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Role of Algae in Mitigating Impacts of Air, Soil and Wastewater Pollution

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Abstract- The environment is constantly deteriorating due to the presence of persistent and mobile air, water and soil pollutants that are altering and bringing disorder to the functioning of ecosphere. The ecosphere processes are inherently dependent on various groups of micro- and macro-organisms that play fundamental roles of production, decomposition, and fixation. One such heterogeneous group which is ubiquitously present in varied environments is the algae that comprise of both prokaryote and eukaryote photosynthetic organisms. The prokaryotic cyanobacteria or blue green algae have performed the cardinal evolutionary function of transforming the Earth's reducing state into the oxidising and life supporting environment. Due to their ecological diversity, algae possess genomic blueprints that code for unique repertoire of enzymes, molecules, and compounds some of which have been exploited; yet the copious bio wealth remain to be tapped. The unsurpassed bio-synthetic machinery performs evolutionary functions that make algae attractive for mitigating many unprecedented toxic environmental conditions. These organisms have biological properties that enable them to adapt to a variety of environmental perturbations such as nutrient starvation, oxidative, heavy metals and temperature stresses and desiccation. Various species of algae are capable of degrading polycyclic aromatic hydrocarbons, environmental hormones, polyethylene, and other class of persistent chemicals. Algae can be used to bio manufacture environmentally friendly products such as bioplastics, biofertilizers and biofuel. Along with bioengineering developments, the expansive understanding of algal biodiversity offers renewable resource of natural origin which is rapidly taking its place as a circular economy approach in integrated environmental restoration goals. Furthermore, algae mediated wastewater treatment offers cost effective bio remedial measures that subsequently reduce the carbon and water footprints in the environment.

***Keywords*:** Algae,bioplastics,hybrid photocatalysts, Phycoremediation, pollutants, water footprint

1 Introduction

Algae are group of photosynthetic micro- and macro-organisms that are ubiquitously found in all types of environments. All algae are not obligate photoautotrophs; some species that tolerate high carbon load can heterotrophically or mixotrophically metabolize organic compounds such as those present in the domestic waste waters. Algae are evolutionary equipped with vivid photosynthetic pigments such as chlorophylls, carotenes, xanthophylls and phycobilins to absorb the photosynthetically active radiations (400-700 nm) of the solar spectrum [1]. These pigments harness the quantum solar energy inside cellular 'bio-factories'to produces vast range of compounds like antioxidants, amino acids, polysaccharides, lipids, fatty acids, polyphones, etc. The algal bio-actives such as antioxidants, mycosporine-like amino acids, polysaccharides and scytonemin provide natural raw materials for human skin care products to combat the toxic impacts of air pollution [2].The intracellular protein and peptide content of blue green alga or cyanobacterium *Spirulina* aid in immobilizing heavy metals and conjugating organic pollutants, making it as an ideal candidate for Phycoremediation including DDT (1,1,1-trichloro-2,2-bis(p-chlorophenyl)-ethane)[3].The free living nitrogen-fixer cyanobacteria namely *Anabaena* and *Nostoc* improve soil productivities and function as organic fertilizers. The increased agriculture production and rapid urbanization are responsible for introducing excessive amounts of agrochemicals, toxic pollutants, and heavy metals that alter the complex soil environment which has huge impact on the micro floral biodiversity including cyanobacteria and algae [4].

The Stockholm convention on Persistent Organic Pollutants (POPs) which has put DDT under the restriction category can still be detected in the food chain around the globe. Despite its ban and restriction, DDT has been found across the globe owing to its environment persistence, illegal and exempted usage [5]for examples; post-ban inventories due to lateral transport in sea sediment cores in China [6], old soil erosion into agriculture watersheds of France [7], and usage for the vector control in South Africa [8]. Alarmingly, the urban populations in developing nations such as India are exposed to the exceeded tolerable daily intake doses via human breast feed [9]. Similar to these persistent organic soil and water pollutants, the major everlasting atmospheric pollutant is CO_2 which has created havoc and need immediate fixing. We are pressed with time to make further non-biological technological advancements and must rely on thorough implementation of biological mitigation technologies using organisms such as algae which have witnessed and have evolved through the pre life-supporting harsh environments of the Earth.

Combined use of high CO_2 flue gas and nutrient laden industrial and domestic wastewaters for microalgae farming with co-production of revenue generating bio-products is the only sustainable win-win solution to reduce the global carbon and water footprints. The algae-based carbon conversion technologies have potential to reduce our dependence on the fossil fuels; and are therefore, gaining worldwide impetus to tackle climate change crisis[10].The raising demands of expanding human and livestock populations put intense pressure on agricultural sector that accounts for 92% of the global water footprint (WF) including grey WF that only take into account the leaching and run-off nitrogen fertilizers [11]. Therefore, the need of the hour is to implement the sustainable solutions that manage agro-pollution with additional benefits of providing fossil alternatives of fertilizers and fuel for the supply value chain.

2 Diversity Of Habitats Make Algae Renewable And Sustainable

The beta diversity which measures the differences of species diversity between multiple habitats is important to understand the functioning of the ecosystems and for management of the biodiversity [12]. With respect to the aquatic ecosystems or niches, the large water bodies such as rivers, lakes, ponds and oceans are the macro habitats whereas the shallow and temporary water sources like water-filled tree caves are classified as micro habitats. The plant held waters or the phytotelma habitats harbour diverse aquatic flora [12]. Some of the species are present in low abundance to be recorded by the culture based isolation methods. These constitute microbial 'Rare Biosphere' which can grow abundantly when the conditions become favourable for their growth [13]. The algal species diversity is largely determined by various environmental factors. In global oceans, the relatedness between species is best described by the temperatures whereas for populations, whole community chlorophyll a is the useful variable [14].

In coastal and estuarine environments, the vertical distribution of algal diversity is determined by the cell size and availability of nutrients. For example in oligotrophic areas, the majority of the assemblages consist of the picophytoplankton and small nanoplankton and in the nutrient replete waters; the dominance is shown by the large nanoplankton and microplankton [15].

2.1 Natural habitats and adaptive strategies towards anthropogenic changes

The natural habitats of algae are found across all three components of biosphere viz. hydrosphere, lithosphere and atmosphere. Due to the non-uniformity of the aquatic environment with respect to changes in salinity, light penetration, nutrient status and biological communities, there occur in many spatial niches which are occupied by distinct groups of algae which are classified as phytoplankton (open surface waters), epipelon (in sediments), epiphytic (on surface of macroalgae or other plants), epilithon (on rock surfaces). Depending on the primary and secondary pigments, algae hold their habitats within aquatic ecosystems which are relative to the amount of sunlight and nutrients available. The analysis of the microalgae pigments using High Performance Liquid Chromatography (HPLC) from the water samples is utilized as biomonitoring tool to assess the water quality and extent of eutrophication [16]. In aquatic habitats, algae exclusively carry out carbon fixation and biologically interact with other organism such as bacteria to obtain nutrients via complex biogeochemical cycles which subsequently providerange of complex organic compounds to the higher trophic levels. These interactions play key functional roles in maintaining the ecosystem via prey-predation and through biochemical interactions including allelopathy.

In the lithosphere, the prokaryotic cyanobacteria colonize rocky substrates where they perform vital functions of carbon sequestration and the non-symbiotic nitrogen fixation which aid in improving the soil environment. Diverse groups of algae (Figure 1) are found in broad spectrum of habitats including the abiotically stressed environments such as arid soils, sand dunes, puddles of bird bath, ditch, hot spring, rocky shores, and snow melts. The spectrum of algae species diversity in aero-terrestrial habitats found on tree barks depend on the exposure to air borne pollutants including ground level ozone, particulate matter consisting of NH_3^+, SO_4^{2-}, NO_3^-, CO, SO_2 and soot [17]. The aerial green algae dominate temperate climates where they are able to colonize varied exposed surfaces. Aerophytic algae including those found in high altitude alpine forests possess cellular adaptive mechanisms such as changing cell volume, producing extracellular matrices, protective biomolecules and forming endo and epilithic biofilms that offer protection against UV radiation, desiccation and temperature fluctuations [18]. In deep contrast, the terrestrial algae grow up to few centimetres beneath arid to saline soils where it can withstand long periods of desiccations. To withstand these conditions, algae synthesize various low molecular weight intracellular carbohydrate osmoprotectants such as sorbitol, polyol, glycerol, ribitol and mannitol which impart them high desiccation tolerance and UV absorbing molecules likemycosporine like amino acids [19]. Due to these adaptive characteristics, algae are used as soil conditioners and bio fertilizers in nutrient-poor abiotically stressful soils. However, the intensive use of chemical fertilizers can lead to reduction in the biodiversity as well as the abundance of soil algae [13].

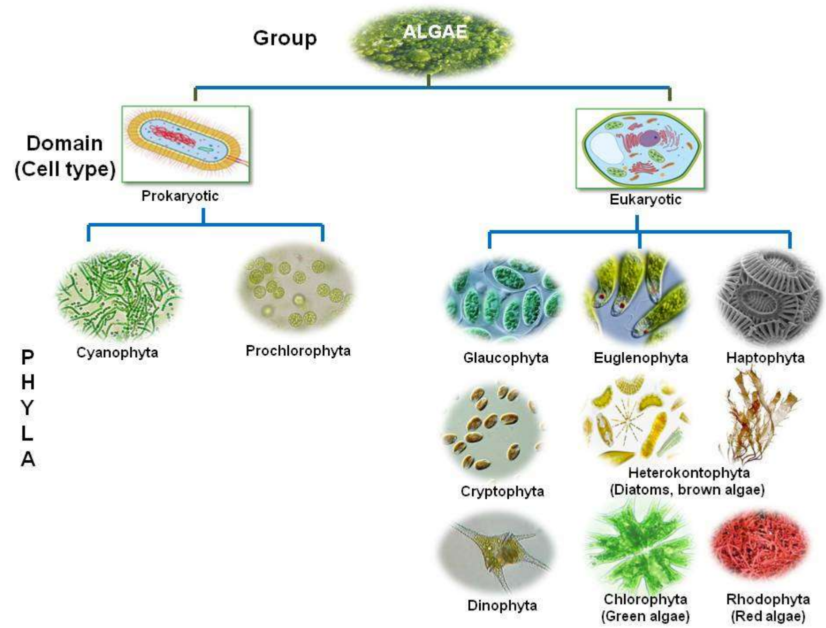

Figure 1: Pictorial representation of the various taxonomic groups of Algae

The extreme habitats of algae include snow where subsets of the terrestrial photosynthetic organisms are found. Several species of green algae show cosmopolitan distribution in the Polar Regions such as those belonging to *Chlamydomonas*, *Raphidonema*, *Chloromonadinia*colonize both the Arctic and Antarctic poles. These species form characteristic red snow during glacier melting owing to the presence of carotenoids which act as light shield against the intense photosynthetically active radiations on the snow surfaces. The specie *Chlamydomonas* cf. *nivalis* is one of the cosmopolitan cryophilic specie that forms spherical red-snow cells [20].

2.2 Algae-plastic interactions

Besides harmful and toxic compounds in the marine and freshwater habitats, the emerging causes of concern are the microplastics that are less than 5mm in size and influence the microbial colonisation in these habitats [21].In the long run, the widely used polyethylene and polypropylene thermoplastics wastes in the water bodies release their toxic additives namely, the plasticizers, polychlorinated biphenyls, dichlorodiphenyltrichloroethane, various heavy metals such as bromium, chromium, cadmium, titanium which inhibit the microalgal flora [22].

The plastic waste presents a neoteric habitat environment to these aquatic flora and fauna communities. The biotic interaction of these physical pollutants in water bodies degrades their surfaces which alter the buoyancy and the plastic polymers sink to the aphotic zones. The extent of surface degradation of plastic pollutants is more extensive when they remain in photic zone due to the exposure to Ultra-Violet (UV) radiations which initiate the degradation process [23]. The algal biofilms on the plastic particles act as a consolidated and temporary sink for micro plastics which when grazed upon by the herbivore communities at the bottom of the food web chain could possibly lead to biomagnifications [23].

3 Algae As Biomonitoring Tool For Pollutant Detection

The ecological parameters such as species richness and composition of algae are the assessment measures for the levels of pollution in habitat niches. Spatial algal assemblages have found to be correlated with the type of pollutants to which they are mostly exposed. For example, soil contaminated by the agrochemical DDT show alteration in algae specie composition through elimination of the sensitive populations as assessed by the viable cell counts [24]. The pollutants such as pesticides, metals, engineered nanomaterials, pharmaceuticals and personal care products impact the interactions of algae with their co-inhabitant bacterial communities. These cross-kingdom interactions are crucial from both evolutionary and environmental perspectives. In order to combat the pollutant stress, the algae-bacterial communities adopt various defense strategies such as cell-to-cell adhesion, substrate exchange, biodegradation of pollutants, activation of signal transduction and the horizontal transfer of mitigating genes [25]. The photosynthetic oxygen evolution by a common micro alga *Chlorella vulgaris* is one of the simplest methods to assess the heavy metal toxicity in the water [26].

The bio indicator marine species such as *Ulva* and *Cystoseira* accumulate heavy metals such as Cadmium (Cd), Thallium (Tl), Zinc (Zn), Copper (Cu), Lead (Pb) and useful Iron (Fe) [27]. As the algae form the base of marine food chain, bio magnification of these toxic metals pose threats to marine fauna and eventually to the human health. The anthropogenic sources of these heavy and toxic metals are the untreated waste water effluents flows, contaminated river discharges, industrial sludge, precipitation, and fall back of the atmospheric pollutants. The impacts of these marine pollutants can be minimized and overcome by exploiting the same algae in artificial ponds constructed on the coastal lands. The effluents from industries and waste water treatment plants should undergo prior treatment with the functional consortia comprising of the marine micro and macro algae. The algal biomass harvested from the 'pre-discharge' effluent treatment ponds can be processed to co-produce bio fuels and bio gas via anaerobic bio digestion.

3.1 Algae response to marine pollution

In addition to the effluent discharged pollutants and contamination with the solid plastic wastes; the marine waters are exposed to the detrimental hydrocarbon rich deep oil spills. The exuberant oil spills inhibit light penetration necessary for photosynthesis which hampers the growth, reproduction and inter-specie interactions that are necessary for healthy and balanced ecosystem functioning [28]. The microbial communities such as in the Mississippi river delta in the Gulf of Mexico are genomically imprinted to respond to the natural oil spills and further possess the bio machinery that can degrade the Polycyclic Aromatic Hydrocarbons (PAHs) in the marine environments [28].

In the coastal regions, there is cause and effect relationship between the nutrient enriched effluents from waste water treatment plants, oil refineries, desalination plants, coastal farming including aquaculture and the uncontrolled growth of harmful algae species with huge impacts on the ecosystem health [29]. Although secondary waste water treatment processes considerably reduce the loads of organic carbon, heavy metals and trace metals; the increased nitrogen flux are high enough to cause ocean eutrophication that subsequently lead to harmful algal blooms. The marine macroalgae or seaweeds comes as a rescue for curbing nuisance algal blooms as these 'macro-photoautotrophs' effectively remove inorganic nutrients, sequester carbon and oxygenate the water column which provide refugia from hypoxia and low oxygen levels which otherwise would be toxic to the aquatic fauna. The seaweed aquaculture has potential to control nutrient pollution (nitrogen and phosphorous) in marine waters along with their application in the production of biofuels [30].

4 Mitigating Impacts Of Pollution

Our environment has become a reservoir of cover-up toxic, carcinogenic, persistent and harmful simple molecules and complex compounds that are showing evident signs of unsteady ecological functioning with compromised vigor and diversity of biological identities. The industrial revolution has come at an enormous environmental cost. The global warming associated with strong emissions of green house gases (mostly anthropogenic) has led to multiple imbalances in the environment. These have a cascading effects resulting into climatic anomalies such as extreme changes in the precipitation patterns leading to unprecedented events of drought, extreme dry conditions, aridity and forest fires. The extraordinary burning of the biomass during severe forest and peat land fire events release primary and secondary organic pollutants including high Volatile Organic Carbon (VOC) that travel miles higher to the Upper Troposphere and Lower Stratosphere (UTLS) (Figure 2). In a case study of Indonesia, the magnitude of the landscape fires that are initiated to increase the agricultural land is intensified many fold due to El-Niño resulting into severe air pollution due to non-CO2 emissions, majorly the VOCs [31]. In addition, the research narrated that the meteorological pattern called Asian Summer Monsoon Anticyclone (ASMA) act as convection pump which hauls the short lived VOC to UTLS affecting the chemical composition of lower stratosphere with marked decrease in the ozone. The surface emissions including reactive oxygen species, organic compounds arising out of anthropogenic and climate change induced natural burning of the biomass are harmful for the entire biosphere. Many researchers have started exploring the role of atmospheric deposition onto the Earth's surface as source of vital nutrients for the phytoplankton[32]; and the redistribution of PAHs arising from forest fires into the terrestrial and aquatic ecosystems [33].The environmental PAHs and those present in the wastewater effluents are found to impact the catalytic functioning in algae which is exploited for Phycoremediation measures (Table 1).

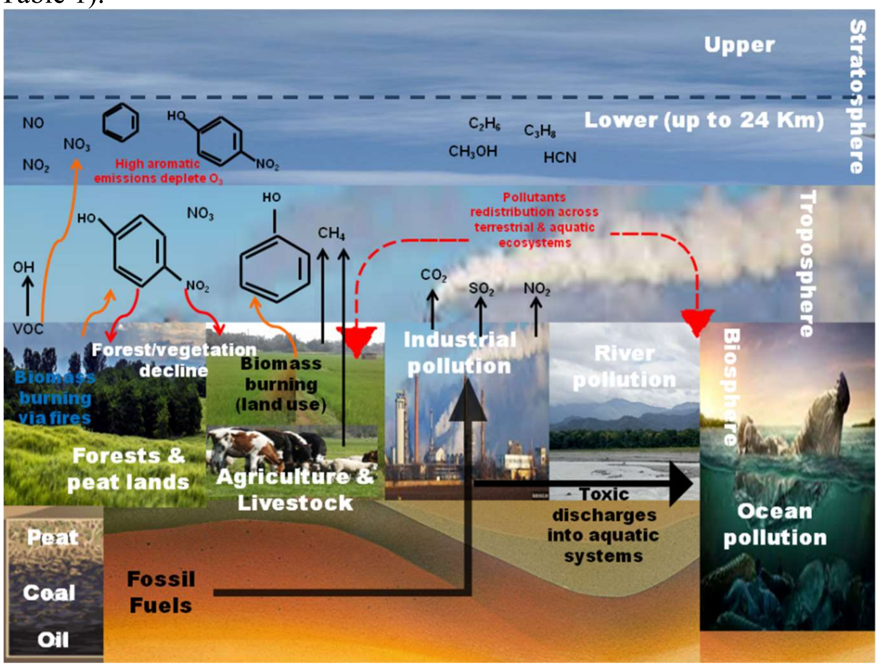

Figure 2: Sources and types of major environmental pollutants and their fluxes across the atmosphere and the biosphere.

4.1 Decontamination of pollutants in aquatic and soil habitats

Many organic compounds and their derivatives that are routinely used in various industrial, agricultural and household applications are difficult to degrade and transform under natural conditions. These potentially carcinogenic and forever chemicals eventually find their way into the livable ecosystems and food chain. The removals of these chemicals by conventional techniques which include photo- and electrochemical decomposition have high efficiencies but are expensive and often associated to cause secondary pollution. Comparatively, the bio degradation is environmentally safe and sustainable option. The abundantly present aquatic algae show high adsorption capacity, intracellular accumulation and decontamination capabilitiesfor these persistent organic chemicals. Blue green algae has been found to effectively degrade the globally phased out endocrine disruptors pesticide namely endosulphan [34].Species of freshwater algae namely *Chlorella*, *Scenedesmus*, *Fibrea* and *Cladophora* can efficiently adsorb, bio transform and degrade group of environmental hormones such as nonylphenol, octylphenol and BisPhenol-A (BPA) [34].

The ways in which algae based bioremediation strategies are adopted includes various steps that determine the efficacy of algae to act against the target chemicals. The various steps involved in such studies are i) identification of widely distributed aquatic algae species; ii) toxicity assays on algae to determine the lethality of various groups of harmful chemicals; iii) screening of tolerant species; iv) capabilities of tolerant species to remove and biodegrade target chemicals; and v) understanding the mechanisms by which these biological systems decontaminate the harmful chemicals. For example, vigorously growing oleaginous strains of marine microalgae *Nannochloropsis oculata* and *Dunaliella salina* achieve higher biodegradation and bioremediation efficiencies in waters contaminated with 0.5 mg/L of the nonylphenol due to their inherent capabilities to bio accumulate and partition organic compounds in lipid-water systems [34].

4.2 Plastic waste management

The two categories of petro-chemically derived plastics are thermoplastics and thermosetting polymers. The thermoplastic waste is basically managed via re-cycling through thermo-chemical processing wherein it gets re-introduced into the industrial production cycles. The difficulty with the thermosetting polymers is that it is composed of irreversible chemical bonds and is non-recyclable category of plastics. The conventional methods of plastics degradation including UV photooxidation, thermo-chemical oxidation, incineration and landfill are not pro end-of-shelf life waste management options. Additionally, these methods have secondary effects that are hazardous to the environment. In lieu of these ecosystem degrading plastics, the naturally degradable biopolymer not only offer safe alternate but also has become the utmost necessity to tackle various forms of environmental pollutions. The two environmentally safe approaches to tackle the menace caused due to plastic waste are a) biological degradation of already existing conventional plastics and b) development of alternative sustainable bioplastics.

The various steps involved in biodegradation of synthetic polymers are bio deterioration, depolymerisation and mineralization. For non-phototrophic microbes, these synthetic polymers act as the sole carbon source which they also utilize for their growth and biomass production [35]. This has disadvantage as for example, the Poly-Ethylene Terephthalates (PET) degrading bacterial systems that rely on plastic as carbon source produce endotoxins. In contrast, microalgae do not produce endotoxins and bypass its trophic requirement for plastic derived carbon by direct photosynthetic capture of atmospheric CO_2 [36]. The vast diversity of algae in its forms, habitat and cellular structure offer unsurpassed repertoire of cellular bio machinery in both fresh and marine waters to tackle plastic waste management. The plastic degrading microbes including bacteria, fungi and algae can be found in various plastic polluted habitats namely buried soil, landfills, marine waters and mangroves rhizosphere.

4.2.1 Phycoremediation of Plastic pollution

The two main steps involved in the plastic biodegradation process by algae are colonisation or attachment to plastic substratum followed by the breakdown of polymer into monomers which eventually lead to mineralisation. Algal colonisation by the members of Cyanophyceae, Chlorophyceae and diatoms (Figure 1) occur through biosynthesis of Extracellular Polymeric Substances (EPS) that aid in substrate adhesion owing to its unique characteristics of surface charge, hydrophobicity and electrostatic forces [35]. In addition, EPS decrease the carbon and oxygen ratio [37]. Various groups of algae colonize Low-Density Poly-Ethylene (LDPE) surfaces in multiple ways. For examples, the cyanobacteria *Dolichospermum spiroides Phormidium lucidum* and *Oscillatoria subbrevis* colonize LDPE respectively through formation of cavities, erosion and pit formation. The filament forming green alga *Uronema africanum* obtained from highly urbanized freshwater lake eroded the LDPE surface by forming abrasions, grooves and ridges to initiate the process of phototrophic biodegradation [35].

Upon physical degradation via surface erosions, cascade of biochemical processes are initiated that allow polymer deterioration. Algae secrete various polysaccharides in the form of carbohydrates and proteins such as EPS which function as degradative agents for conversion of polymer to monomers. The members of cyanobacteria and microalgae can biodegrade LDPE without prior oxidative treatments. The ligninolytic and exopolysaccharide enzymatic machinery of algae assist plastic degradation process upon adhesion onto the plastic surfaces. Generation of saturated fatty acids, carboxylic acid, esters, nitro compounds and amino groups are some of the key determinants to assess the in-situ process of LDPE biodegradation [35]. The common green microalga *Chlorella vulgaris* in conjugation with *Aeromonas hydrophilia* bacteria efficiently degrade other widely used plastic such as BPA without estrogenic activity [36]. When used as a consortium, species of cyanobacterium and Chlorella has been found efficient in acting against both low and high-density polyethylene [37]. The anthropogenic aquatic pollution caused due to the plastic debris and micro plastics have created an unnatural ecosystem called plastiphere where unique diversity of microbes including algae are thriving on these floating debris. The examples presented above clearly demonstrate the unique abilities of algae either freely or in symbiotic association with bacteria to colonize plastiphere and their key functional role in bio-deterioration, fragmentation and mineralization of the plastic polymers.

4.2.2 Cradle-to-cradle approach to obtain algal biopolymers as environmentally safe alternative to synthetic plastics

Tackling the increasing global plastic pollution is the need of hour. Relying on recycling usage is neither sustainable nor efficient way to mitigate the aggravated pollution caused by plastics waste in our water bodies and on land. The production of synthetic plastics require fossil derived energy supply which in turn release green house gases into the atmosphere; additionally discharging hazardous wastes into the water bodies causing dual air and water pollution. Therefore, their replacement with biological feedstock simultaneously allows mitigation of carbon emissions and both pre- and post manufacturing environmental pollution. The agricultural crop based bio plastics such as that made from potato and corn are not sustainable due to land, water and nutrients requirements which in turn create viscous circle of generating waste and would potentially threatens the global food security. Although agriculture waste is one of the proponents for bioplastics, the availability and insufficient supply make it an unsuitable option for extensive purposes. Alternatively, algae which are widely distributed and encompass enormous diversity have captivating position in the global market. Incomparably, algae based bio plastics derived from the wastewater by adopting cradle-to-cradle approach boost sustainable economic development goals. Apart from obtaining bioplastics or biopolymers, various other chemicals that can be derived from algae include biofuels, biolubricants, natural colouring additives, agrochemicals, defoamers, food additives, organic acids [38].Poly Hydroxy Butyrate (PHB) which is biodegradable and biocompatible thermoplastic is one of most promising non-petrochemical plastics obtained from photoautrotrophs including cyanobacteria and algae

4.3 Carbon footprint reduction by photosynthetic capture of toxic and green house gases

The food production relies on heavy dosages of nitrogenous fertilizers, manufacturing of which consume fossil fuels resulting in enrichment of CO_2 in the atmosphere. The nitrate fertilizers applied in the agricultural field are often under utilized by the crops and large proportions are lost as Nitrous oxide (N_2O) and N_2 due to denitrification by bacterial communities to the atmosphere and remaining get leached to the ground waters [39]. The emissions of nitrogen compounds originating as by-products of nitrate fertilizers persists in air causing depletion of stratospheric and tropospheric ozone and production of other fine pollutants which has serious impacts on the terrestrial biodiversity and human health [40].

The remediation of green house gases and particularly CO_2 is obligatory to mitigate the effects of global warming and climate change. The technological methods and innovations have huge carbon, water and other environmental footprints. Bio remediation of GHGs via algae have following advantages i) abundance across the globe; ii) cost effective, renewable and sustainable; iii) co-produce useful commodities, iv) tolerate harsh and fluctuating environmental conditions such as temperature, pH and salinity and v) possess unique biological machinery to capture CO_2 and other noxious gases. For example, the marine micro alga *Heterosigma akashiwo* equipped with a unique chimeric protein called NR2-2/2H N metabolize nitric oxide (NO) at 150 ppm into cellular nitrogen in presence of high CO_2 concentrations (12%) and is also a potential source of biodiesel [41].

Table 1. Examples of algae playing role in mitigating toxic environmental pollutants

Algae specie/ strain	Pollutants	Pollutant class or Source	Phycoremediation potential	Reference
Chlorella vulgaris	Fluoranthene (FLT), Pyrene	Polycyclic aromatic hydrocarbons (PAH)	48% degradation in 7 days	[42]
Selenastrum capricornutum			78% degradation in 7 days	[42]
Tetraspora sp. NITD 18	Cyanide	Coke-oven wastewater	80% removal at optimal concentration of 2 ppm	Laboratory case study (14 days)[43]
	Phenol		79% removal at optimal concentration of 100 ppm	
	Ammoniacal-N		74% optimal concentration of 400 ppm	
Chlorella vulgaris	FLT	PAH	Upto 94% removal at 25 μM (through enzymatic action of catechol 2,3, dioxygenase)	Laboratory case study (7 days) [44]
Isochrysis galbana Parke MACC/H59	Phenol	Phenolics	100% removal at 200 ppm and 92% at 300 ppm (possess biodegrading enzyme called phenol hydroxylase)	Adaptive laboratory evolution (5-10 days) [45]

Chlamydomonas reinhardtii	Phenol	Phenolics	Alginate immobilised beads remove 122 ppm	Laboratory case study (10 days)[46]
Gelidium omanense	Methanol	Industrial wastewater	80%removal of Chemical Oxygen Demand (COD)	Biosorption experiments [47]
Uronema africanum	Low density polyethylene (LDPE)	Plastic waste in freshwater lake	Profuse colonization, bio deterioration of LDPE into carboxylic acid, esters, nitro compounds, amino groups within 30 days	Laboratory case study [48]
Arthrospira platensis	Tetracycline (TET)	Water and soil contamination with antibiotic drugs	Lightweight Cu-microalgae hybrid photocatalysts were developed using biotemplating process to degrade TET in pH range of 6.0 and 8.0 with an efficiency of 76.5% and 98.3% respectively after 80 min of LED irradiation.	[49]
Phaeocystis globosa, Nannochloropsis oculata, Dunaliella salina and Platymonas subcordiformis.	Nonylphenol (NP)	Endocrine disruption compounds (Environmental hormones)	Biodegradation and biotransformation by various algae at different concentrations of NP.	[34]

5 Water Footprint Reduction By Algae

Environmental footprints are the quantitative measure of unexercised and illegal utilization of natural resources by humans for several purposes. Each footprint represents specific classes of pressures connected to process, product or activity from the viewpoint of the lifecycle. Water footprint is the indicator of direct and indirect use of water by consumers or producers of the manufacturing goods. It is categorized as blue water footprint (utilization of freshwater), green water footprint (utilization of rainwater), and grey water footprint (an indicator of water pollution). There is an acute worldwide shortage of fresh water such that it has taken the shape of planetary crisis. The extensively large water footprint that we have created is beyond the level of sustainability. Thus, the evaluation of water footprint in each sector of the economy has become crucial in an ever-increasing water-demand society. Plenty of water is required to meet the rising demands of the growing population for food, clothing, fuel, health and infrastructure across the globe. Increase in agriculture production by 50% will be needed by 2050 to meet the basics demands of food, fibre and non-conventional fuels [50].

5.1 Constricting water footprints by setting up algae-wastewater biorefinery

Eutrophication in the water bodies are globally associated with the surplus and uncontrolled growth of various group of algae, some of which tend to produce harmful toxins and are referred to as harmful algal blooms. Therefore, the fundamental attribute of algae to opportunistically sequester the nutrients from the environment can be milked via integration of algae into the tertiary water treatment processes. In the conventional primary and secondary wastewater treatment processes involving the use of various anaerobic and aerobic microbes manage the inorganic, organic and the dissolved particles which are most often being discharged into the fresh and coastal water bodies. These effluents are loaded with dissolved nitrogen, phosphorous and other toxic chemicals that pollute water bodies. By introducing the tertiary water treatment using microalgae and transforming the biomass into biofuel, bio-feed, bio-fertilizers and bio-plastics is an effective win-win strategy to overcome the menace of the nutrient and plastic pollutions in our ecosystems.

In contrast to the marine algae, the cultivation of freshwater microalgae is associated with high blue water footprint which is the major bottleneck of microalgae cultivation process. The minuscule microalgae biofactories that grow in sunlight and CO_2 feeds are also efficient in obtaining nitrogen and phosphorous from the nutrient rich wastewater streams. This potential strategy to recycle water along with high density cultivation of microalgae significantly reduce water footprint associated with the production of third generation biofuel that address the fossil fuel crisis [51].Processed and hydrolysed microalgal biomass obtained from the wastewater treatment effluent can also support the growth of recombinant *Escherichia coli* for maximum biosynthesis of polyhydroxybutyrates [52].

6 Advanced Photo-Decontamination Of Pollutants Using Microalgae

The categories of chemical substances that are emerging as new potential threats in the environment are various types of pharmaceutical products including antibiotics that are also routinely used in the rapidly growing livestock sectors. These antibacterial drugs find their way into the aquatic ecosystems due to inefficient treatment and degradation during the wastewater treatment process. The second route of their discharge is through feces and urine of drug administered animals and livestock in the soil environment. The high levels of antibodies due to poor water management practices are leading to increased multidrug resistance in various disease causing microbes. Due to high structural complexities, stability and poor biodegradability of these drugs, their removal from environment is not only crucial but is also complicated. It is challenging to find suitable adsorbents and efficient photo catalysts that aid in the removal of these antibiotic drugs from the aquatic environments.

The release of organic acids and chlorophyll molecules by microalgae in aquatic media absorb photons to induce the production of active radicals. Based on this photochemical process, algal cells are combined with other photochemically active substances and nanomaterials that act as photo catalysts. Further, the efficiency of these photocatalytic systems are improved through immobilizing algae cells onto the nanofiber mats which have improved antimicrobial, optical and photocatalytic properties. Such photo reactive bionano hybrid materials are also made using harmful algal bloom specie such as *Microcystis aeruginosa* by immobilizing the cells onto the Polyacrylonitrile (PAN)/TiO_2/Ag nanofiber mats that synergistically degrade organic and inorganic pollutants such as antibiotic tetracycline and heavy metal Cr(VI)[53].In another holistic approach of water decontamination, this principle of green and circular chemistry was integrated for the synthesis of competitive state-of-the-art hybrid helical Cu@Cu2O@CuO–microalgae photocatalyst using *Arthrospira platensis*that photodegraded the tetracycline class of antibiotics [49].

7 Conclusions

The diverse groups of organisms living in the biosphere including algae perform fundamental ecological functions namely primary production, energy flow, nutrient cycling, and pollutants degradation. The anthropogenic pollutants originating from the agricultural and industrial production are released into the hydrosphere, lithosphere, profusely expanded into the atmosphere and thus completely contaminate the biosphere. The toxicological impacts of these pollutants on the environment are complex due to their intra- and inter reactions among each other and other abiotic factors respectively. Due to their persistent nature, these toxic environmental agents including green house gases in the atmosphere and oceanic pollutants in hydrosphere are the main causes of climate change. Apart from this, the aquatic macro and micro pollutants negatively impact the socio-economic development, tourism, ecosystem functions, and meteorological phenomenon. Thus, the mitigation of these degrading environmental agents is of the utmost importance globally. Compared to the conventional environmental decontamination methods, the uses of algae bring numerous advantages. Being ubiquitously present in the biosphere, the decontamination, degradation and mitigation of simple, complex and diverse groups of pollutants using algae present an efficient, cost-effective, renewable and sustainable biotechnological option. Most importantly, the use of algae in mitigating various kinds of pollutants including fertilizers, pesticides, heavy metals, polycyclic hydrocarbons, phenols, and green house gases like CO2, NOx, SOx reduces the carbon footprints with potential to generate useful bioproducts and natural alternatives to the fossil fuel derivatives. The algae mediated Phycoremediation is ecosystem friendly method that reduce the plastic pollution and overcome the invasive dispersal of otherwise pathogenic and toxin producing microbes involved with the biodegradation process. This has important implications as invasive pathogenic plastic colonizing microbial populations producing endotoxins can have adverse effects via the aquatic food web and food chain that ultimately impact human health. Furthermore, the intensity of global food and water scarcity crisis can be de-escalated by revolutionizing the scope of services offered by widespread diversity of algal resources in forms of super food, livestock feed, nutrient supplements and reclamation of the grey waters that simultaneously reduce production associated water footprints.

References

[1] R. Blankenship, Molecular mechanisms of photosynthesis, Third ed., John Wiley & Sons Ltd, 2021, p. 352.

[2] A. Aslam, A. Bahadar, R. Liaquat, M. Saleem, W. Waqas and m. Zwawi, “Algae as an attractive source for cosmetics to counter environmental stress,” *Science of The Total Environment,* vol. 772, p. 144905, 2021.

[3] M. Kurashvili, T. Varazi, G. Khatisashvili, G. Gigolashvili, G. Adamia, M. Pruidze, M. Gordeziani, L. Chokheli, S. Japharashvili and N. Khuskivadze, “Blue-green alga Spirulina as a tool against water pollution by 1,1'-(2,2,2-trichloroethane-1,1-diyl)bis(4-chlorobenzene) (DDT),” *Annals of Agrarian Science,* vol. 16, pp. 405-409, 2018.

[4] Z. Hakkoum, F. Minaoui, M. Douma, K. Mouhri1 and M. Loudiki, “Impact of human disturbances on soil cyanobacteria diversity and distribution in suburban arid area of Marrakesh, Morocco,” *Ecological Processes,* vol. 10, p. 42, 2021.

[5] L. Tian, J. Li, S. Zhao, J. Tang, J. Li, H. Guo, X. Liu, G. Zhong, Y. Xu, T. Lin, X. Lyv, D. Chen, K. Li, J. Shen and G. Zhang, “DDT, Chlordane, and Hexachlorobenzene in the air of the pearl river delta revisited: a tale of source, history, and monsoon,” *Environmental Science & Technology,* vol. 55, no. 14, pp. 9740-9749, 2021.

[6] Z. Wu, T. Lin, L. Hu and Y. G. Z. Li, “Semi-centennial sediment records of HCHs and DDTs from the East China marginal seas: Role of lateral transport in catchment,” *Chemosphere,* vol. 263, p. 128100, 2021.

[7] T. Gardes, F. Portet-Koltalo, M. Debret and Y. Copard, “Historical and post-ban releases of organochlorine pesticides recorded in sediment deposits in an agricultural watershed, France,” *Environmental Pollution,* vol. 288, p. 117769, 2021.

[8] N. Wolmarans, L. Bervoets, R. Gerber, Y. Yohannes, S. Nakayama, Y. Ikenaka, M. Ishizuka, P. Meire, N. Smit and V. Wepener, “Bioaccumulation of DDT and other organochlorine pesticides in amphibians from two conservation areas within malaria risk regions of South Africa.,” *Chemosphere,* vol. 274, p. 129956, 2021.

[9] N. Anand, P. Chakraborty and S. Ray, “Human exposure to organochlorine, pyrethroid and neonicotinoid pesticides: Comparison between urban and semi-urban regions of India,” *Environmental Pollution,* vol. 270, p. 116156, 2021.

[10] V. Anguselvi, R. Masto, A. Mukherjee and P. Singh, “CO2 Capture for Industries by Algae,” in *Algae*, Y. Wong, Ed., IntechOpen, 2019.

[11] A. Hoekstra and M. Mekonnen, “The water footprint of humanity,” *PNAS,* vol. 109, no. 9, p. 3232–3237, 2012.

[12] N. Dalkıran, O. Külköylüoglu, S. Dere, D. Karacaoglu, E. Akay, M. Yavuzatmaca, D. Akdemir and E. Çelen, “Effect of habitat type on algal species diversity and distribution at high altitudes.,” *Ecohydrology & Hydrobiology,* vol. 21, p. 189–199, 2021.

[13] S. Subashchandrabose, B. Ramakrishnan, M. Megharaj, K. Venkateswarlu and R. Naidu, “Mixotrophic cyanobacteria and microalgae as distinctive biological agents for organic pollutant degradation,” *Environment International,* vol. 51, pp. 59-72, 2013.

[14] K. Martin, K. Schmidt, A. Toseland, C. Boulton, K. Barry, B. Beszteri, C. Brussaard, A. Clum and e. al., “The biogeographic differentiation of algal microbiomes in the upper ocean from pole to pole.,” *NATURE COMMUNICATIONS,* vol. 12, p. 5483, 2021.

[15] A. Ansotegui, A. Sarobe, J. Trigueros, I. Urrutxurtu and E. Orive, “Size distribution of algal pigments and phytoplankton assemblages in a coastal—estuarine environment: contribution of small eukaryotic algae.,” *Journal of Plankton Research,* vol. 25, no. 4, p. 341–355, 2003.

[16] M. Lee, N.-I. Won and S. Baek, “Comparison of HPLC Pigment Analysis and Microscopy in Phytoplankton Assessment in the Seomjin River Estuary, Korea.,” *Sustainability,* vol. 12, p. 1675;, 2020.

[17] K. Freystein, M. Salisch and W. Reißer, “Algal biofilms on tree bark to monitor airborne pollutants.,” *Biologia,* vol. 63, no. 6, p. 866—872, 2008.

[18] P. Nowicka-Krawczyk, M. Komar and B. Gutarowska, “Towards understanding the link between the deterioration of building materials and the nature of aerophytic green algae.,” *Science of The Total Environment,* vol. 802, p. 149856, 2022.

[19] C. Medwed, A. Holzinger, S. Hofer, A. Hartmann, D. Michalik, K. Glaser and U. Karsten, "Ecophysiological, morphological, and biochemical traits of free-living Diplosphaera chodatii (Trebouxiophyceae) reveal adaptation to harsh environmental conditions.," *Protoplasma,* 2021.

[20] T. Segawa, R. Matsuzaki, N. Takeuchi, A. Akiyoshi, F. Navarro, S. Sugiyama, T. Yonezawa and H. Mori, "Bipolar dispersal of red-snow algae," *NATURE COMMUNICATIONS,* vol. 9, p. 3094, 2018.

[21] J. Barros and S. Seena, "Plastisphere in freshwaters: An emerging concern," *Environmental Pollution,* vol. 290, p. 118123, 2021.

[22] H. Hadiyanto, A. Khoironi, I. Dianratri, S. Suherman, F. Muhammad and S. Vaidyanathan, "Interactions between polyethylene and polypropylene microplastics and Spirulina sp. microalgae in aquatic systems.," *Heliyon,* vol. 7, p. e07676, 2021.

[23] I. Smith, T. Stanton and A. Law, "Plastic habitats: Algal biofilms on photic and aphotic plastics.," *Journal of Hazardous Materials Letters,* vol. 2, p. 100038, 2021.

[24] P. Fu and F. Secundo, "Algae and their bacterial consortia for soil bioremediation.," *Chemical Engineering Transactions,* vol. 49, pp. 427-432, 2016.

[25] X. You, N. Xu, X. Yang and W. Sun, "Pollutants affect algae-bacteria interactions: A critical review.," *Environmental Pollution,* vol. 276, p. 116723, 2021.

[26] H. Eom, M. Park, A. Jang, S. Kim and S.-E. Oh, "A simple and rapid algal assay kit to assess toxicity of heavy metal-contaminated water," *Environmental Pollution,* vol. 269, p. 116135, 2021.

[27] A. Parus and B. Karbowska, "Marine algae as natural indicator of environmental cleanliness," *Water Air Soil Pollut,* vol. 231, no. 97, 2020.

[28] A. Quigg, M. Parsons, S. Bargu, K. Ozhan, K. Daly, S. Chakraborty, M. Kamalanathan, D. Erdner, S. Cosgrove and E. Buskey, "Marine phytoplankton responses to oil and dispersant exposures: Knowledge gained since the Deepwater Horizon oil spill.," *Marine Pollution Bulletin,* vol. 164, p. 112074, 2021.

[29] A. Trottet, C. George, G. Drillet and F. Lauro, "Aquaculture in coastal urbanized areas: A comparative review of the challenges posed by Harmful Algal Blooms.," *Critical Reviews in Environmental Science and Technology,* 2021.

[30] P. Racine, A. Marley, H. Froehlich, S. Gaines, I. Ladner, I. MacAdam-Somer and D. Bradley, "A case for seaweed aquaculture inclusion in U.S. nutrient pollution management.," *Marine Policy,* vol. 129, p. 104506, 2021.

[31] S. Rosanka, B. Franco, L. Clarisse, P. Coheur, A. Pozzer, A. Wahner and D. Taraborrelli, "The impact of organic pollutants from Indonesian peatland fires on the tropospheric and lower stratospheric composition.," *Atmos. Chem. Phys.,* vol. 21, p. 11257–11288, 2021.

[32] D. Hamilton, M. Perron, T. Bond, A. Bowie, R. Buchholz, C. Guieu, A. Ito, W. Maenhaut, S. Myriokefalitakis, N. Olgun, S. Rathod, K. Schepanski, A. Tagliabue, R. Wagner and N. Mahowald, "Earth, Wind, Fire, and Pollution: Aerosol Nutrient Sources and Impacts on Ocean Biogeochemistry," *Annual Review of Marine Science,* vol. 14, no. 1, 2022.

[33] I. Campos and N. Abrantes, "Forest fires as drivers of contamination of polycyclic aromatic hydrocarbons to the terrestrial and aquatic ecosystems.," *Current Opinion in Environmental Science & Health,* vol. 24, p. 100293, 2021.

[34] L. Wang, H. Xiao, N. He, D. Sun and S. Duan, "Biosorption and biodegradation of the environmental hormone nonylphenol by four marine microalgae.," *Scientific Reports,* vol. 9, p. 5277 , 2019.

[35] E. Sanniyasi, R. Gopal, D. Gunasekar and P. Raj, "Biodegradation of low-density polyethylene (LDPE) sheet by microalga, Uronema africanum Borge," *Sci Rep,* vol. 11, p. 17233, 2021.

[36] W. Chia, D. Tang, K. Khoo, A. Lup and K. Chew, "Nature's fight against plastic pollution: Algae for plastic biodegradation and bioplastics production.," *Environmental Science and Ecotechnology,* vol. 4, p. 100065, 2020.

[37] N. Govindan, P. Bhuyar, ,. H. Feng, M. Rahim, G. Maniam, S. Sundararaju and S. Muniyasamy, "Evaluation of microalgae's plastic biodeterioration property by a consortium of Chlorella sp. and cyanobacteria sp.," *Journal of Environmental Research,Engineering and Management,* vol. 77, no. 3, pp. 86-98, 2021.

[38] R. Madadi, H. Maljaee, L. Serafim and S. Ventura, “Microalgae as Contributors to Produce Biopolymers,” *Mar. Drugs,* vol. 19, no. 8, p. 466, 2021.

[39] A. Rachael, A. Gospel, N. Timothy, C. Gabriel, N. Ulunma, E. Christian and A. Godswill, “A Review on the Role of Biofertilizers In Reducing Soil Pollution and Increasing Soil Nutrients.,” *Himalayan Journal of Agriculture,* vol. 1, no. 1, pp. 34-38, 2020.

[40] W. Vries, “Impacts of nitrogen emissions on ecosystems and human health: A mini review.,” *Current Opinion in Environmental Science & Health,* vol. 21, p. 100249, 2021.

[41] J. Stewart, C. Bianco, K. Miller and K. Coyne, “The marine microalga, Heterosigma akashiwo, converts industrial waste gases into valuable biomass.,” *Frontiers in Energy Research,* vol. 3, no. 12, 2015.

[42] A. Lei, Z. Hu, Y. Wong and N. Tam, “Removal of fluoranthene and pyrene by different microalgal species.,” *Bioresource Technology,* vol. 98, no. 2, pp. 273-280, 2007.

[43] A. Rai, J. Chakrabarty and S. Dutta, “Phycoremediation of pollutants from coke-oven wastewater using Tetraspora sp. NITD 18 and estimation of macromolecules from spent biomass,” *Journal of Water Process Engineering,* vol. 39, 2021.

[44] R. J. A. Tomar, “Enzymatic pathway involved in the degradation of fluoranthene by microalgae Chlorella vulgaris.,” *Ecotoxicology,* vol. 30, p. 268–276, 2021.

[45] H. Li, J. Tan, T. Sun, Y. Wang and F. Meng, “Acclimation of Isochrysis galbana Parke (Isochrysidaceae) for enhancing its tolerance and biodegradation to high-level phenol in seawater.,” *Ecotoxicology and Environmental Safety,* vol. 207, 2021.

[46] T. Nazos and D. Ghanotakis, “Biodegradation of phenol by alginate immobilized Chlamydomonas reinhardtii cells,” *Archives of Microbiology,* 2021.

[47] N. Rajamohan, P. Kumar, M. Rajasimman and F. Qasmi, “Treatment of methanol industry effluent using algal biomass,Gelidium omanense- kinetic modeling,” *Chemical Engineering Journal Advances,* vol. 5, p. 100068, 2021.

[48] E. Sanniyasi, R. Gopal, D. Gunasekar and P. Raj, “Biodegradation of low-density polyethylene (LDPE) sheet by microalga, Uronema africanum Borge.,” *Sci Rep,* p. 17233, 2021.

[49] A. Serrà, E. Gómez, J. Michler and L. Philippe, “Facile cost-effective fabrication of Cu@Cu2O@CuO–microalgae photocatalyst with enhanced visible light degradation of tetracycline,” *Chemical Engineering Journal,* vol. 413, p. 127477, 2021.

[50] M. Mekonnen and W. Gerbens-Leenes, “The Water Footprint of Global Food Production,” *Water,* vol. 12, p. 2696, 2020.

[51] A. Pugazhendhi, S. Nagappan, R. Bhosale, P. Tsai, S. Natarajan, S. Devendran, L. Al-Haj, V. Ponnusamy and G. Kumar, “Various potential techniques to reduce the water footprint of microalgal biomass production for biofuel—A review,” *Science of The Total Environment,* vol. 749, p. 142218, 2020.

[52] A. Rahman, R. Putman, K. Inan, F. Sal, A. Sathish, T. Smith, C. Nielsen, R. Sims and C. Miller, “Polyhydroxybutyrate production using a wastewater microalgae based media,” *Algal Research,* vol. 8, pp. 95-98, 2015.

[53] L. Wang, C. Zhang, R. Cheng, J. Ali, Z. Wang, G. Mailhot and G. Pan, “Microcystis aeruginosa synergistically facilitate the photocatalytic degradation of tetracycline hydrochloride and Cr(VI) on PAN/TiO2/Ag nanofiber mats.,” *Catalysts,* vol. 8, p. 628, 2018.