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Unveiling the Potential: Biodegradation of Plastics by Algae : A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Plastic pollution is a serious environmental and ecological issue and disposal methods such as burying, burning, and chemical breakdowns harm biodiversity. To reduce those negative impacts it is crucial to find effective plastic-degrading techniques. According to recent research studies, biodegradation of plastic by microalgae is likely a sustainable solution.This paper reviews the research done on the role of algae in plastic biodegradation, current research revealed that numerous algae and cyanobacterial species such as *Chlamydomonas reinhardtii, Scenedesmus dimorphus, Oscillatoria* and *Chlorella vulgaris,* degrade various types of plastic by using enzymes such as ligninolytic and exopolysaccharide. These species are useful in reducing "white pollution". This study gives a brief process of algal biodegradation of plastic by various species giving insights into the previous 07 years of research work and the future potential in this field.

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1. INTRODUCTION

In this globalised world, it was in the 1970s that plastic carrier bags came into the picture and became prevalent in our daily lives [1]. They are generally used for clothing, groceries and other daily tasks [2]. Plastic has been a vital component of our way of living for decades. However, it is tough to degrade or decompose. Incineration, landfilling, and chemical processes are conventional procedures for disintegrating plastic. While, landfilling requires more than a thousand years to break down plastic, chemical and incineration processes pollute the air to a large extent. One of the petroleum-derived products is high-density polyethylene often used to manufacture synthetic organic polymers such as polyethylene plastics. Globally, 24% of total plastic waste happens to be burned and only 18% of plastic waste is recycled, the remaining 58% is landfilled or thrown into the environment where it accumulates and lasts for an extremely long time [3]. Currently, in the US 19% of the entire municipal solid waste is made of plastic, wherein the landfill rates for used plastics exceed 75% [4]. It is estimated that by 2050, the worldwide plastic waste accumulation in the environment and landfills will reach a peak of almost 12,000 Metric tonnes [5,3]. In news reports [4]. According to some publications "plastics" may not decompose [6]. However, these claims often do not mention the specific type of plastic and environmental conditions [4]. When buried in landfills, polythene remains unaffected for decades due to its inert nature and is tough to degrade in environmental conditions [4]. However, a negligible amount of weight loss and inadequate degradation was observed when polythene was kept in moist soil for 12-32 years [7]. Polythene exhibits certain properties that contribute to its distinctive characteristics. These include its insolubility in water, ability to repel water, level of crystallinity, the presence of a central backbone composed of carbon atoms, and its high molecular weight [8,9,10]. Based on the different characteristics such as branching level, density and presence of a functional group, low-density polythene is differentiated into linear and branched low-density polythene [11]. Low-density polythene films are widely used for the packaging of edible and non-edible items, used as a coating in paper and textile industries as well as for the production of trays and plastic bags [12], because they are transparent, toxin-free have low water vapour permeability and have better heat-sealing ability [11]. High-density polythene is a thermoplastic produced with little branching by a catalytic process, when compared with low-density polythene, has greater stability and is more tough, opaque, and durable at higher temperatures. Hence it is extensively utilised in industries and everyday applications such as water pipes, detergent bottles, garbage bins, etc [13]. The widespread utilisation of polythene has led to the ingestion of plastic waste, which can obstruct the intestines and cause digestion issues in birds, fish, and marine mammals. Additionally, it poses a significant environmental threat to marine and terrestrial ecosystems and has pushed many species to the brink of endangerment [14,15,16,17]. India generated approximately 5.6 million metric tons of plastic waste. Only 60% of all the plastic waste produced in India was collected and recycled. In India; Mumbai, Delhi, Chennai, and Kolkata generated 4.43%, 7.49%, *4.66%, and 4.62% of plastic waste respectively and these four major metropolitan cities contributed about 21.2% of the total plastic waste generated in India [18]. It is estimated that the consumption of plastic bags is approximately 500 billion bags per year. They can persist in the environment for up to 1000 years without degradation. It is crucial to manage plastic waste management and to do it only three degradation methods including recycling, landfills, and incineration are widely done on a large-scale basis.

There are three main methods for disposing of plastic waste: landfilling, burning, and recycling. These are the most widely used techniques for breaking down plastic waste materials. When plastics are incinerated, they release dangerous chemicals such as dioxins, carbon monoxide, NOx, SOx, and heavy metals into the atmosphere immediately [19,2]. However, the residual effects of these methods have severe adverse effects on the environment. Landfilling on the other hand also releases dangerous gases into the environment with the disadvantage of requiring large amounts of land. To solve these environmental matters linked to landfilling and incineration, recycling plastic waste is used as a solution, but it comes with its own set of drawbacks; it is comparatively less efficient and reduces polymer properties. In addition, the procedure is less cost-effective, lowering the motivation for investing in recycling plants [2]. Waste plastics usually get burned or disposed of in landfills, however, both of these processes have very significant negative consequences on the environment. Plastic incineration leads to the release of harmful greenhouse gases including dioxins and furans. They are responsible for the decline of the ozone layer. Dioxins may severely hamper the functioning of the human endocrine system, posing substantial risks to human health and they can also severely contaminate the land [2].

An artificial organic polymer can serve as a carbon and energy source for one or more types of microorganisms, resulting in the process called biodegradation [20].

In bioremediation, the process of biosorption is metabolism-based and it includes two steps: 1) The adhesion of the pollutant to the cell's surface, or vice versa, is determined by the size ratio 2) The movement of pollutants into the cell can be achieved through either active or passive means. To enhance the uptake of plastic particles, biomass may be immobilised or coupled with membrane separation. Biodegradation can be summed up in four important steps. (i) Bio-deterioration is characterised by superficial degradation that begins in the initial phase of biodegradation, with mechanical and chemical properties of the macromolecular structure being attacked. This process is typically carried out via abiotic parameters such as mechanical, thermal, and chemical, including air turbulence, sunlight, and atmospheric pollutants [21]. The development of biofilm begins to form on the plastic particles and the microorganisms initiate the production of extracellular polymeric compounds which leads to the development of cracks through penetrating the plastic pores. Further degradation is carried out by chemolithotrophic bacteria by the production of nitrous acid [22]. (ii) Bio-fragmentation is mainly carried out by microbes utilising oxygenases to weaken central chains of carbon by creating alcohols through the insertion of oxygen to the carbon chain, or by hydrolases like proteases and lipases [22,21]. (iii) Assimilation can only be accomplished by microorganisms when certain transporters like receptors are utilised to traverse the cytoplasmic membrane [22,21]. As the particles of building blocks are inside, energy is produced by the oxidation and synthesis of biomass through catabolic pathways like aerobic respiration, anaerobic respiration, and fermentation. (iv) Mineralization is referred to as total disintegration as secondary metabolites are manufactured by the biodegrading organism via absorption, which can be utilized by other organisms. CO2, CH4, H2O and CH4 are oxidised metabolites as well as final products. Plastic fragment degradation by living photosynthetic bacteria should be considered a future strategy [21].

1.1 Need for Biodegradation

Hence, in such situations, the microbial degradation of plastic stands out as a contemporary, eco-friendly approach [23]. Waste made up of plastic can be degraded without causing any harm to the environment by biodegradation. Currently, no methodology would make it possible for the commercial-scale biodegradation of polyethylene. Given the enormous metabolic capacity of microorganisms, more study is ongoing, on the biodegradation of plastic polymers [9]. Complete biodegradation of the organic polymer is only possible when it provides growth and energy as a substrate for the biological agent. The final product of this process is microbial biomass [2]. We cannot eliminate plastic as it has several advantages in construction, sterile medical applications, and food packaging. However, its long lifespan leads to continued plastic pollution [4,3]. Therefore, having an understanding of the process of biodegradation is crucial for the decomposition process. Biodegradation occurs at varying levels in different plastic materials. Some plastics like polythene, polycaprolactone, and polystyrene, exhibit low levels of biodegradation, whereas others like polyhydroxybutyrate and polylactic acid, show higher biodegradation rates [20,24]. Various factors, such as the material being broken down and microbiology and ecosystem parameters, can impact the rate of polymer biodegradation in natural environments [20].

1.2 Effects of Microplastic (MP’s) /White Pollution

Microplastics (smaller than 5mm) derive from products such as drugs or personal grooming products or through macroplastics that have been destroyed abiotically. The resulting microplastics were almost omnipresent and continued to degrade into even smaller nanoplastics, which measure less than 100 mm in size [25]. Microplastic pollution has been found in even the most remote and inaccessible regions, including Antarctica. Microplastics contain lethal substances such as pollutants and heavy metals that enter the ecosystem at the level of microbes and small animals due to their tiny size and physical properties [26]. Plastic products are broken down into small particle sizes as nanoplastics (less than 1 μm), microplastics (1 μm to 5 mm), mesoplastics (5 mm to 5 cm), macroplastics (5cm to 50 cm), and mega plastics (above 50 cm) as a result of various physicochemical and biological reactions [27]. These particles can be found anywhere in the ecosystem, including air, soil, water, and environmental media [28]. They are even able to travel great distances in air and water currents. Of all, food chains are a direct route for microplastics to get into the human body. Therefore, it poses a serious risk for humans [29]. Their complex and varied characteristics, including composition, form, and size, are linked to their toxicity. According to reports, naturally occurring microplastics with a fibre-like form and extremely small size are more harmful [30]. There are two primary characteristics of plastic toxicity to organisms: –

1) Consumption or accumulation of plastics, damages an animal's and human's natural metabolism, affecting their neurological activity, reproductive health, and intestinal functions. In extreme circumstances, this can be fatal as it produces a self-toxic effect [31]. Plastics are often made with additional ingredients like flame retardants, colour pigments, biocides, and UV stabilisers. Unfortunately, these substances can be released into the environment when plastics are exposed to stressors like strong water and air pressure, intense UV light, and natural weathering. This can be harmful to the natural biota around us [32].

2) Microplastics, due to their small size and large surface area, have a high adsorption capacity for heavy metals (such as Zn, Cu, and As) and persistent organic pollutants (POPs). Adsorbent materials can move upwards, which can harm the natural food chain. These materials are toxic and persistent, which harms the ecosystem in many ways. Therefore, it is essential to eliminate plastic and microplastics to ensure a healthy future for the environment [33,34].

2. METHODOLOGY

We searched for literature-related papers from 2017 to 2024 databases available on PubMed (Medline), Google Scholar, NCBI, Web of Science, and SCOPUS to find the studies done on Biodegradation of polythene by microalgae and cyanobacteria. We used phrases or keywords such as “biodegradation of plastic”, “degradation of polythene by microalgae”, and “degradation of polythene by cyanobacteria”. To find other relevant studies, we also looked through various references of the papers that were discovered in review articles, and other relevant publications.

2.1 Algal Biodegradation

Previous research suggests that microalgae are promising candidates for biodegradation due to their lack of endotoxins and no need for a carbon source, unlike bacterial systems, and further research studies indicate that identifying algae and their toxic substances capable of degrading plastic materials through biological methods could effectively mitigate the harmful effects of "white pollution” [35,36].

Coastal habitats accumulate most plastic pollution, which isn't suitable for PETase-producing microorganisms like *I. sakaiensis* [26,37].

Moreover, the transversal area of Polyethylene sheets colonised by algae exhibits surface degradation or breakdown. Previous studies have recognised five biodegradation mechanisms that include fouling, leaching, penetration, hydrolysis, corrosion, and pigmentation through polymer diffusion. Fouling is the term used to describe how the development of biofilm on polymer surfaces changes their properties and contaminates the surrounding media. The leaching method involves the breakdown of leaching components, like monomers and additives. The components might leak out and serve as a food source. Embrittlement and a lack of stability are the results of this type of degradation. The next technique is corrosion, in which the polymer's surface is significantly eroded. The hydrolysis and penetration procedures are next. Biofilms serve as an optimal electrolyte that increases surface conductivity and swelling because they're made up of more than 80% water. Colouration involves the production of pigments by certain microbes that tend to penetrate through the polymers, giving them an odd colouration rather than the precise destruction of the polymers [2,38].

2.2 Enzymes used for Biodegradation

In sewage water, it has been observed that algae grow on synthetic materials such as plastic surfaces, this growth is determined to be least

Table 1. Algae and cyanobacteria which are commonly used for biodegradation

Name of algae	Kingdom	Phylum	Availability	Habitat	Type of plastic degraded	Time taken for plastic degradation
Dunaliella salina	Plantae	Chlorophyta	Common in Saltwater lakes	Brackish Water	Oxo- degradable plastic	70% after 12 weeks (84 days)
Dunaliella salina	Plantae	Chlorophyta	Common in saltwater lakes	Brackish Water	Oxidised HDPE	
Chlamydomonas reinhardtii	Plantae	Chlorophyta			PET(TPA)	
Scenedesmus dimorphus	Plantae	Chlorophyta	Common in sewage water	Freshwater Bodies	LDPE	3.74% (+/-0.26) after 45 days of incubation
Anabaena spiroides	Plantae	Chlorophyta	Common in sewage water	Freshwater Bodies	LPDE	8.18% +/-0.66 after 45 days of incubation
Navicula pupula	Plantae	Chlorophyta	Common in sewage water	Freshwater Bodies	LDPE	4.44% (+/-0.82) after 45 days of incubation
Phaeodactylum tricornutum	Chromista	Heterokontophyta	Common in brackish water	Brackish water	PET	
Uronema africanum Borge	Chromista		Common in freshwater lake	Freshwater Bodies	LDPE	
Oscillatoria princeps	Bacteria	Cyanobacteria	Common in sewage water	Domestic sewage water sites	LDPE	
Oscillatoria limosa	Bacteria	Cyanobacteria	Common in sewage water	Domestic sewage water sites	LDPE	
Oscillatoria subbrevis	Bacteria	Cyanobacteria	Common in sewage water	Domestic sewage water	LDPE	4% Carbon used after 6 weeks of incubation
Oscillatoria vizagapatensis	Bacteria	Cyanobacteria	Common in sewage water	Domestic sewage water site	LDPE	
Oscillatoria okeni	Bacteria	Cyanobacteria	Common in sewage water	Domestic sewage water sites	LDPE	
Oscillatoria limosa	Bacteria	Cyanobacteria	Common in	Domestic	LDPE	

Name of algae	**Kingdom**	**Phylum**	**Availability**	**Habitat**	**Type of plastic degraded**	**Time taken for plastic degradation**
			sewage water	sewage water sites		
Oscillatoria laete-virens	Bacteria	Cyanobacteria	Common in sewage water	Domestic sewage water sites	LDPE	
Oscillatoria amoena	Bacteria	Cyanobacteria	Common in sewage water	Domestic sewage water sites	LDPE	
Chlorella sp (Chlorella vulgaris)	Plantae	Chlorophyta		Marine water	LDPE	
Phormidium lucidum	Bacteria	Cyanobacteria	Common in sewage water	Domestic sewage water sites	LDPE	3% Carbon used after 6 weeks of incubation
Lyngbya	Bacteria	Cyanobacteria				
Spirulina sp,	Bacteria	Cyanobacteria			Polypropylene & PET	

toxic and dangerous [19]. The process of plastic biodegradation is initiated by the adhesion of algae onto its surface, which in turn produces ligninolytic and exopolysaccharide enzymes [39]. The biodegradation process is started by macromolecular interactions between the polythylene surface and the algal enzymes in a fluid medium [40]. Algae utilise polymers as a carbon source, large cellular materials such as proteins and carbohydrates were discovered in the species that were developing on the PE surface, and a significant development rate was also observed [41]. Biodegradation is appealing due to its eco-friendliness and cost-effectiveness. However, it has disadvantages such as time consumption, implementation challenges, and species-specific gaps [33].

2.3 Insights into Biodegradation Studies

The papers discussed below have thorough and diversified insights on plastic biodegradation by distinct microalgae and cyanobacteria species which are abundantly found and are most commonly used to degrade polyethylene. The discussion below offers a comprehensive, broad perspective on the degradation of plastic including fundamental processes, comparing results, and applications used during the process of degradation. The inclusion of these studies is justified based on importance, diversity, and potential for future research and solutions.

1. Degradation by Micro Algae –

Dunaliela salina is a prevalent microalga found in the ocean. It plays an important role as it contains a high amount of protein, lipids, and carotenoids, which serve as a food source and contribute to socioeconomic worth [42]. Using microalgae *D. Salina*, Hadiyanto et al. [43] studied the biodegradation of oxidised HDPE and oxido-degradable plastic in 2022. One of the innovative environmentally friendly plastics is Nexium. To accelerate the breaking of macromolecular bonds in polythene, pro-oxidants, or oxo chemicals, are added to polymers derived from standard polyolefins to create oxo-degradable plastics. Acetyl coenzyme A, a product of plastic biodegradation contributes to the production of proteins, carbs, and fats, which causes this additional biomass. Numerous research has demonstrated that microalgae can biodegrade microplastics [44,45]. The work examined the breakdown of oxium and oxidised high-density polyethylene microplastics. Adding microplastic and treating them with oxidised HDPE reduces D. salina’s growth rate. This showed that oxidised HDPE microplastic’s hydrophobicity has a greater effect on their ability to get inside *D. salina* cell membranes than the oxium microplastic. This study suggests that microalgae can help decompose microplastics by reducing microbial activity. However, because of the large concentrations of pollutants and carbon adsorbed onto microalgae cells, microplastics themselves negatively affects the suppression of microalgae growth. More research is needed on the oxidising capacity and impacts of hydrogen peroxide before treatment on microalgae during HDPE oxidation. This study's findings should serve as a foundation for future studies [41]. Oxo-degradable plastic bags broke down by about 70% after 12 weeks (84 days) at sea, according to Chiellini et al. [46]. Additionally, Parsy et al. [47] analysed how *D. salinum* development was influenced by plastic biodegradation. Furthermore, De Souza Celente et al. [48] showed that *D. salina* grew by using the inorganic carbon dioxide (CO_2) that was created from the nutrient sodium bicarbonate ($NaHCO_3$) instead of organic carbon in culture. *D. Salina* cell density increases as a result of the catalysis production of carbon dioxide (CO_2). Thus, microalgae do not directly consume microplastics as an essential form of carbon. There was no development in the growth of *D. salina* when organic carbon molecules were present from microplastics or other sources. S. Wang et al. [42], researched the effects of polystyrene (PS) and aged polystyrene (A-PS) microplastics on *D. salina.* They assessed the physiological and metabolic properties. polystyrene (PS) and aged polystyrene (A-PS) showed no hazardous effect on *D. salina*, whereas it hindered the growth rate of *D. salina* and stimulated pigment synthesis in algal cells. Polystyrene (PS) and aged polystyrene (A-PS) caused significant levels of reactive oxygen species (ROS) is responsible for oxidative damage to algal cells. Aged polystyrene (A-PS) boosted glutathione metabolism in *D.salina* and also increased metabolites of glycerophospholipids demonstrating that polystyrene (PS) and aged polystyrene (A-PS) initiated membrane lipid peroxidation. The damage in the aged polystyrene (A-PS) group was more severe than that in the PS group.

Chlamydomonas reinhardtii is a unicellular, photosynthetic microalgae used as a model organism, as it has various advantages [49,50] (Harris, 2009). Appropriate for ecologically friendly applications since it is regarded as "generally recognised as safe (GRAS)." Kim et al. [51] studied the expression of PETase, an enzyme that degrades PET (polyethylene terephthalate), in green microalgae *Chlamydomonas reinhardtii*. They concentrated on *C. reinhardtii's* PETase's functional expression in their investigation. To produce a stable transformant, they compared two strains of *C. reinhardtii*. They used western blotting to verify PETase expression upon transformation. Researchers used SEM and liquid chromatography with high performance to quantify and qualitatively demonstrate PETase activity. The researchers used the CC-124 strain of *Chlamydomonas reinhardtii,* which contains mutations such as nit1 and nit2 and is commonly utilised in labs for the transformation of genes. *C. reinhardtii* strain CC-503, which has no cell wall, a mutant of CC-125, was used to have effective transformation. They looked for PETase gene expression and transformation in these two strains. Using the ShBle-2A fusion expression system, the codon-optimized PETase gene was substituted for the mCherry gene in pBR9_mCherry_Cre to create pBR9_PETase_Cre, a high-strength expression vector for C. reinhardtii [52,53]. They electroporated two strains with this plasmid (pBR9_PETase_Cre) to transform them. Using the chosen clones, they carried out a western blot analysis to verify the presence of PETase. The results show that CC-124 is a better choice for PETase expression. Also, their study showed that the marine algae *P. tricornutum* develops less effectively than the green algae species like *Chlamydomonas* and *Chlorella* [54,55,56]. Since *C. reinhardtii* is a freshwater microalga and grows efficiently they decided to use it as an alternative host. *C. reinhardtii* derivatives utilised in their investigation revealed morphological and chemical alterations only after 4 weeks, indicating a considerably slower rate of breakdown. PETase from *C. reinhardtii* catalysed PET with a rapid degree of conversion, despite the slow speed reaction. Kim et al. [51]. discovered functional PETase expression in *C. reinhardtii*, a green microalga. Additionally, they used HPLC analysis to find TPA, or the completely decomposed form of PET, to establish the catalyst functioning of PETase. In addition, after PETase treatment, morphological changes on the PET film surface were examined using electron microscopy. The research on the biodegradation of polythene using 3 photosynthetic microalgae (*Scenedesmus dimorphus, Anabaena spiroides & Navicula pupula)* was conducted by Kumar et al. [1]. He gathered samples of used plastic bags and water contaminated by photosynthetic microalgae in January 2016 from freshwater bodies such as ditches, ponds and pools in Tamil Nadu, India. A total of 20 discarded plastic bags covered with mats of photosynthetic algae were collected. Maduravoyal (8 samples), Vanagaram (5 samples), and Poonamallee (7 samples). *Scenedesmus dimorphus* was determined to be dominant when microalgae were isolated and identified from the collected samples in the lab. *Anabaena spiroides* were notably predominant among the blue-green algae in comparison to all three locations. In a similar vein, it was discovered that *Navicula pupula* dominated the other isolated Diatoms. The transverse section of the polyethylene sheets that Kumar et al. [1] collected revealed microalgae causing surface breakdown or degradation caused by hydrolysis, fouling, corrosion, leaching components degradation, and pigmentation which diffused into the bonds of polymers. All three microalgae showed all five biodegradation processes in the t-section of plastic bags. The selected algae grew well in the control flask of the 3 culture mediums compared to treatment flasks of low-density polythylene and high-density polythylene sheets. The blue-green algae *Anabaena spiroides* showed more mass growth on the low-density polyethylene sheets than the other two. Furthermore, compared to the other treated microalgae, *Anabaena spiroides* was more successful in colonising the surface layer of the low-density polythylene sheet. The average rate of degradation for green algae, *Scenedesmus dimorphus*, is 3.74% (+/-0.26), while the average percentage for blue-green algae, *Anabaena spiroides*, is 8.18% with +/-0.66. Approximately 4.44% (+/-0.82) of the deterioration is attributed to *Navicula pupula*. *Anabaena spiroides* showed a significant breakdown percentage in the low-density polythylene sheet. Additionally, *Scenedesmus dimorphus* cells grasped to the LD polythene sheet even though the surface of the sheet appeared unaltered, according to the author's SEM analysis. On the other hand, blue-green alga *Anabaena spiroides* was discovered to have both colonised and perforated the LD polythene sheet, leaving a tiny hole on its surface. The diatom *Navicula pupula* showed the low-density polythene sheet's surface erosion. SEM study results revealed that microbial organisms collected from the forestry soil and the vehicle wash-out sludge were breaking down the polythene by creating cavities on its surface after 45 days of incubation [57]. The SEM investigation demonstrates that *Anabaena* *spiroides* (blue-green algae), is one of three varieties of algae treated on the LDPE sheets to generate a void on the surface. Some erosion was seen by *Navicula pupula* on the surface of the LDPE. Researchers concluded that *Anabaena spiroides,* is the filamentous form of microalgae that is most successful in the biodegradation of polythene sheets among other groups of microalgae [58].

2. Degradation by Cyanobacteria-

Sarmah et al. [59] investigated the colonisation of algae patterns on LDPE polyethylene surfaces, focusing on blue-green *Oscillatoria* species which are filamentous and non-heterocystous found in sewage water in domestic sites in Silchar, Assam. They found that 20 different species of Oscillatoria were dispersed throughout submerged polythene, from which the most often found species include *Oscillatoria princeps, Oscillatoria subbrevis, Oscillatoria limosa, Oscillatoria amoena, Oscillatoria vizagapatensis, Oscillatoria okeni, Oscillatoria limosa, and Oscollatoria laete-virens.* To determine, the impact of sewage water parameters on Oscillatoria diversity, they conducted correlation research. Algal colonisation development and biodegradation are influenced by physicochemical parameters such as pH, temperature, BOD, COD, Free CO2, nitrate, ammonia, phosphate, etc. They gathered algal-colonized polyethylene bags from Silchar town's residential sewage water drains and studied them under an 80x magnification microscope connected to a computer. Their observation displayed attachment of *Oscillatoria princeps* with thallus dispersed throughout the polythene surface. On the polythene surface, *Oscillatoria princeps*, which were present in every research site, created dark blue-green mats. During the period of intense sunshine, brownish mats were also visible. *Oscillatoria subbrevis* colonises and breaks down polyethene without any pro-oxidants effectively and *Oscillatoria limosa* in conjunction with *Lyngbya* species spreads enormously and initiates the breakdown of polyethene. *Oscillatoria tenius* appeared to be alone on the polythene surface. *Oscillatoria geitleriana* and *Oscillatoria earlei* were seen in conjunction, and *Oscillatoria peronata* contributed to both, wastewater and polythene surface colonisation. They observed that during sunlight the *Oscillatoria* species proliferate and the production of mats is more visible, along with the polythene surface the mats formed also float in the sewage water. Physicochemical parameters like Water temperature, BOD, pH, DO, Total alkalinity, Suspended Solid, Nitrate, Calcium, Sulphate and free CO2 have a positive correlation with Oscillatoria species. Whereas, COD has a negative correlation with Oscillatoria Species and total dissolved solid does not correlate with Oscillatoria Species. Maximum colonisation on polythene surfaces is seen during winter months. Oscillatoria and other algae species made up around 49% of the overall algal cover. This coincides with *Oscillatoria*, the major genus found in submerged polythene bags in sewage water [60].

In a 2021 study, Bhuyar et al. [61] evaluated plastic biodegradation characteristics with *Chlorella* and *Cyanobacteria* species, as a consortium. In January 2019**,** three locations near Kuantan City, Pahang, Malaysia- “Teluk Chempedak (five samples), Taman Gelora (three samples), and Pekan Coast (two samples)-” provided ten discarded polyethylene bags containing an algae-covered green mat of photosynthetic microalgae.They used sterile distilled water to serially dilute the microalgal samples from the water samples and the plastic bags. The researchers employed inoculations (1 ml) ranging from 10-1 to 10-10 in distinct solid media, including BG-11 for blue-green algae and BBM for green microalgae, on a spread plate. The inoculated Petri plates were cultured for an entire week at a temperature of room (25±2 °C) with twelve hours of light. Microalgae colonies consequently begin to develop on the surface of solid substances. Different streak plate techniques and solidified media were used to extract pure microalgal cultures. When compared to the individual species growth of *Cyanobacteria* and *Chlorella sp*., which are both microalgae, the consortium of these two species displayed the highest growth, suggesting that the consortium's growth was greater than the individual sp. growth. They performed growth analysis using a spectrophotometer method and it revealed that both species were supporting one another's growth within their consortium. HDPE and LDPE were both biodegraded with the help of the consortium. Based on the study they conducted, the consortium —a combination of *Chlorella* and *Cyanobacteria* species—was able to biodegrade LDPE without the use of chemicals or capping agents. According to their assessment, the consortium functions as a cost-effective stabilising and reducing agent to break down polymers smaller than 100 nm. They utilised a consortium that secreted several exopolysaccharides, including proteins and sugars. That might convert polymers into monomers by colonising them and acting as degradative agents. The microalgae successfully attached to the surface of LDPE, resulting in maximal aggregation. The consortium's qualities were analysed using several methodologies, including UV-Spec, FESEM, EDX, CHNO, FTIR, and DSC. This included morphological, and physiochemical properties of treated polyethylene samples. Their results clearly show the consortium's capacity for aggregation as they progressed through the phases of biodeterioration, bio-fragmentation, assimilation, and mineralisation. The consortium’s microalgal colonisation effectively removes both polyethylene that is HDPE and LDPE, according to their research. This biodegradation process deals with plastic waste pollution and offers an environmentally beneficial solution. Thus, they inferred that the consortium had effectively degraded the polyethylene sheet among various types of microalgae. Sarmah and Rout et al. [39] researched LDPE biodegradation with freshwater algae on immersed polyethylene in domestic sewage water. The researchers selected two cyanobacteria, *P. lucidum* and *Oscillatoria subbrevis,* to examine their biodegradation capabilities. They gathered immersed material colonized by algae from the sewage of the Indian state of Assam’s Silchar town. Following the collection and microscopic inspection of specimens that had grown on submerged polyethylene carry bags, the two most prevalent species were selected for monotonous development. On ten PE strips that had been made, they examined the algae's capacity for biodegradation. After one week of inoculation, *P. lucidum* and *Oscillatoria subbrevis* began to colonise the PE. This was believed to be the result of initial degradation that enabled hydrophilic groups to be inserted into the PE strips because microorganisms prefer hydrophilic surfaces. They believed the polymer served as a carbon supply for the cyanobacterial colonisation that took place on the PE surface [2]. It was discovered that the species growing on polyethylene surfaces had higher cellular contents (protein and carbs) than the biotic control. As a result, they noticed that the cyanobacteria on polyethylene surfaces had a greater specific growth rate (doubling time) than the biotic control. After six weeks of treatment, they looked at the biodegradation of PE using scanning electron microscopy (SEM) and observed surface erosion, pitting, and cavity formation on the treated PE's surface. Strips treated with *Oscillatoria subbrevis* exhibited higher surface degradation than those treated with *Phormidium lucidum.* They evaluated the biodegradation of polyethylene strips using FT-IR spectroscopy. The control PE strip's spectrum showed several absorptions that demonstrated the PE's complexity. Incubation with *Phormidium lucidum* and *Oscillatoria subbrevis* resulted in variations in the strength of bands in different spots. The existence of nitrogen-containing bio-ligands was confirmed by peaks at 667 and 468 cm^{-1}, as observed in *Oscillatoria subbrevis*-treated PE. The uCO peak at 1633 cm-1 is consistent with the existence of a carboxylic group. PE biodegradation had been confirmed by related indices, with highly diagnostic FT-IR signatures for ester compounds, ketos, vinyl and internal double [62]. The indices such as KCB, ECB, VB and IDB increased in treated *P. lucidium.* Incubating PE strips with cyanobacteria results in higher KCB and EBC values due to the organisms' enzymatic activity [42]. Incubation with *Oscillatoria subbrevis* resulted in increased bond indices (KCB, ECB, and VB), but decreased IDB. Additionally, they indicated that cyanobacterial interaction could increase the PE's surface hydrophilicity by forming extra groups that the microbes can use, including carbonyl [63,62]. For both the algal-treated PE strip and the control, the carbonyl index - a crucial indicator of biodegradation - rose significantly. Using CHN analysis, Sarmah and Rout [41] also determined the elemental concentration of carbon. Following six weeks of incubation, a carbon assay showed that 84% of the carbon was present in the control PE strips. *P. lucidium* used 3% of the carbon of the PE strips while *Oscillatoria subbrevis* used 4%. Cyanobacteria's attachment to PE surfaces confirms their ability to exploit it as a renewable energy and carbon source, possibly due to the medium's low carbon supply. In addition, they analysed several variables using methods like TGA-DSC analysis, Tensile property, Growth study and PE degradation, Enzymatic activity, and NMR spectroscopy. The study found that pro-oxidant chemicals and pretreatment are not required for fast-growing, widely available, and conveniently isolable cyanobacteria to efficiently grow on PE and utilise carbon. The results are important as freshwater nontoxic cyanobacteria, which are less harmful than other bacteria or fungi and more efficient in their biodegradation process, can be used to create a biodegradation procedure for PE. These cyanobacterial species can break down polyethylene even more quickly in the natural environment, providing a real substitute for managing trash made of polyethylene [64].

The paper includes the most common species of microalgae and cyanobacteria used for the degradation of plastic, other species are also involved in biodegradation and their studies are at the nascent stage, for example, a marine microalgae *Phaeodactylum tricornutum,* was used in 2019 by Moog et al. [65]. The *P.tricornutum* is a model organism used for synthetic biology and biotechnology due to its advantages over bacterial expression techniques for producing photosynthetic PETase for biological polyethylene terephthalate PET degradation in marine habitats. Moog et al. [65] isolated *P.tricornutum* to use synthetic biology to break down PET. The microalgae were genetically engineered to secrete PETase into saltwater. PETase released by *P.tricornutum* can degrade PET for diverse substrates, even under mesophilic conditions and also convert it into (TPA and EG) the reusable monomers of polyethylene. The acquired results show how the produced microbial cell factory can be used to construct efficient photosynthesis-driven PET bioremediation methods. the study found that *P. tricornutum*, a marine diatom, may be used to synthesize and release recombinant PETaseR280A-FLAG into medium fractions using Western Blot and GFP fusion proteins. These studies provide the first evidence that the marine diatom-produced PETaseR280A-FLAG enzyme can break down PET in the model system's mesophilic environment. The study demonstrated successful production and release of recombinant proteins, as well as enzyme functioning towards several PET materials (PET, PETG film, and shredded PET) under different circumstances. These findings indicate substantial potential for future study and practical uses related to PET degradation. Another example is a cyanobacterial species namely *Spirulina sp*, which was used by Khoironi et al. [66], to degrade Polypropylene (PP) and Polyethylene terephthalate (PET). The association between the microalgae and microplastic was analysed for 112 days in a 1 L glass bioreactor containing microalgae *Spirulina sp.* and microplastics Polypropylene and Polyethylene terephthalate with a size of 1 mm at varied concentrations (150 mg/500 mL, 250 mg/500 mL, and 275 mg/500 mL). The findings revealed that the breaking point of microplastic Polyethylene terephthalate fell by 0.9939 MPa/day, whereas Polypropylene declined to 0.1977 MPa/day. The EDX study of microplastics revealed that Polyethylene terephthalate (48.61%) had an increasingly reduced carbon level than Polypropylene (36.7%). The Fourier Transform Infrared Spectroscopy examination of *Spirulina sp* cells revealed that the CO2 evolution caused by Polyethylene terephthalate microplastic was more than that of Polypropylene microplastic. The growth rate of *Spirulina sp* treated with microplastic was lower than the control, and increasing the concentration of microplastic reduced algal growth by 75%. The study concluded that biological degradation plays an essential part in the degrading process of plastic [66]. Also, Sanniyasi et al. [67], *Uronema africanum Borge* was discovered in a trash plastic bag found at a residential waste dumping site in a freshwater lake. The microalga underwent further treatment with a low-density polyethylene sheet in culture media. Results from light microscopy, dark field microscopy, GC-MS, FT-IR, SEM, and AFM indicate that the microalgae began to degrade the low-density polyethylene (LDPE) sheet within thirty days of incubation. Corrosions, abrasions, grooves, and ridges resembled microalga morphology. The radially disc-like adhesion structure of microalgae resembles abrasions on the outermost layer of a low-density polyethylene sheet, with an average diameter of 20-30 µm.

The species mentioned above are most abundantly found and are most commonly used for degradation, but from the above-mentioned microalgal species Chlamydomonas reinhardtii and Scenedesmus dimorphus have potential metabolic capabilities and are adaptable to various environmental conditions. However, a recent study reveals that *Scenedesmus dimorphus* is more effective in the biodegradation of plastic as it has high lipid and enzyme production, which fosters the breakdown of complex polymers present in plastic. Whereas, from the cyanobacterial species mentioned, *Oscillatoria* is typically thought to be more effective at plastic degradation than P. lucidum. This is due to Oscillatoria's higher yield of extracellular polymeric substances (EPS) and particular enzymes capable of breaking down complex polymers. Its capacity to build dense biofilms improves its ability to connect with plastic surfaces, resulting in more effective breakdown. Furthermore, Oscillatoria's endurance in a variety of environmental circumstances facilitates long-term breakdown methods, making it a more promising choice for plastic bioremediation [68-72].

Table 2. Summary table

Author	Year	Location of study	Study period	Study design	Species	Type of polythene	Result
Sarmah P, Rout J	2017 [60]	Silchar town, Assam, India	July-Dec,2013.	Experimental study	*Oscillatoria* species	LDPE	*Oscillatoria* is the largest genus to submerge in LDPE polythene bags in sewage water.
Hadiyanto Hadiyanto	2022 [43]	Indonesia	2022	Experimental study	*D.salina*	Oxidised oxium & HDPE	*D.salina* aids in the decomposition of microplastic but microplastics have a negative effect on its growth hence hydrogen peroxide should be added for HDPE degradation.
Pampi Sarmah, Jayashree Rout	2018	Silchar town, Assam, India	2022	Comparative study	*Phormidium lucidum* & *Oscillatoria subbrevis*,	LDPE	*O. Subbrevis* showed more damage on LDPE strips compared to *Phormidium lucidium*. Also, this species can break down polythene more quickly in a natural environment.
Ramachandran Vimal Kumar.	2017	Chennai City, Tamil Nadu, India	January, 2016.	Experimental study	*Scenedesmus dimorphus, Anabaena spiroides* & *Navicula pupula*	LDPE	*Anabena spiroides* is the most successful in the degradation of polyethylene sheets. Diatom *Navicula pupula* displayed some erosion, and the cells of green algae were stuck to LD polythylene sheets.
Ji Won Kim	2020			Experimental Study	*Chlamydomonas reinhardtii*	PET (polyethylene terephthalate)	PETase produced from *C. Reinhardtii* catalysed PET highly.
Natanamurugaraj Govindan	2020	Kuantan City, Malaysia		Experimental Study	*Chlorella sp. & Cyanobacteria sp.*	LDPE and HDPE	The consortium of blue-green microalgae successfully

						destroyed LDPE polyethylene sheets, and they also worked against HDPE.
Daniel Moog	2019	2019	Experimental study	*Phaeodactylum tricornutum*	PET (polyethylene terephthalate)	*Phaeodactylum tricornutum* Degrades PET by secreting PETase.
Khoironi et al.	2019		Experimental study	*Spirulina sp.*	PET (polyethylene terephthalate)	*Spirulina sp.* Degrades Polypropylene and PET.
Sanniyasi et al.	2021 [67]			*Uronema africanum Borge*	LDPE	*Uronema africanum Borge* degrades LDPE sheets.

3. CONCLUSION

This review report concludes that many studies on plastic breakdown by algae have been conducted, and many more are now underway. Algal Degradation is the need of the time as it is crucial to manage plastic waste. The majority of the algal species used for plastic degradation are those listed in the review study; however, other diverse species of algae also contribute to the degradation of plastic.

Future studies can be conducted utilising several techniques, such as the use of transgenic algae, the extraction of degrading toxins or enzymes from algae, or the use of eco-friendly plastics like oxo-biodegradable plastic, which is an engineered plastic with full carbon as a backbone also known as Oxium. The given review partially fulfils the lacuna for further studies in the area.

CONFERENCE DISCLAIMER

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Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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