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Algae Based Solutions for Polluted Environments to Restore Ecosphere Equilibrium

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Abstract-*The polyphyletic group of photosynthetic organisms which are commonly called algae have acquired evolutionary significant repertoire of genes from diverse groups of microorganisms including heterotrophic bacteria. Algae occur in different colours, morphologies, sizes, and habitats. The mosaic genomes of algae code for cellular and bio-chemical machinery to support their existence in varied habitats ranging from open oceans to oligotrophic lakes, from polar caps to the hotsprings and from pristine waters of mountains to anthropogenic polluted urban black waters. The implacable impacts of human activities on environment are causing undeviating ecosystem imbalances and depletion of resources. The formations and recycling of the natural resources is driven through bio-geochemical process which involve vivid biological diversity. Microalgae play vital role to support various ecological functions. Due to their ability to efficiently sequester CO_2 and grow rapidly in both fresh and marine waters, the microalgae offer sustainable solutions to mitigate the impacts of anthropogenic activities on the environment. At the cutting edge of environmental crisis are the global water shortages and environment pollution which includes eutrophication due to excessive nutrient discharges and the presence of emerging pollutants. The bioremediation of blooming waste waters by means of exploiting vast diversity of microalgae can play central role in attaining sustainable development of the renewable and non-conventional resources. Microalgae can efficiently capture inorganic nutrients such as N and P, the synthesis of which heavily rely on the consumption of fossil fuels. The world wide vicious circle of fossil fuel consumption, nutrient depletions, and food, feed and water shortages could be freed by utilizing microalgae. The paper addresses the role of microalgae in achieving the sustainable development goals for ecosystem restoration by adopting circular economy approach.*

Keywords: Algae, biodegradation,carbon capture, microplastics, wastewater.

1. Introduction

Human interventions and activities namely overexploitation of natural resources, land use, urbanization, intensive agriculture, industrial manufacturing of synthetic products, deforestation, domestication of animals, and on-going expansion of our footprints in pristine ecosystems are leading to environmental alterations. In the name of development, humans are invading and degrading most of the prevailing ecosystems on the planet including the pristine Antarctic ecosystems [1], biodiversity rich Amazon rainforests [2], and coral reefs [3].

Pristine environments of the various biodiverse ecosystems worldwide are being disturbed due to the introduction of non-biological or synthetic substances released by different anthropogenic activities as listed in previous paragraph. The various synthetic compounds that adversely affect the ecosystem services and human health are known as emerging contaminants (ECs)[4] or pollutants (EPs)[5]. The different types of emerging contaminants enter environment through various sources of pollution as shown in Figure 1.

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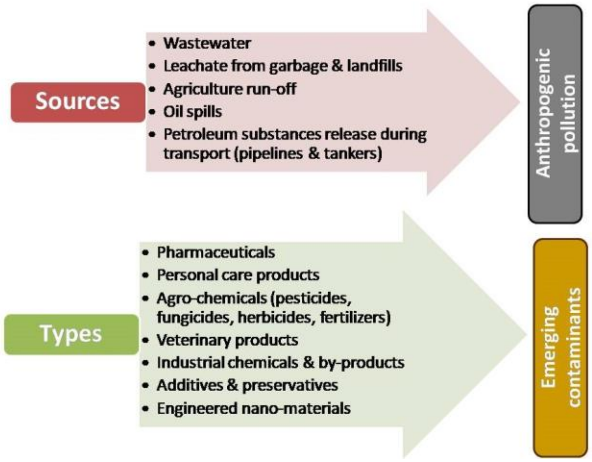

Figure 1. The various sources of pollution and types of emerging contaminants released from those sources.

Humans have been exploiting natural reserves and resources to meet their rapidly diversified demands for natural and synthetic products. The agriculture, forestry, livestock and aquaculture products are overproduced at environmental cost, yet we face world-wide food shortages. Ever increasing demands of humanity for food, shelter, clothing and agro raw materials are met through unsustainable nutrient intensive production systems which not only deplete mineral ores but consistently degrade the natural ecosystems and environment. The intensive use of synthetic fertilizers, pesticides and other toxic agro-chemicals in monoculture agriculture production systems generate harmful run-off wastewaters. . The nutrient loaded wastewaters from agro-livestock are most often discharged into the natural water bodies leading to eutrophication and the distortion of natural biotic assemblages. The imbalance between N and P levels in run-off discharges into the lakes due to inadequacy of upstream wastewater treatment process cause unbiased growth of toxin producing cyanobacterial species[6]. Additionally, the wastewater discharges from animal husbandry contain variety of antibiotics and antibiotic resistance genes that interfere with human health through propagation of pathogenic microbes [7].

The industrial production of these synthetic compounds and agro-chemicals rely on the combustion of non-renewable energy resources such as coal, crude oil and gasoline which further emits a class of persistent organic pollutants namely polycyclic aromatic hydrocarbons (PAHs). The European Environment Agency (EEA) provides differential PAHs emissions from various sectors of the economy in EEA member countries [8] as represented in Figure 2. PAHs are also naturally synthesised by organisms and have been circulating through biogeochemical cycles for millions of years. Their widespread distribution in the marine environments due to anthropogenic pollution and oil spills is mainly controlled through microbial degradation and mineralisation [9]. Bacteria, fungi and algae play significant roles in the PAH degradation and its removal from the marine sediments [9].

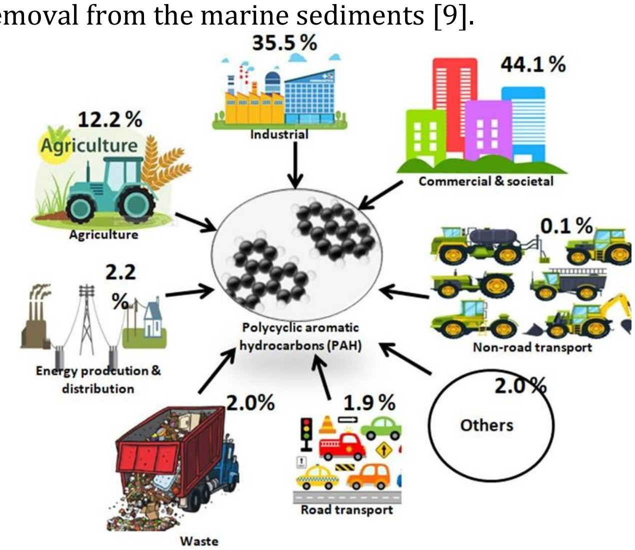

Figure 2. Representation of the percentage share of PAH emissions by various sectors of the economy in European countries. Data obtained from EEA [8].

As major primary producers in the aquatic ecosystems, the microalgae play important role in the fate of PAH in water bodies. Various forms of PAHs such as naphthalene, phenanthrene, anthracene and benzopyrene get metabolized and transformed by the enzymatic machinery of different strains of cyanobacteria and green microalgae namely *Oscillatoria* sp., *Agmenellum quadruplicatum*,*Selanastum capricornutum*, *Scenedesmus acutus* and *Ankistrodesmus braunii*, *Chlorella vulgaris*, *Scenedesmus platydiscus*, *Scenedesmus quadricauda*, *Prototheca zopfii* and diatom species *Skeletonema costatum* and *Nitzschia* sp[10].

The synthesis of different kinds of synthetic chemicals, compounds and raw materials in manufacturing units or industries further pollute every component of the biosphere namely hydrosphere, lithosphere and atmosphere. The industrial pollution release various xenobiotic compounds some of which belong to class of endocrine disrupting chemicals which can resemble key hormones [11].Toxic phenolic compounds such as Bisphenol-A (BPA) cause ecological destabilization by interfering with the reproductive growth and development of the freshwater and marine fauna including the edible fish (Tilapia)[11].This affects both the quality and quantity of aquaculture produce. Through trophic magnification, these environmental pollutants enter human bodies and alter the endocrine system which affects our well being. For example BPA, an ingredient of poor grade plastics and packaging materials is an emerging pollutant which can bind to the estrogens receptors to activate the genes associated with proliferation of breast cancer cell lines [12].

The excessive nutrient loadings and leaching of the toxic xenobiotic compounds into the lithosphere and hydrosphere distort the microbial and other biotic assemblages causing ecosystem disturbances. The disequilibrium in the physical environment, particularly in the atmosphere due to release of thermogenic gases and other chemically active air pollutants has far reaching planetary consequences such as the climate change, global warming, and increase penetration of UV radiations due to damage to the stratospheric ozone.

Various physio-chemical methods and technologies are being developed to minimise the risks associated with environmental pollutants. Principally, three approaches viz adsorption, photo-catalytic degradation and membrane process are adopted for the development of various physio-chemical methods of treatment which are filtration (ultra and nano), advanced oxidation processes, reverse osmosis, adsorption using activated carbon and other porous materials [13], [14].

Solutions offered by the conventional methods are both expensive and rely on the use of exhaustible and non-renewable resources; thus they are deemed unsustainable. On the other hand, bioremediation is safe, renewable, environment friendly and sustainable option towards mitigating the impacts of almost all types of environment degrading agents such as antibiotics, phenolic based xenobiotic compounds, green house gases and microplastics.

In this paper, we have presented various examples to highlight the importance of algae in biodegradation of environment pollutants. The paper also present phycoremediation (algae based bioremediation) as a sustainable biotechnological approach towards realising the green circular economy by minimising the carbon and water footprints.

2. Related Work

Based on physical and chemical properties, the EPs are categorised into three different groups namely persistent organic and more polar compounds (PAHs, pesticides, pharmaceuticals, industrial chemicals), inorganic compounds such as nutrients and heavy metals, and particulate contaminants like nanoparticles and microplastics[5]. The EPs occur in the environment through on-site leaching of pesticides, fertilizers and herbicides into the soil and through wastewater discharges. Unless the EPs undergo considerable biodegradation and transformation, their presence in the environment is concerning. The non-biological technologies for pollution mitigation are expensive, rely on non-renewable resources and are therefore unsustainable. Most importantly, the implementation of advanced physio-chemical technologies for pollutant degradation or transformation on global scale is unrealistic as these are unaffordable for many developing countries. Alternatively, the biological resources which are cosmopolitan and are abundantly available everywhere on the globe act as nature's own strategy for mitigating the effects of EPs on ecosystem functioning.

Algae represent suitable bio resource for tackling various forms of environment pollution as algae have evolved through the pre life-supporting oxidising environments of the Earth. Algae converted Earth's reducing environment to an oxidising one and thus supported the evolution of biodiversity on the planet. Algae are polyphyletic group of organisms which are predominantly photosynthetic and are bio-structurally equipped to transform quantum energy to various forms of biomolecules using CO_2 and some form of water. Algae are among the oldest group of organisms which have evolutionary evolved and possess vivid diversity in terms of shape, size, colour and habitats.

The various ways in which algae support the restoration of ecosystems and environment are:-

i) Sequestration of CO_2 and capture of other flue gases

ii) Nutrient recovery from wastewaters

iii) Provide oxygen to the aquatic biota

iv) Algal blooms are potential carbon and nutrient sink in ocean ecosystems

v) Biodegradation of various EPs

vi) Biodegradation of microplastics

vii) Renewable alternative to fossil fuels and petrochemical products

viii) Support organic farming and form biofertilizer

ix) Algae are biomonitoring tool for detection of pollutants and heavy metals

Certain heavy metals such as Hg^{2+}, Cr^{6+}, Cd^{2+} and Pb^{2+} inhibit the photosynthetic activity and so the oxygen evolution by algae. A rapid and suitable heavy metal test kit is formed using microalga *Chlorella vulgaris* in which the toxicity of heavy metals (in terms of concentration) in water sample is assessed through oxygen evolution by alga [15].

3. Mitigation of Plastic Pollution

Water scarcity is the pressing environment issue affecting all living beings inhabiting air, water or land. The report from United Nation Meteorological Organization suggests that by 2050 over half the world's population would not have access to enough potable water. Along with climate change impacts, the freshwater ecosystems are being endangered by the water pollution due to toxic compounds and physical debris including the microplastics. Microplastics of less than 5mm create incessant floating habitats for the various types of microorganisms (including toxin producing microbes) in the freshwater ecosystems which is termed as plastisphere [16]. Apart from biotic interactions, the microplastics also form sorption matrix for toxic hydrophobic chemicals including pesticides, polychlorinated biphenyls and PAHs [17].

In absence of any technological interventions for the physio-chemical treatments of the natural water bodies, the fate of plastic pollution in aquatic habitats is vastly determined by the biofouling of plastic by degrading bacteria, fungi and algae. Different types of synthetic polymers such as Low Density Polyethylene (LDPE), Polyproplene (PP) and Polyethylene Terephthalate (PET) provide substrate for the formation of biofilms. The microorganisms associated with biofilms potentially degrade the plastic surfaces and alters its buoyant properties which ultimately leads to the sinking of decayed plastic particles to the bottom or aphotic zones of the water bodies. Among algae, the colonisation of different types of plastics by cyanobacteria simultaneously allow the fixation of free nitrogen in aphotic and photic environments [18].

Microalgae exhibit vast habitat diversity and within aquatic habitats, the distribution of different species of algae form various niches associated with physio-chemical factors such as nutrients, presence of grazers, and distribution of light. Therefore, the algal assemblages in aphotic and photic environments of the water bodies show considerable variations. For example, the plastisphere in aphotic zones have higher abundance and diversity of pennate (biliateral symmetry) diatom species which are well adapted to low light and high Si concentrations [18].

Microalgae naturally inhabit surfaces of plastic sheets found in polluted aquatic bodies and wastewaters. Many research studies have been conducted on the microalgae derived from the naturally occurring algal flora on anthropogenic materials. Some of the dominant microalgae species found in plastisphere are *Scenedemus dimorphus*, *Anabaena spiroides*, and the diatom *Navicula pupula*[19]. The filamentous blue green alga *Anabaena spiroides* form mucilaginous films and cavity on the surfaces of low density polyethylene sheet that effectively degrade structure of the polymer [19]. The biodegradation by microalgae significantly decrease the weight percentage of carbon in LDPE, making it brittle and prone to fragmentation [20]. Biochemically, the colonisation and further biodegradation of plastics is triggered by secretion of extracellular polysaccharides and exo-enzymes by microalgae species particularly cyanobacteria and diatoms. The production of ligninolytic and exopolysaccharides by plastisphere algae assist plastic degradation process upon adhesion onto the surfaces.

Algae colonize 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[21].Various degraded products such as saturated fatty acids, carboxylic acid, esters, nitro compounds and amino groups which are formed due to the enzymatic activity represent the key determinants to assess the *in-situ* process of LDPE biodegradation[21].

Plastic pollution is not only restricted to water bodies and landfills, rather the production of synthetic plastics which rely on fossil fuels further cause green house gas emissions causing air pollution. The replacement of plastic with algal feedstock thus offers dual mitigation strategy to combat both pre- and post manufacturing environmental pollution. Although agriculture biomass is one of the proponents for bio plastics, the bio-based plastics from potato and corn are unsustainable as they compete with food crops for land, water and nutrients resources which would potentially create worldwide food insecurity, change in land use, water pollution and scarcity. Alternatively, variety of biopolymers can be derived sustainably from the algae thriving in diverse habitats such as fresh and wastewaters (bluegreen and green microalge) and marine ecosystems (seaweeds) Figure 3.

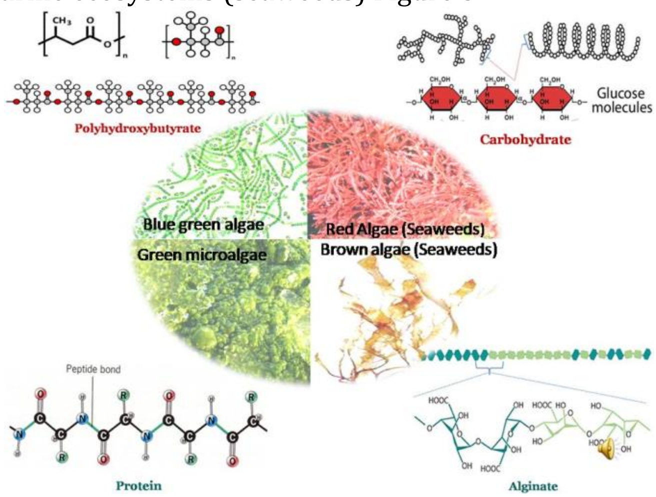

Figure 3. Macromolecules produced by different groups of algae provide eco-friendly feedstock for biopolymers.

Examples of bio-polymer derived from cyanobacteria and algae are Poly Hydroxy Butyrate (PHB) most promising non-petrochemical plastics which is biodegradable with biocompatible (for complete biodegradation) and thermoplastic (to enhance usage value) properties. Polyhydroxyalkanoates (PHAs) are the natural polyester comprising of the hydroxy-alkanoic acids units, with properties similar to petroleum plastic which are produced as a reserve source of carbon and energy that get accumulated within the microalga cell[22]. The species of cyanobacteria under several specific cultivation conditions efficiently synthesize PHB and its copolymer polyhydroxybutyrate-co-valerate (PHB-HV) [23].

4. Algae Production Systems Support Decarbonised Bio-Economies

The agriculture sector requires massive inputs of nitrogenous fertilizers, the synthesis of which is energy intensive process requiring fossil fuels. In addition, 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[24]. Furthermore, the emissions of nitrogen compounds originating as byproducts of nitrate fertilizers persists in air, causing depletion of stratospheric and tropospheric ozone and production of other fine pollutants which have serious impacts on the terrestrial biodiversity and human health[25].

The remediation of green house gases (GHGs), particularly CO_2 is obligatory to mitigate the effects of global warming and climate change which have become planetary crisis. CO_2 is one of the potent greenhouse gases which remains accumulated in the atmosphere over longer periods, and any non-zero emission would further elevate it in the atmosphere. Some possible methods to address increasing CO_2 in environment include industrial recycling, compressing it into the ocean floor, replacing fossil fuels with solar energy and planting trees. The technological methods and innovations have huge carbon, water and other environmental footprints. Planting trees is expensive, require vast fertile lands, massive inputs of nutrients, and most importantly it take years to establish a carbon negative terrestrial forest ecosystems. Phycoremediation 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. The various steps involved in implementation of Phycoremediation process which determine the efficacy of algae to act against the target chemicals include 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.

Additionally, use of algae address issues of environment pollution by offering multiple solutions such as nutrient recovery through wastewater cultivation with industrial waste CO_2, use of sea water for marine microalgae and cultivation of seaweeds. The use of marine algae or seaweeds and extremophilic species is the only viable option to combat the effects of climate change on changing environment and ecosystems. For example, the rising sea levels associated with climate change impact the coastal ecosystems due to salinity intrusions which degrade the freshwater ecosystems and decline the coastal productivities of both plants and aquaculture.

A group of microalgae species belonging to the genus *Dunaliella* have significant roles to play in addressing environment issues due to their unique characteristic of adapting different and harsh habitats. For example *D. Salina* a high light and low temperature tolerant specie form important phytoplankton communities in hypersaline and marshy environments. Another specie called *D. acidophila* flourish in environments with pH as low as 0-1[26].

In general, the use of open microalgae production systems offer economical, less energy intensive and sustainable green solution to overcome multiple environmental issues related to water and air pollution. The bioremediation approach which include both microbial (bacteria and fungi based) and phycoremediation (algae based) is the only eco-friendly option for wastewater treatment that can mitigate various environment impacts of water pollution such as eutrophication, loss of agriculture nutrients, deterioration of water quality in aquifers including groundwater and loss of biodiversity due to xenobiotics.

In bioremediation process, the microorganisms mineralise and detoxify complex chemicals via conversion into simple inorganic molecules such as CO_2, CH_4 and remediated water. The municipal wastewaters which comprises of many hazardous organic waste and inorganic nutrient compounds of nitrogen and phosphorous can be treated in specifically designed open ponds. After the removal of large debris and floating matter through bar screening and primary settling tank, the sewage is pumped into the waste stabilization ponds system which comprises of anaerobic and facultative ponds. These large artificial lagoons or basins are cost-effective, reliable and easy to operate bioremediation systems in which raw sewage is treated through natural process involving bacteria and algae. The photosynthetic oxygen generated by algae is consumed by aerobic bacteria which oxidise the organic waste into inorganic nutrients including CO_2 for uptake by the algae counterparts[27]. The symbiotic association between bacteria and algae is exploited in efficient wastewater treatment process. The hydraulic retention time in synergistically operated facultative ponds is high due to slow treatment involving natural processes. Once the wastewater is sufficiently treated in facultative ponds, the water gets pumped into the high rate algal ponds where algae assimilate inorganic nutrients (N, P) and further breakdown the dissolved organic matter to provide secondary and tertiary treatment process [28]. The reclaimed water is reused in aquaponics to simultaneously generate food crops and aquaculture produce Figure 4.

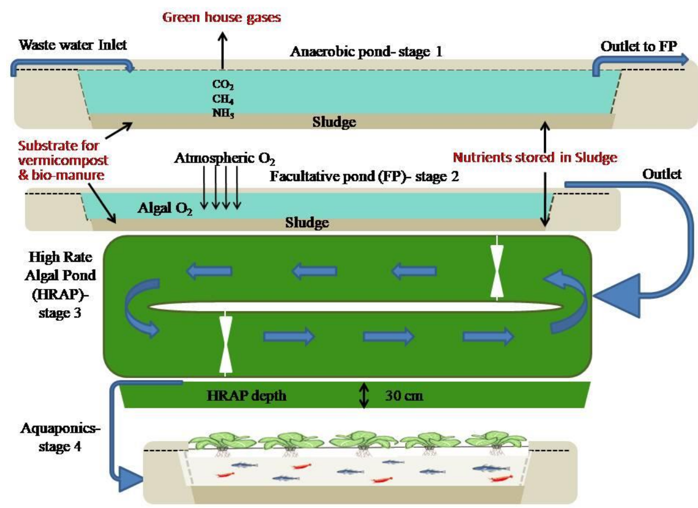

Figure 4. Diagram showing integrated secondary biotreatment process for municipal wastewaters. The phycoremediated water is reused in aquaponics to support circular bio-economy at regional level.

4.1. Removal of pollutants

The pollutants from wastewaters are removed by algae through various strategies such as biosorption, bioaccumulation, biocoagulation and bioconversion. For the biosorption by algae, the biomass is immobilized or embedded in biopolymers obtained from seaweeds such as carrageenan and alginate. The biosorbents obtained from brown macroalgae namely *Sargassum* sp. contain carboxyl and hydroxyl groups in the alginates obtained from cell walls which act as pollutant binding sites for the ion-exchange mediated removal process [29].Various functional groups such as sulphated polysaccharides, carbohydrates and fibril matrix [30] of the algal cell walls complexed with heavy metals to form organometallic compounds and thus reduce the concentration of metal ions in the water [31]. The diatom species namely *Aulocosera granulate*, *Nitzschia* spp., *Ulnaria ulna*, *Pinnularia*, *Gomphonema psuedoaugur* and members of Cymbellales and Naviculales show high tolerance to the heavy metals and thus show significant adsorption [31]. The domestic sewage also contains many pharmaceutical by-products including commonly used pain relief drugs. The biomass of cyanobacteria specie *Synechocystis* sp. and green microalga *Scenedesmus* sp. show removal capabilities for diclofenac from water via biosorption [30].

Another way in which the pollutant is removed by algae is through bioaccumulation of toxic metals and ions. The toxic pollutant ions form complex structures with algal cell membranes and cause structural damage and physiological changes in algal cells. Bioaccumulation of toxic metals in algal cells initiate cascade of events which involve the production of reactive oxygen species, inhibition of chlorophyll production, reduce cell growth and lipid accumulation [29]. During heavy metal shock, algae produce proline within their cells to improve their tolerance and detoxification abilities [31].

Algae have abilities to adapt to various anthropogenic environments. For example, algae possess repertoire of enzymes such as azo reductase, laccase and polyphenol oxidase for the biodegradation of dyes present in the wastewaters [29].

4.2. Algae bioproducts to support circular economy

Algae possess mosaic genomes which they have acquired from diverse group of organisms including non-photosynthetic organisms and heterotrophic bacteria. Their genomes are unique blueprints that code vast variety of enzymes, molecules and compounds some of which have been exploited; yet the copious bio wealth remain to be tapped. Some of the compounds synthesised by algae enable them to adapt to a variety of environmental perturbations such as nutrient starvation, oxidative, heavy metals and temperature stresses and desiccation. Algae accumulate various useful compounds that are being exploited for making eco-friendly products to reduce the anthropogenic environment footprints Figure 5. Most of the algal derived products can be obtained from the integrated wastewater treatment and algal production systems such as HRAPs.

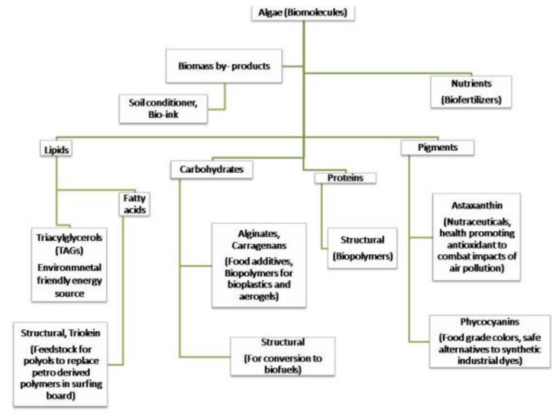

Figure 5. Algae are renewable and sustainable resource for various types of eco-friendly products.

5. Advanced Photo-Decontamination of Pollutants Using Microalgae

The over use of pharmaceutical products particularly the antibiotics and the insufficient waste management leads to uncontrolled discharge in environment which alters the metabolic functioning of the biotic communities in aquatic ecosystems. 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 crucial and 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.

Sunlight presents the most abundant natural source of photonic energy and ultraviolet radiations which must be exploited for the photo-decontamination of toxic pollutants. The photosynthetic algae act as molecular bio-factories that synthesize and release organic acids and chlorophyll in their environments. These organic compounds further absorb photons to generate active radicals in the photo-decontamination process. The efficiency of this process can further be enhanced using bio-nanno hybrid systems in which a bloom forming (fast growing, competitive specie) cyanobacterium specie such as *Microcystis aeruginosa* is coated onto the Polyacrylonitrile (PAN)/TiO_2/Ag to form green nanofiber mats [32]. Such hybrid systems display synergistic enhancement in the photocatalytic degradation of antibiotics such as tetracycline and heavy metals like Cr (VI) [32].

6. Conclusions

Globally, the economies rely on energy intensive agriculture and industrial production systems to address the raising demands of overpopulation. Further, the demographic changes are affecting the consumption pattern and living standards which implies that the demands for industrial products are expanding rapidly. For example, the changing dietary habits of many populations around the globe are leading to unsustainable expansion of the livestock and aquaculture. The rapid urbanization and reduction in subsistence farming is changing land use which accounts for loss of natural habitats those play significant roles in providing the ecological services. The industrialised agriculture and livestock sectors accounts for huge water footprint (WF) globally including grey WF which only take into account the leaching and run-off nitrogen fertilizers. The emerging organic soil and water pollutants from all sectors of the economy along with the increasing atmospheric CO_2 concentrations have created havoc and need immediate fixing. We are pressed with time and conventional resources to achieve sustainable technological advancements and must rely on thorough implementation of biological mitigation technologies.

The conventional techniques such as photo- and electrochemical decomposition are expensive, difficult to scale up, rely on non-renewable resources and are often associated with secondary pollution. Comparatively, the bioremediation is environmentally safe and sustainable option. The diverse photosynthetic algae which perform fundamental ecological functions namely primary production, energy flow and, nutrient cycling offer renewable solutions for recovering inorganic nutrients, capturing and storing CO_2 and eco-restoration through degradation of toxic chemicals. Aquatic algae show high adsorption capacity, intracellular accumulation and decontamination capabilities for large variety of emerging pollutants.

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. Most importantly, the use of algae in mitigating various kinds of pollutants including fertilizers, pesticides, heavy metals, polycyclic hydrocarbons, phenols, and CO_2 reduces the carbon footprints with potential to generate useful bioproducts and natural alternatives to the fossil fuel derivatives.

Phycoremediation is ecosystem friendly method that reduces 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 colonising 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.

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