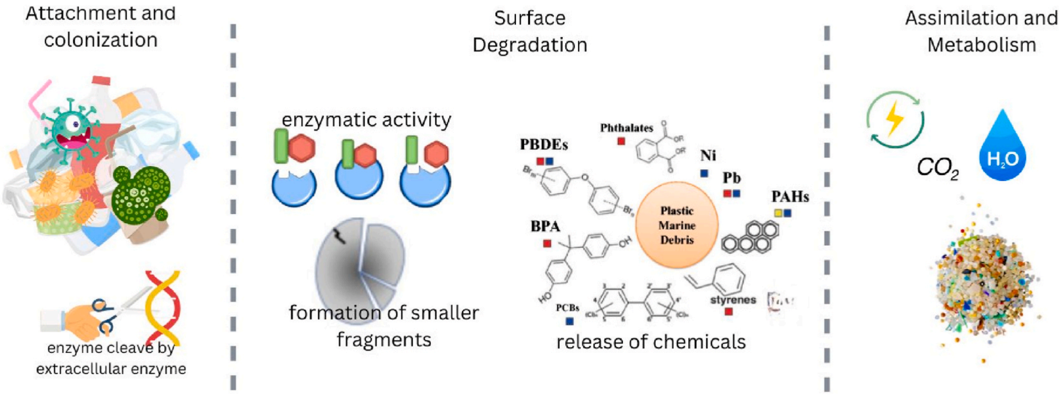

Fig. 2. The degradation pathway of plastic to microplastic by microorganisms [53,54].

After the biodegradation process, biodeterioration takes place in the system [57]. Biodeterioration is the alteration process of something that loses function due to exposure to plastic-degrading microorganisms or their enzyme [42]. During this phase, plastic-degrading microorganisms will form biofilm on the surface of the microplastic. Biofilm consists of polysaccharides, proteins, and nucleic acids, namely extracellular polymeric substances (EPS). These EPS substances will form a hole in the surface of the microplastic. Thus, physical biodeterioration occurs on the microplastic [46]. Research by Song et al. (2020) [58] shows that adding microplastic can improve the EPS production for *Chlorella* sp. by 1.4 times and *Phaeodactylum* sp. by 2.2 times compared to the control group. However, the different behaviour of microalgae must be observed for future research.

Large plastic polymers are hard for microbes to assimilate. Microbes release exoenzymes or free radicals to break the plastic polymers into smaller pieces. They need various electrical potentials to conduct the lysis process and chemical reactions. Next is the assimilation of plastic polymers with their plastic-degrading microorganisms. Plastic will act as the carbon source for microorganisms to form biomass [42]. Components in the plastic that cannot assimilate with the microorganism will be released by microbial cells to be used by other microorganisms [46]. The final stage is the termination step, where inert gas is produced. All carbon sources will produce carbon dioxide (CO_2) during this step.

The product of microbial degradation usually consists of functional aldehydes, ketones, and other carbonyl groups [34]. Carbonyl groups are any carbon atom molecule with a double bond with an oxygen atom. The reactivity of carbonyl groups depends on the polarization of the C=O itself. Aldehydes are the most reactive molecule in the carbonyl group as hydrogen is a smaller particle; the C=O group attract many molecules to itself.

Carbon is a basic building block of almost every living thing, as it can form many sequences of chains that produce different chemical properties. Carbon also acts as renewable energy for living or non-living things. The characteristics such as the chemical structure, polymer chain, crystallinity, and polymer formula's complexity affect the plastic degradation process in the environment. Enzymes select the specific functional groups and can be processed. Microorganisms can be employed to retrieve the carbonyl functional group from plastic waste (see Table 4). Generally, polymers with a shorter chain, more amorphous part and less complex formula are susceptible to microorganisms' degradation. Moreover, the environment where polymers are placed or disposed of is key to their biodegradation. The pH, temperature, moisture, and oxygen content are among the most significant environmental factors that must be considered in the biodegradation of polymers.

3.1.4. *Degradation by microalgae*

Theoretically, microplastic will alter the physical properties when exposed to microalgae and a similar situation when exposed to other microorganisms. However, it depends on the type of microalgae and microplastic itself. Whether they are suitable for each other and demonstrate an optimum degradation. Most of the MP and microalgae assimilations will sink at the bottom of the water bodies. The research found that *C. neogracile* assimilated with microplastic sank faster than other microalgae [42]. Aldaby & Mawad (2019) [44] found that between *Oscillatoria* sp. and *Chlorella* sp., Oscillatoria sp. has more positive results in the degradation of pyrene, a type of polycyclic aromatic hydrocarbon (PAH) contained in the MP. Several microalgae species can be found on the surface of polyethylene plastic isolated from polyethylene plastic bags that have been dumped into a water body in Chennai, India [42].

Research by Khoironi et al. (2019) [59] states a decrease in the tensile strength of microplastics, namely PP and PET, by 0.1977 MPa/day and 0.9939 MPa/day, respectively. The decreasing tensile strength shows that there was once a chemical bond in the MP, which later has been broken. It occurs after the MP and microalgae (*Spirulina* sp.) are incubated in the same glass reactor. It is noted that algal biofilm production promotes the degradation of plastic. In addition, other bacteria will enhance the degradation of MP as they all have specific functions and enzymes secreted.

Microalgae possess certain characteristics that make them capable of degrading microplastics. (see Table 4). Microalgae can produce enzymes that can break down microplastic chemical bonds, facilitating their degradation [60]. A study by [61] shows that *Chlorella* sp. is a type of microalgae that has been found to contribute to the degradation of plastics through enzymatic activity.

Microalgae can adhere to the surface of microplastics, forming biofilms that enhance the degradation process. The adhesion of microalgae on microplastics increases the density of the colonized polymer [62]. The biofilms created by microalgae can provide a conducive environment to produce enzymes and other degradation mechanisms [60]. The attachment of microalgae to microplastics can also facilitate the transfer of microplastics to higher trophic levels in the food chain [63]. The adhesion of microalgae to microplastics is facilitated by various factors, including the surface properties of the microplastics and the extracellular polymeric substances (EPS) produced by the microalgae. The EPS produced by microalgae can act as a glue, allowing the microalgae to adhere to the surface of the microplastics [60].

Some microalgae can synthesize toxins interacting with microplastics, leading to their degradation [60]. Microplastic particles can include harmful additives and, because of their small size and physical properties, can adsorb toxic compounds such as heavy metals and organic pollutants [64].

Microalgae can colonize different types of microplastic polymers, increasing the density of the colonized plastic and affecting its fate in the environment [62]. Algae can withstand various salinity with different pH values, temperatures, and light intensity, which make them tough living organisms. There are several classes of algae, which are green (*Chlorophyta*), red algae (*Rhodophyta*), and brown algae (*Phaeophyta*). It can be classified based on sizes bigger than microalgae [65].

Microalgae can thrive in various environmental conditions, including in aquatic environments where microplastics are prevalent [66]. Algae are types of biomass sources which can adapt to future challenges. They are suitable sources for liquid and gaseous biofuels and valuable co-products within bio-refineries [67]. They can be easily accessible and available, have high growth and reliable yield per unit area, and not compete for land cultivation. Being sustainable, using algae biomass as a fuel alternative for renewable energy to replace petroleum has become rising attention among researchers [68]. The algae consist of two types, which are microalgae and macroalgae, as photosynthetic aquatic organisms. Chlorophyll is the key photosynthetic pigment to fix atmospheric carbon dioxide (CO_2) in photosynthesis. Microalgae do not have stems, roots, or leaves, which makes them advantageous as they are easy to handle and can be harvested in the bioreactors [69]. On the other hand, macroalgae have stems, roots, or leaves. Here, the greenhouse effect due to petroleum can be reduced as the algae biomass (microalgae and macroalgae) can capture the carbon to reduce the impact of carbon emissions contributing to climate change [67].

Nowadays, studies on renewable energy from microalgae have been greatly considered. This species uses light and water to conduct photosynthesis and produce potential biomass along with oxygen as their product. This oxygen will then attract electrons towards them, and the current will flow [70]. Marine microalgae have become the main oxygen contributor in the aquatic environment [71]. Besides that, microalgae reduce nitrogen and phosphorus in wastewater [72]. The advantage of utilizing microalgae is that they can consume CO_2 through photosynthesis and be converted to the substrate (useful substances) [71].

Microalgae can exercise several metabolic pathways for their growth. Here, microalgae are considered phototrophic. A metabolism that uses light as the energy source for photosynthesis and promotes chemical energy. They are also a heterotrophic organism that uses organic compound as energy and produces oxygen. Some microalgae species, such as *Chlorella*, can be heterotrophic or phototrophic. It depends on the availability of the substrates [73]. In the microbial fuel cell, microalgae comprehend nitrogen and phosphorus from wastewater as the energy source for growth while aiding in removing the total phosphorus and nitrogen in wastewater. It also can

Table 2
The relationship of microorganisms in degrading microplastic and the related Sustainable Development Goals (SDGs).

Sustainable Development Goals (SDGs)	Descriptions	Reference
3 GOOD HEALTH AND WELL-BEING	Good Health and Well-being Microorganisms can contribute to the reduction of microplastic pollution, which can have adverse effects on human health. By degrading microplastics, microorganisms help mitigate the potential risks associated with microplastic ingestion and exposure.	[80]
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Industry, Innovation, and Infrastructure Microorganisms offer a potential biotechnological approach for improving the biodegradation of plastics. Research on the enzymes and mechanisms involved in microplastic degradation by microorganisms can lead to innovative solutions and technologies for plastic waste management.	[81]
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Responsible Consumption and Production Microorganisms play a role in the biodegradation of microplastics, reducing plastic waste in the environment. By degrading microplastics, microorganisms support the goal of responsible consumption and production by promoting the circular economy and reducing the accumulation of plastic waste.	[80]
14 LIFE BELOW WATER	Life Below Water Bacteria and algae aid in deleting microplastics in marine environments. By breaking down microplastics, microorganisms help mitigate the negative impacts of plastic pollution on marine ecosystems and preserve marine life.	[82]
15 LIFE ON LAND	Life on Land Microorganisms also play a role in the degradation of microplastics in terrestrial environments. By breaking down microplastics, microorganisms contribute to the restoration and preservation of land ecosystems, reducing the harmful effects of plastic pollution on biodiversity and soil health.	[82]

lower wastewater's chemical oxygen demand (COD) [74]. All algae comprise protein, carbohydrates, lipids, and nucleic acid, depending on the type of algae itself.

Moreover, they are easily cultivated due to their ability to endure several climate conditions. They also produce many interesting byproducts, such as fats, sugar, and several functional and bioactive compounds. Some algae have a high percentage of fatty acid (oil) that can be converted into biodiesel as a source of energy [75].

4. Waste management of plastic

Nowadays, there are three main plastic disposal methods: burying in landfills, incineration, and recycling, and each has its constraints. The problem needs to be overcome as there needs to be more space to cater to the high volume of plastic waste in landfills. Moreover, it takes time for this material to be degraded. Plastic in landfills adds to the secondary pollutants to the environment. It includes volatile matters such as benzene, xylene and trimethylbenzene [50]. Bisphenol A (BPA) released from the landfill generates a high amount of hydrogen sulphide, which is fatal to the ecosystem [76]. Incineration has overcome the landfills problem as incinerator only requires a little space [50]. However, as plastic is incinerated, many harmful gases are released into the atmosphere. The greenhouse gases include carbon dioxide, oxygen free radicals and polycyclic aromatic hydrocarbon (PAH). From the shortcomings of these two approaches, recycling can be introduced to vanquish it. Several methods of recycling PET were hydrolysis, aminolysis and methanolysis [50].

Waste management of plastics is a critical environmental and societal issue, as plastic pollution poses significant threats to ecosystems, wildlife, and human health. Proper waste management is essential to mitigate these problems. The most effective way to manage plastic waste is to reduce its generation in the first place. It can be achieved by using fewer plastic products, opting for reusable alternatives, and encouraging businesses to minimize single-use plastics [77]. Governments play a vital role in regulating and promoting reuse and reducing plastic [78].

Plastic waste management is a global challenge that requires efficient and sustainable solutions (see Table 2). Recycling is a crucial component of plastic waste management. Plastics can be sorted, cleaned, and processed into new products. Commonly recycled plastics include PET (used in bottles), HDPE (used in containers), and PVC (used in pipes and other products). Effective recycling programs involve collection, sorting, processing, and manufacturing. Integrated solid waste management strategies, such as waste characterization, collection, and treatment, are essential in addressing plastic waste [79]. Community recycling programs, curbside collection, and recycling centres play a role in this process.

Some plastics, particularly non-recyclable or low-value plastics can be converted into energy through incineration or pyrolysis. While this can reduce the volume of plastic waste, there are better solutions than this due to potential environmental and health concerns associated with emissions from burning plastics. Landfilling is often the least desirable option for plastic waste management, especially for non-biodegradable plastics, as it takes up space and poses environmental risks if not properly managed. Modern landfills are designed to minimize environmental impacts, but reducing reliance on landfills should be a priority.

4.1. *Emerging technologies for microplastic reduction*

4.1.1. *Mechanical methods for microplastics reduction*

Mechanical technologies encompass a range of procedures employed to physically extract microplastics from water or wastewater to mitigate their presence. Membrane techniques, such as ultrafiltration, can effectively eliminate microplastics from water through the physical separation mechanism of filtration. One simple and renowned method of membrane process is electrocoagulation, which uses electric current to coagulate and remove the pollutant [83]. Implementing skimming and settling techniques in wastewater treatment facilities has proven effective in removing microplastics. These methods involve the entrapment of microplastics inside the sludge, facilitating their separation from the wastewater. The pulse clarification process involves utilizing a technique aimed at effectively eliminating microplastics within wastewater treatment facilities [84].

Mechanical aeration scouring is a process that can be used to remove microplastics from water. This process involves using air bubbles to detach microplastics from surfaces and remove them from water. The most recent methods for microplastic removal are based on mechanically assisted aeration scouring, in-situ chemical cleaning, and enzymatic and bacterial degradation. Leslie et al. (2017) [85] found that aeration during secondary treatment in a wastewater treatment plant removed 99% of microplastics captured with 0.25 μm–5 μm mesh. However, conventional wastewater treatment plants are not fully capable of removing microplastics, and the microplastic removal efficiency is approximately 25% during primary treatment and 50–98% during secondary treatment. Mechanical, chemical, and biological treatment processes removed approximately 99% of the microplastics entering a wastewater treatment plant. Applying aeration can reduce the deposition of solid particles on the membrane surface by air scouring effect, but irreversible membrane fouling is challenging. Overall, mechanical aeration scouring is a promising microplastic reduction technology, but it must be combined with other methods to achieve high removal efficiency [85,86].

4.1.2. *Chemicals methods for microplastics reduction*

There is also a chemical approach of technologies in reducing the microplastic pollution in water. The chemical approach involves adding certain types of chemicals that can aid in removing the pollutant. For example, adding either inorganic or organic coagulant in chemical coagulation will help clumping the microplastic and settling it out from the water bodies [87]. The mechanisms for microplastic removal during coagulation are charge neutralization and hydrophobic interaction between microplastics and coagulant flocs [88]. Some chemicals can attract and bind microplastics. Hence, the process name is adsorption [89]. Biochar is one of the emerging adsorbents for removing microplastics from water, and its adsorption efficiency has been demonstrated [90].

Photodegradation is a process that can be used to break down microplastics using light energy [89]. Chemical digestion is a process that can be used to remove microplastics from samples by treating them with reagents such as KOH, HNO_3, or H_2O_2 to dissolve the matrix and separate the microplastics by filtration or gravimetrically [91]. Digestion can be used to remove organic matter from samples containing microplastics, and protocols can vary depending on the sample type and the microplastic being analyzed. Alkaline digestion protocols have been developed and tested to preserve small microplastic particles while removing organic tissue material. Digestion can be used alone or with other methods to achieve high removal efficiency.

4.1.3. Biological methods for microplastics reduction

4.1.3.1. Potential of fuel cell technologies. More discussions and research are needed to evaluate the microplastic disintegration process, especially in the wastewater environment via a fuel cell. This analysis will state the possibility of microplastic degradation in a microbial fuel cell. Microorganisms have the potential for electricity production, which can be tapped using microbial fuel cells. Microbial Fuel Cells (MFC) are biochemical devices that produce electricity during microorganisms' aerobic or anaerobic respiration [91]. The MFC has been considered an innovative and environmentally friendly bioenergy technology with great potential for generating electricity for energy storage [93]. The microorganisms oxidize the organic substrates in their anode chamber in the anode electrode, which produces protons and electrons. Then, the electrons will move towards the cathode externally, and the protons will diffuse through the membrane. They will be reduced to water with the help of the oxygen in the cathodes.

Several studies have used ambient air, mechanical aeration, or algae growth in the cathode chambers [94]. From the Sustainable Development Goals perspective, microorganisms are vital to maintaining life [95]. The positive functions of the microbes in the environment can be illustrated in this MFC technology. Therefore, the integration of microbial technology in the Fourth (4th) Industrial Revolution to achieve the SDG Goals needs to be put forth. Besides reducing plastic waste pollution, particularly in marine environments, MFC renewable and sustainable technology can potentially restore energy demand, reducing climate changes due to greenhouse gases [96].

4.1.3.2. Microbial fuel cell. MFC is an advanced renewable energy technology that converts chemical reactions in organic and inorganic compounds into electrical energy. Hence utilizing the microbe's activity as a catalyst [97]. MFCs offer great opportunities for an environmentally friendly approach to the electricity produced directly from biodegradable materials. MFCs typically consist of an ion-conducting membrane separating between an anode and cathode compartment [98]. There are several obstacles in implementing this MFC system, which consumes a high installation expenditure with an expensive proton exchange membrane (PEM). The common material used for the electrode is Platinum (Pt). However, low power has been detected due to electron transfer output [70]. Many efforts are made to overcome this weakness, such as using single-chamber MFC. Research has been done without using PEM and changing the Pt electrode with other economical materials such as carbon. Thus, more types of MFC technology exist due to the advancement of this exploration (see Table 3).

Microalgae-microbial fuel cells (MMFC)s have been demonstrated to be effective in removing nitrogen (N) and phosphorus (P) compounds from wastewater through the symbiotic relationship between microalgae and bacteria [62]. Based on their research, the chemical oxygen demand (COD) removal is lower in continuous mode than in batch mode. It maybe because, in the continuous mode, the new wastewater sample is continuously injected. Hence, the COD will always increase.

There are a variety of studies which have employed MFC technology in treating wastewater. Research done by Costa & Hadiyanto (2018) [70] has cultivated the potency of bioelectricity produced from microalgae growth in tapioca wastewater in cathode and anode chambers, respectively. The output from the investigation achieved the maximum power density of 4433 mW/m^2 on day 6. The configuration for the microbial fuel cell, whereas the *Spirulina platensis* was placed in the cathode chamber, and the tapioca wastewater was added in the anode compartment. The graphite electrode with a 15-W lamp was inserted in the MFC. The membrane has been arranged between the anode and cathode compartment, including a multimeter digital. Campo et al. (2013) [98] studied that the oxygen provided by the aeration technique in the MFC can be replaced with the oxygen produced from the photosynthesis process of

Table 3
Microbial fuel cells (MFCs) that employ microalgae for microplastic breakdown have their benefits and drawbacks.

Advantages	Disadvantages
Microalgae-based MFCs efficiently remove nitrogen, phosphorus, and CO2 from wastewater, treating organic pollutants.	MFCs are beneficial for wastewater treatment and energy production, but microalgae may not directly degrade microplastics, therefore other processes or treatments may be needed.
MFCs can generate bioelectricity by growing microalgae in the cathodic chamber, which consumes less CO2 and contributes to sustainable energy production.	Integrating technologies like microbial electrolysis cells and algal cathodes might complicate system design and management.
Microalgae-microbial fuel cells and microbial electrolysis cells can treat residential wastewater simultaneously, providing a complete wastewater treatment and energy generation solution.	Microalgae's efficiency in degrading microplastics in MFCs may need additional optimisation to provide practical and scalable solutions.
MFC algal cathodes may treat wastewater and produce microalgal biomass, recovering energy and removing pollutants.	
Bacteria-microalgae metabolism in biofuel cells may improve MFC performance.	

Table 4
Previous research on the degradation of microplastic with microbes and microalgae used with its physical condition.

Types of plastic	Types of microbes and microalgae	Contact time	Temperature	pH	Summary	Comments/Future Development	Reference
HDPE and LDPE	*Bacillus* sp.	3–12 month	30 °C	7.5	There is a reduction in the surface polymer. However, it is less than 20% after a year of experimentation.	This paper investigates whether microalgae can degrade microplastic pollution not in the water environment. There is a future need to investigate in the MFC system.	[114]
Polyethylene	Electroactive bacteria (EAB)	7 days	Room temperature	7	The concentration of PE microplastic affects the highest current density from 1.99 A/m2 to 0.74 A/m2, and there were fewer electroactive bacteria in the exoelectrogenic biofilm. No specific microalgae were used.	The microalgae used in this research is not specified however, it reveals the impact of PE microplastics on exoelectrogenic biofilms, and probable pathways exist.	[115]
Polyethylene terephthalate	*Phaeodactylum tricornutum*	14–42 days	21 °C	8	Eukaryotic microalgae can be a base frame for the decay of PET through synthetic biology. This study gives an insight towards the bioremediation of PET-polluted seawater.	It is found that microalgae *P.tricornotum* can be a frame to generate an engineered version of PETase to degrade PET.	[64]
Polypropylene	*Spirulina* sp.	112 days	24–26 °C	7–8	This study found that with microplastic in the environment, the growth rate of microalgae itself is slower compared to the environment without microplastic.	The test results show that PET and PP are biodegrading, but it's still not clear that the process of biodegradation with microalgae works best. Further experiment needs to be done.	[59]
PP, PE, PET, and PVC	*Chlorella* sp. and *Phaeodactylum tricornutum*	96 h	25 ± 1 °C	7	The experiments showed that microplastics stopped the growth of *Phaeodactylum tricornutum* with an inhibition ratio of up to 21.1%. On the other hand, *Chlorella* sp. showed a strong ability to respond to microplastics. It was also seen that microalgae might be used as an alternative bio-solution to clean up microplastics.	Microplastics inhibited *P. tricornutum* growth by up to 21.1%, according to experimental results. However, *Chlorella* sp. adapted well to microplastics. SEM and TEM photos confirmed the harmful effects of tested microplastics on both microalgae, including variations in critical enzyme concentrations.	[58]
PE, PP and PS	Marine microbes	54 days	25–30 °C	<2	They used the solar simulator to make the microplastic undergo photodegradation. However, the leachates of the microplastic degraded can have varied effects on oceanic microorganisms.	From this research, it is found that, while microalgae can help in degrade microplastic, microplastic can harm or inhibit the growth of microalgae, by the leaching of its additives.	[45]
Plastic polymer (disposable mask)	*Chlorella* sp.	3 months	24–26 °C	7–8	The surface membrane of Chlorella sp. cells was shown to be damaged based on the results of the SEM examination. Disposable masks have resulted in declining water quality and adverse effects on microalgae due to their growth-inhibiting properties.	Research has revealed that worn disposable masks can harbour a variety of microorganisms, making them a significant environmental concern.	[116]
Polystyrene	*Spirulina platensis*	30 days	23 ± 2 °C	7	The Fourier Transform Infrared (FTIR) study reveals a discernible alteration in the functional group on the Styrofoam material. The SEM-EDX test findings indicate that polystyrene possesses the potential to serve as a source of nutrition, particularly in terms of carbon, for the photosynthetic activities of *S. platensis*. The culture experienced a notable increase in carbon content, namely by 24.56%.	SEM-EDX tests indicate that polystyrene can provide S. platensis with nutritious carbon for photosynthesizing. It is found that while carbon content increase in a culture, Styrofoam also damage *S. Platensis* cell.	[117]
Polyethylene terephthalate	*Spirulina* sp.	14 days			The findings suggest that the presence of *Spirulina* sp. impacts the salinity system of medium-added PET. However, the highest increase occurred during the PET augmentation in media containing a salinity of 7 parts per thousand (ppt). It indicates that PET salinization can be degraded by *Spirulina* sp. when utilized as a source of polysaccharides. Polyethylene terephthalate (PET) exhibits resistance to degradation due to its aromatic component.	PET and salinity, lowered *Spirulina* sp. growth rate by 0.174 day–1 and nitrogen elimination rates in culture. However, the salinity system on medium-added PET showed that Spirulina sp. can breakdown PET in water with a salinity of 7 ppt.	[118]

microalgae in the cathode chamber. The system has simultaneously supplied the CO_2 at the cathode as the microalgae source in photosynthesis. They monitored the evolution of cell voltage and dissolved oxygen consumption each day. From the investigation, the values of dissolved oxygen uptake were not constant throughout the day. However, they reached their maximum values at 14:00 h and 20:00 h (during the dark phase when algae needed oxygen consumption). A high-power density of 13.5 mW/m^2 has been attained at a steady state condition. Therefore, this system has demonstrated an effective approach to treating wastewater independently.

Trusek etl al (2018) [99] examined the application of two-chamber microbial fuel cells using *Saccharomyces cerevisiae* as microbes. The experiment used glucose as a carbon source (substrate) and implemented it in the batch system. An initial yeast concentration has been observed in the trial. From the observation, it is found that when the substrate concentration is higher than the yeast, the voltage reaches the maximum value (30–38 mV). Moreover, the factors influencing the yeast's concentration have been detected. The study has acknowledged the notion of an integrated process comprised of membrane separation and bioreactor processes.

MFC comprises several important components of the system, which includes the electrode. Premalatha et al. (2022) [100] studied the types of electrodes used for MFC. In their study, research has been done for carbonized carbon bread bioelectrodes producing carbon bread foam and carbon cloth with carbon bread foam coated to the carbon cloth. Subsequently, the bioelectrodes were prepared, and the properties were analyzed. The XRD has proven the existence of carbonization in bioelectrodes. The XRD analysis concluded that carbon bread foam bioelectrode has the maximum ionic conductivity value compared with the other two. Hence, the compact MFC has been built from the carbon bread foam bioelectrode. The output voltage of a single MFC has been measured, demonstrating the current carbon-bread-foam bio-electrodes that offer potential use in electrochemical devices.

Studies by Chen et al. (2014) [92] is one of the earliest research projects which compared the performance of anaerobic and aerobic microbial fuel cells (MFC). The aerobic MFC system requires the presence of oxygen to complete the system, while the other way around is for the anaerobic system. In the anaerobic system, the design needs to prevent the exposure of biomass sludge to the air. From their experiment, the anaerobic MFC can generate high electricity, while aerobic MFC can produce the same energy capacity aided by the diluted substrate. Both MFC systems are supplied with different substrates which is glucose for the anaerobic system and glucose with yeast for the aerobic system.

4.1.3.3. Single chamber MFC. In this design, the cathode and anode electrodes are placed in the same chamber, separated by a membrane (see Figure 3). The ohmic resistance can be reduced by decreasing the interelectrode spacing. Joining the two-chamber eludes the use of catholyte, raising the power density [97].

Hernández-Flores et al. (2015) [101] produced a new, inexpensive single-chamber microbial fuel cell. Their research also compared the newly developed MFC with the one equipped with a Nafion membrane. From the comparison, the research found that the internal resistance of both types of MFC has a slight difference at 112 and 110 for the new MFC and the Nafion MFC, respectively. This value showed a promising result due to the minor internal resistance obtained from both systems. The maximum volumetric powers of the new MFC are 15% less than the Nafion MFC. However, this method is less expensive than the previous one. A positive result has been obtained from the outcome for single chamber types of MFC.

Anappara & Krishnan (2021) [102] studied metal removal with energy generation in a synthetic wastewater medium in a single-chamber microbial fuel cell (SCMFC). They used *Shewanella putrefaciens* as biocatalyst. The experiment is carried out in two different modes: batch and continuous. The higher voltage obtained for batch mode was 0.769V, with a metal removal efficiency of 91.1%. For the continuous mode, the maximum voltage produced is 0.81V with iron removal of 86.4% after 13 h retention time. Therefore, this study found that there is a possibility to treat heavy metals in actual wastewater using this technique, according to the data produced.

Another study by Din et al. (2020) [103] used the SCMFC in treating potato wastewater to reduce the chemical oxygen demand (COD). Thus, the highest voltage of 1.12V with COD removal of 40% was obtained as the experiment's output. The optimum condition of pH 7, under room temperature, and 12.45 mA current generation has been set for this investigation.

From the SCMFC, many approaches have been made to reduce the cost of membranes employed in the dual chamber of MFC. However, the power output voltage is still higher in dual chamber MFC.

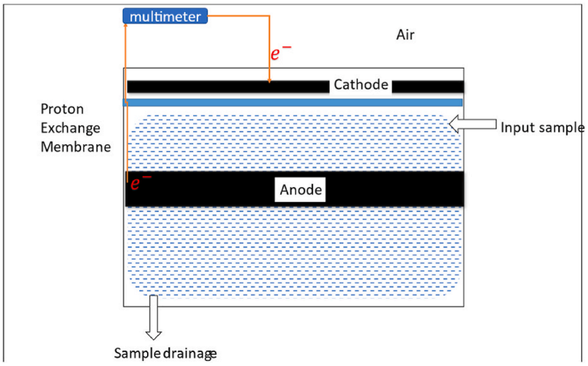

Fig. 3. Example of schematic design of single chamber microbial fuel cell [104].

4.1.3.4. Dual chamber MFC. The typical design of a Microbial Fuel Cell consists of two sides of the chamber divided by a Proton Exchange Membrane (PEM) or salt bridge. The electrode is placed on both sides of the chamber and is a transport medium for electron transfer. Bacteria cultivation will occur at the anode side of the chamber, while wastewater will be treated at the cathode side (see Figure 4). Normally, this MFC is operated using batch mode [97].

Most research on dual chamber MFC has been conducted at the laboratory scale level. Karuppiah et al. (2022) [105] tried electroplating industrial wastewater as raw material in DCMFC to remove organic content and simultaneously produce energy. They intend to examine the influence of organic load (OL) on removing organic matter and power generation. From the results obtained, the optimum removal condition has been achieved at OL of 1.5 gCOD/L. During this OL value, maximum power and current density have been evaluated at 260 mW/m^2 and 364 mA/m^2, respectively. At the same time, it has been observed that the total oxygen demand (TCOD) was at 87%, the soluble oxygen demand (SCOD) was at 79%, and the total suspended solids (TSS) were at 72%. Therefore, these findings on the method approach can overcome the problem of electroplating industries.

A recent study by Do et al. (2022) [106] examined the DCMFC-based biosensors by analyzing copper (Cu) and arsenic (As) in municipal wastewater. From their observations, the concentrations of copper and arsenic had affected the voltage output. The maximum voltage of the biosensor and the concentration of heavy metals were shown to be significantly correlated linearly, with the coefficients of $R_2 = 0.989$ and 0.982 for copper and arsenic, respectively. The concentration-dependent inhibition ratios for copper and arsenic showed that the activity of the electrogenic bacteria on the anode surface mostly influences the electrochemical changes. This research opened a new possibility for using microbial fuel cells as a heavy metal biosensor.

Another research by Do et al. (2022) [107] observed the DCMFC as a biosensor for in-situ monitoring Bisphenol A (BPA) pollutants in wastewater. BPA is used in the manufacturing of epoxy resin and other polymers. However, BPA is a dangerous pollutant that disrupts living organisms and the environment. From this exploration, they found that the biosensor's cell voltage generated was enhanced with the addition of BPA. Images taken with a scanning electron microscope (SEM) showed that the surface electrode with BPA injection had a better biofilm layer than without the BPA. These findings demonstrated the capability of electroactive biofilm based MFCs for detecting the BPA in wastewater.

Samudro et al. (2021) [108] stated that reactor design and configuration is one of the key elements in improving the performance of microbial fuel cells (MFCs). It can be denoted that the double anode chamber dual-chamber microbial fuel cell (DAC-DCMFC) system was used in assessing the regressors and their operational parameters to evaluate the performance. Two anode chamber sections with a separator and cathode chamber comprise its basic structure. For eight days, the DAC-DCMFCs functioned in parallel (60 days after the acclimation period). They were periodically pumped-fed with the various organic loading rates (OLRs) using simulated wastewater made of chemically enriched sucrose. The applied OLRs were changed between 0.4 kg/m^{3}d and 2.5 kg/m^{3}d at low, medium, and high ranges. There were two different cathode materials for type 1 and type 2 reactors. From the evaluation of analytical tools, the following parameters were measured: pH, temperature, oxidation-reduction potential (ORP), optical density 600 (OD600), chemical oxygen demand (COD), and total organic carbon (TOC). The power production process attained a maximum power density of 866 mW/m^2, a volumetric power density of 5.15 W/m^3, and an 84% coulombic efficiency. At a medium range of OLR, two-stage COD and TOC removal have produced results between 60 and 80%, respectively. For the DAC-DCMFC in improving the power generation and organic elimination, medium OLR has been suggested to be implemented. It can be explained that the dual anode chamber of microbial fuel cells with its anode chambers split into two sections with various organic loadings has expressed more understanding of the integrated MFCs for wastewater treatment.

4.1.3.5. Microalgae-microbial fuel cell. A microbial fuel cell (MFC) is a device that can induce energy by oxidizing the organic matter with the aid of bacteria as its catalyst. MFC is renowned as an inventive device used to treat wastewater and concurrently generate

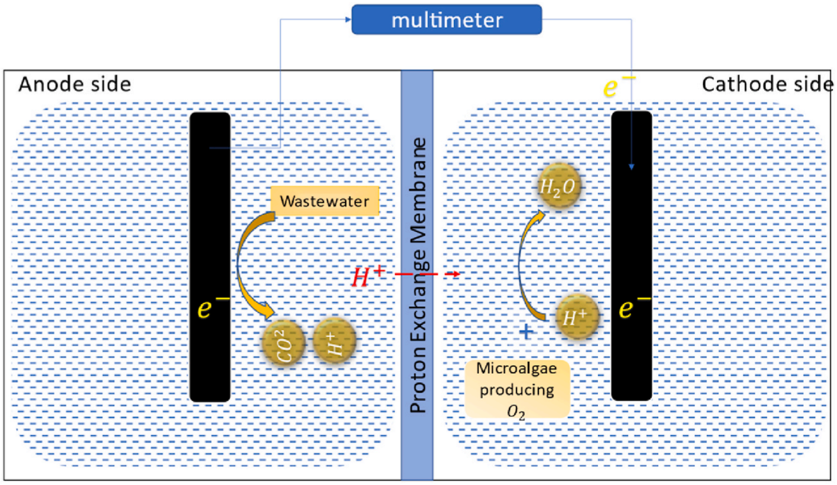

Fig. 4. Example of schematic design of dual chamber microbial fuel cell [109].

power, which aids in the operational cost of wastewater treatment [74]. An MFC device will exploit a redox reaction between the side of the chamber, which is the cathode and anode, with an ion-exchange membrane separating them. Biocatalysts of substrate oxidation produce electrons and protons [72]. During electron transfer, electrical energy is produced. Meanwhile, biomass and oxygen are produced in the cathode chamber due to the photosynthesis of microalgae (See Figure 5) [70]. The biochemical reaction occurs at the cathode, and the anode is as follows:

$$\text{Anodic}: aHC + bH_2O \xrightarrow{oxidation} cCO_2 + de^- + eH^+ \tag{1}$$

$$\text{Cathodic}: fO_2 + eH^+ + de^- \xrightarrow{reduction} bH_2O \tag{2}$$

$$\text{Overall}: aHC + fO_2 \rightarrow \ cCO_2 + bH_2O \tag{3}$$

$$6\mathrm{CO_2} + 12\mathrm{H}^+ + 12\mathrm{e}^- \rightarrow \mathrm{C_6H_{12}O_6} - (\text{biomass}) + 3\mathrm{O_2}$$

Hydrolysis of microalgae occurs during the pre-treatment before introducing it to a microbial fuel cell. From equation (1), it is shown that the oxidation process converts glucose ($C_6H_{12}O_6$) that comes from the consumption of bacteria in wastewater (H_2O) into carbon dioxide (CO_2), hydrogen ion (H^+) and electron (e^-). Equation (2), at the cathode side of the chamber, CO_2 reacts with proton and electron from the anode to produce biomass ($C_6H_{12}O_6$) and oxygen (O_2). During hydrolysis, glucose and mannitol are secreted from the reaction process. Glucose is important for fuel cells, as it will later generate electricity. It is proven from previous research by Zhao et al. (2018) [110] that a voltage of 0.5V is produced without a lag time due to the high concentration of glucose and mannitol formed during pre-treatment. From their experiment, it has been observed that an amount of 95% has been removed for TCOD.

4.1.4. *Application in the degradation of plastic*

It is necessary to find the most suitable microalgae for the degradation process of MP. In contrast, the laboratory environment can be controlled with certain parameters which can be optimized. It is different from the natural ecosystem. However, it is important to know the influence of dominant parameters on the reduction of MP. Various bacteria attributed to the biofilm colony can uptake MP as the substrate. Therefore, combining the microalgae in MFC will be a promising method for MP degradation.

Microplastics, or microfibres, are pollutants produced by the breakdown of plastics or the fragmentation of textile products. The activity of washing the synthetic textiles contributed to at least 35% of MP in the water [111]. Research by Talvitie et al. (2017) [112] found that removing microplastic pollution from wastewater during treatment has been recorded between 40% and 99.9%. From their investigation, the highest removal of MP recorded was using a membrane bioreactor.

Several bacteria, such as *Escherichia* and *Bacillus*, can secrete PETase enzymes that catalyze the degradation of polyethylene terephthalate (PET) microplastics [113]. This PETase enzyme can maintain its activity at a lower temperature of 21 °C and in the marine environment. The photosynthetic microalgae of *Phaeodactylum tricornutum* aided the microbial fuel cell in enhancing the production of PETase in the surrounding medium. Terephthalic acid (TPA) and mono (2 hydroxyethyls) terephthalic acid (MHET), which are expected to occur in the micromolar range under the chosen reaction conditions, were the primary products arise from the breakdown of the PET substrate. From the analysis, it can be demonstrated that the diatom *P. tricornutum* could be effectively transformed into a reasonable frame for biological PET degradation using synthetic biology. This proof-of-concept highlights the diatom system's potential for future biotechnological applications in biological PET degradation, particularly for bioremediation strategies for PET-polluted seawater [64].

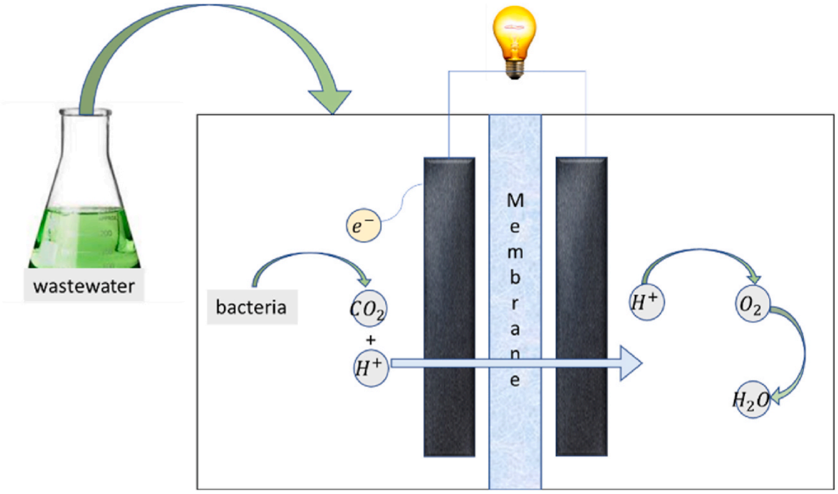

Fig. 5. Illustration for dual chamber MFC separated by Proton Exchange Membrane (PEM).

Data from Sudhakar et al. (2008) [114] have proven that environmental factors such as temperature, pH, and contact time affect the biodegradation of microplastic. The initial increase in carbonyl index, evident in the FTIR spectrum, was probably caused by the oxidation of dissolved oxygen (abiotic factor). Long-term contact with living organisms caused the carbonyl index to fall due to the biodegradation process (biotic) using a photochemical reaction with ketones and aldehydes or by ester production. In the presence of *B. sphericus*, the tensile strength of thermally pre-treated LDPE and HDPE, as well as unpretreated starch-blended LDPE, fell by 27%, 14.8%, and 30.5%, respectively, and their crystallinity reduced by 8%, 2.2%, and 8.5%, individually.

Previous research has established that polyethene-microplastic (PE-MP) adversely impacts microbial electrolysis cells (MEC) compared to MFC. The maximum current density (from 1.99 to 0.74 A/m^2) and quantity of electroactive bacteria (EAB) in the exo-electrogenic biofilm appeared to drop as the PE microplastics content in the MECs rose from 0 to 75 mg/L. While in the MFCs, the current production had minimal effect, and the amount of EAB at 25 mg/L microplastics barely increased. The functionality of bio-electrochemical systems depends on exo-electrogenic biofilms. This study lays a methodological foundation for developing effective water treatment technologies. It gave the first glance at the impact of PE microplastics on the exo-electrogenic biofilm and revealed the probability for future processes at the gene level [115].

Khoironi et al. (2019) [59] studied the impact of microplastics PET and PP towards the microalgae *Spirulina* sp. The experiment is done by putting the microplastics and microalgae in the same glass bioreactor. From the observation, the tensile strength of PP and PET decreased by 0.9939 MPa/day for PET and 0.1977 MPa/day for PP. The EDX analysis also proved a reduction in carbon for both microplastics. This result showed that microplastic degradation occurs when introduced with *Spirulina* sp.

Previously, Song et al. (2020) [58] studied the various microplastics, including PP, PE, PET, and PVC interactions with microalgae of *Chlorella* sp. and *Phaeodactylum tricornutum.* According to the experimental findings, microplastics inhibited the growth of *Phaeodactylum tricornutum* MASCC-0025, with an inhibition ratio as high as 21.1%. However, in contrast, *Chlorella* sp. L38 shows a strong capacity for adaptation to microplastics. Their observation proves it through TEM and SEM. It has been detected that additives are potentially leaching from the four studied microplastics, which could cause a harmful effect. Additionally, it was noted that microalgae might be employed as a substitute for bio-solution for the treatment of microplastics.

5. Conclusion

The degradation of microplastics can be potentially accomplished using MFC chambers as an oxidation-reduction process. Both sides of the MFC chambers need a sufficient supply. This source comes from bacteria from wastewater that will consume microplastic. Later, the byproduct of carbon dioxide can be utilized by microalgae growth in another chamber. This system will later produce the oxidizing agent, oxygen, which combines with hydrogen-producing water in the cathode. Energy cultivation happens when electrons pass through the anode to an external circuit, generating a current. Thus, this promising technique can be implemented for long-term best management practices in reducing pollutants, especially the MP. However, further investigation on the condition and suitability of the microalgae and their behaviours towards MP needs to be put forth.

Data availability statements

The authors declare that the data supporting the findings of this study are available within the paper. Should raw data files be needed in another format, they are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Nurfadhilah Zaini: Writing – original draft. **Norhafezah Kasmuri:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Amin Mojiri:** Supervision. **Tomonori Kindaichi:** Formal analysis. **Satoto Endar Nayono:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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