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Challenges and opportunities of bioplastics produced from algae

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ABSTRACT

The high awareness of the synthetic plastics pollution problem demands more efforts by the scientific community to find an alternative source (bioplastics) to protect our environment and health too. The production source of bioplastics should be plant-based raw materials, and natural polymers like carbohydrates, protein, and others (fatty acids, sugar, disaccharides, etc.). Polyhydroxy butrate (PHB), Polyhydroxy alkanoates (PHA), and starch are the basic compounds produced by algae that enter bioplastic composition. Bioplastics have become essential in various industrial applications such as horticulture, composting bags, hygiene, biomedical, structural, electrical, and other consumer products. The most common algal species used in bioplastics production are *Ulva lactuca* and *Gelidium sesquipedale* from macroalgaeplus *Chlorella* and *Spirulina* from microalgae. The seaweeds are collected naturally or cultivated while microalgae need cultivation to obtain a high biomass. The most accepted common systems are the open system (raceway) and the closed photobioreactors. The present techniques for microalgal bio-composite include melt mixing, compression molding, hot molding, injection molding, twin screw extrusion and solvent casting. Although algal bioplastics are promising on a laboratory scale large scale faces some challenges including species selection, polymer selection depending on biodegradability, and released products from bioplastic degradation. Further innovative studies using genetic engineering and new biotechnology to produce low-cost bioplastics are opportunities.

INTRODUCTION

Algae are divided into microalgae and macroalgae (seaweed) both of them give novel potential in production of bioplastics. They may be planktonic, submerged in the water column (phytoplankton) and benthic (epilithic, epiphytic and epizoic). They were found as aquatic, subaerial and submerged in fresh, brackish and marine environment. They can withstand a wide variety of temperature, pH, turbidity, and nutrient levels, and have a great tolerance for other extreme environmental conditions. (Zaher and Helal, 2020). So, large numbers of subaerial algae were found to live on land (HobAllah *et al.*, 2019). Some algae species are eco-friendly organisms that able to produce effective beneficial compounds so, they may be used as alternatives in bioeconomy. Recently, certain algae species have a potential in production of bioplastics (Hempel *et al.*, 2011).

World demands to plastics has been increased and caused stress on our environment where there are tons of wastes specifically plastics discharged in oceans as a result of anthropogenic activities. Besides, undegradable plastics persist in nature for many centuries. Also, plastic debris has been found in the aquatic habitat leading to severe effects on marine life including coral reefs and ocean animals (Chen and Yan, 2020; Chia *et al.,* 2020). The marine plastics are frequently ingested by aquatic biota and affect their food chain, growth, and reproduction (Rochman *et al.,*2015; Galloway *et al.,*2017). Although ordinary low degradable plastics out grown since 1950s, but plastics pollution led to many trials to find an alternative eco-friendly product which promotes bioplastics (Abdul-Latif *et al.,*2020). Global high demands of traditional plastics, increase cost manufacture and undegradable are challenges forced the scientists to find an alternative source can obtain from algae (Abdo and Ali, 2019).

The synthesis of bioplastics from carbohydrates (starch and corn) (Jerez *et al.,* 2007) represents a high competition with food so the synthesis of bioplastics from macroalgae is the challenge nowadays (Abdul-Latif *et al.,* 2020) and microalgae (Hempel *et al.,*2011). With regard to the benefits, bioplastics get attention due their ability to save fossil fuels, CO_2 emission reduction, and decrease environmental pollution. Bioplastics production growth is predicted to exceed 400% in some countries (China, India and Thailand) according to world bioplastic market (White worth, 2014). Marques (2017) found that two macroalgal species (*Ulva lactuca* and *Gelidium sesquipedale)* contained 37% and 48% carbohydrate content (dry weight), respectively. Abdo and Ali (2019) investigated the ability of three microalgal species plus two microalgal biomasses gathered from High-Rate Algal Ponds (HRAP) to produce polyhydroxybutrate component. Also, HRAP is an amazing source for the synthesis of bioplastic (Stevens, 2002). Wang (2014) tested the polymer performance produced by *Spirulina* biomass using plasticization, blending and compatibilization. Biopolymers could be obtained by three approaches; direct extraction, renewable raw materials and microorganisms either naturally or modified genetically. The algal polymers are mainly composed proteins that consist of up to 20 different amino acids, while a synthetic polymer consists of identical monomers, covalently bonded in a long chain. The diverse building blocks of proteins and their unique structures produce a large variety of biodegradable materials have functional properties (Garrett and Grisham, 1999).

Plasticizers are small, non-volatile, organic molecules added to polymers to improve flexibility, durability, and processability. The internal plasticizers would be turned into portion of the polymer molecules by copolymerized or grafted to the polymer construction, which affect the close compact of the polymer chains. The plasticization decrease the relative number of polymer-polymer contacts by reducing the rigidity of the three dimensional structure, allowing deformation without rupture (Mekonnen *et al.,* 2013).

Blending is a common method to modify polymer properties and involves a physical mixing of multiple polymers exhibiting characters of all mixture polymers. The compatibility of the polymers regulates the composition and features of the resulting polymer blend. The polymers involved should be thermally compatible (Verbeek and van den Berg, 2010).

Compatibilization, the main disadvantage of integrating a natural polymer into a synthetic polymer is their compatibility. Natural polymers are hydrophilic while synthetic polymers are hydrophobic in nature. The blend of two kinds of polymers is generally immiscible (Mir *et al.,*2011). Compatibilizers as additives modify the interfacial properties and stabilize the melt blend. Use of thermoplastic maleic anhydride graft copolymers is one the most successful techniques. Algae-based bioplastics belong to agro-polymers (low degradation temperature) processed from extracted biomass either with or without modification. Mixing and shaping of polymers are referred to as processing polymers (Stepto, 2006). Agro-polymers do not behave thermo-plastically without some additives. This review is an attempt to describe the challenges and opportunities to synthesize bioplastics from algae and to explain the effect of algal species, cultivations, growth conditions, systems, harvesting, processing on synthesis efficiency.

2. Production of Bioplastics

Bioplastics are made fully or partially from biomass or renewable sources such as food crops and they have the identical function as the petroleum-based plastics (Mekonnen *et al.,* 2013). Bioplastic are mainly classified (European Bioplastics, 2018) into four items:

- Bio-based but non-compostable plastics; polyethylene (PE), Poly Propylene (PP), Poly Ethylene Terephthalate (PET), Polytrimethylene.
- Polytrimethylene terephthalate (PTT) or Polyester elastomers (PE).
- Bio-based and degradable plastics: Polylactic acid (PLA), Poly Hydroxy Alkonate (PHA), starch, cellulose.
- Fossil resource-based plastics that are biodegradable: Polybutyleneadipate terephthalate (PBAT).

Bioplastic could be used in many industries; packaging materials, textile production, automotive industry, transportation, construction, pharmaceutical and cosmetics (Alaerts *et al.,*2018; European Bioplastics report, 2021). Also, they have become essential in various industrial applications such as horticulture, composting bags, hygiene, biomedical, structural, electrical, and other consumer products. Figures (1 &2) describe the total capacities of bioplastics in Asia, Europe, America and Australia, In addition to bioplastics global change detected from 2011 to 2021, the global production total capacities till 2025 are described in Figure (3).

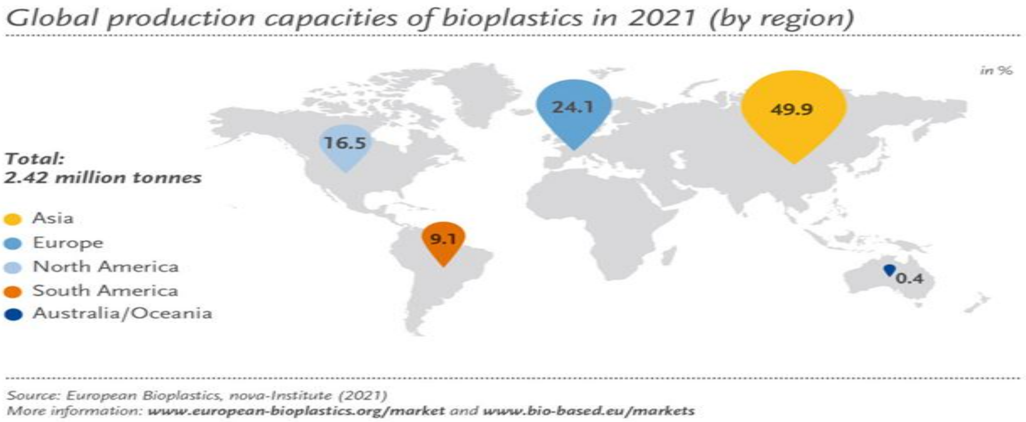


Fig. 1: Global production capacities of bioplastics in 2021 (by region).
Source: European bioplastics, nova-Institute (2021).

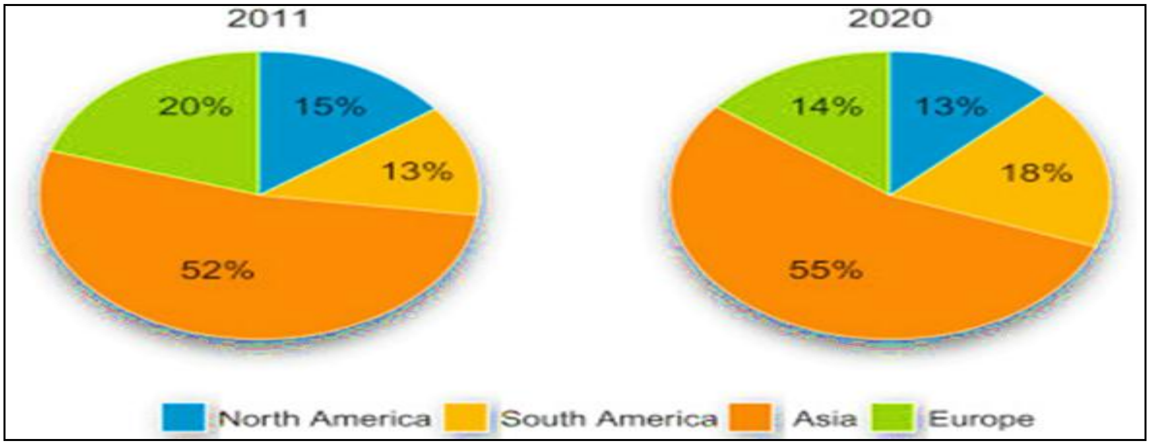


Fig. 2: Overview of the change in global bioplastics productions by regions from 2011 to 2020.
Source: Ashter (2016)

Fig. 3: Global production capacities of bioplastics 2019 to 2025.
Source: European bioplastics, nova-Institute (2020).

Materials and polymers for bioplastics production

The plant-based raw materials, natural polymers like carbohydrates and protein and some other small sized molecules (fatty acids, sugar, and disaccharides) are the main source for bioplastics production (Thielen, 2014). However, production of bioplastic from terrestrial crops as potatoes and corn has many disadvantages because it needs to large land areas, excess water supply and nutrients as well as compete with human food supply (Rahman and Miller, 2017). Also, this production faces many problems based on commercial scale (Digregorio, 2009) so; the amazing use of microalgae in production of bioplastics is the challenge (Mohan *et al.*, 2019). Bioplastics production attracted the interest as number of publications in 2016, and then increased to achieve a spike in 2019.

Recently microalgae are used in green material production due to their ability to produce polymers naturally. In general, production of bioplastics from algae is the challenge nowadays where polymers (such as starch and PHAs) used in plastic production are already produced by microalgae (Johnsson and Steuer, 2018).

The role of Algae

Algae as novel potential biomass source for bioplastics, due to their cultivated on non-arable lands, short time of harvest, and no competition with human food (Chew *et al.*, 2017; Tang *et al.*, 2020), tolerate harsh environmental conditions and can remediate waste water releasing CO_2 as nutrient source for their biomass (Zhang *et al.*, 2019). In algal based plastics production, the encapsulation of non –biodegradable polymers, such as polyolefin in thermoplastic algal blends, can store and capture CO_2 in biomass, and CO_2 did not emit back to the atmosphere (Shi *et al.*, 2012). Figure (4) shows microalgal potential in bioplastics production compared to conventional plastics.

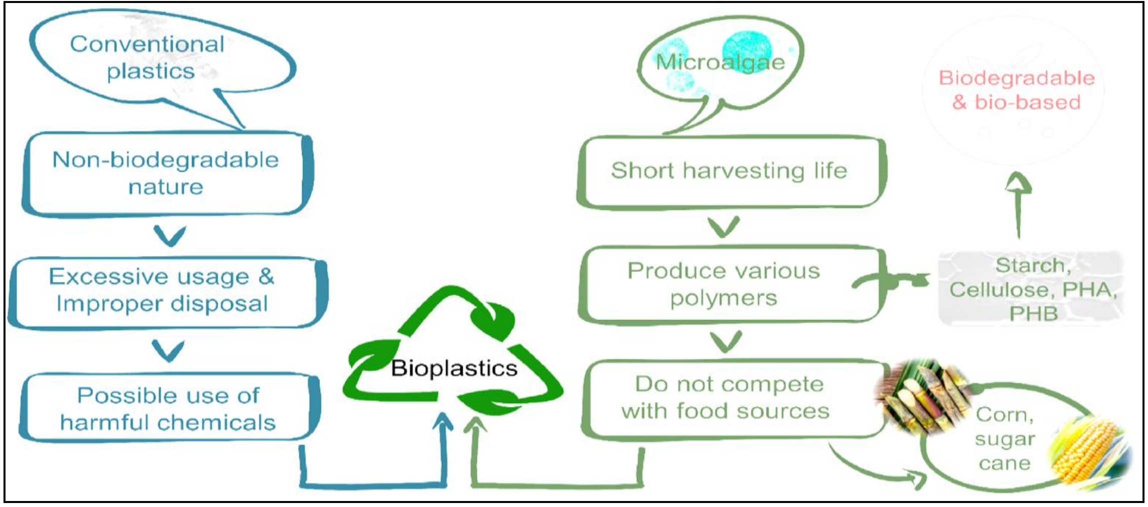


Fig. 4: Potential of microalgae in producing bioplastics.
Source: Chia *et al.* (2020)

Algal species used in bioplastic production

Macroalgae

Macroalgae contain diverse species obtained naturally from the wild or can be cultivated either in marine farms or in tanks system. Large scale macroalgal cultivation has been implemented in more than 50 countries. The average global yield of macroalgae recorded 12 to 60 T/ha (Abdul-Lateif *et al.*, 2020). About one million tons of macroalgae annually harvested from natural stocks. Also, macroalgae can be cultivated in tanks culture system with suitable cultivation conditions of aeration and nutrients supply, at the same time aqua-culturists prefer growing macroalgae in the sea (Table1).

Table (1): Macroalgal large scale cultivation and the expected yield (t\ha) of phenol for bioplastic production.

Large scale Cultivation method	Expected yield	Expected annual Seaweed production	Expected annual Phenol production	Expected total yield in 2050	Expected total phenol in 2050
Sea farming	36	13.968	10.385	475.524	353.077
Self-cultivation	60	0.6	0.446	20.4	15.147
Total		14.586	10.831	495.924	368.224

Source: Abdul-Latif *et al.*, (2020).

Two species *Ulva lactuca* (green seaweed) and *Gelidium sesquipedale* (red seaweed) are considered the most common macroalgae used in bioplastics production (Marques, 2017). Photos of these species are shown at (Fig.5).

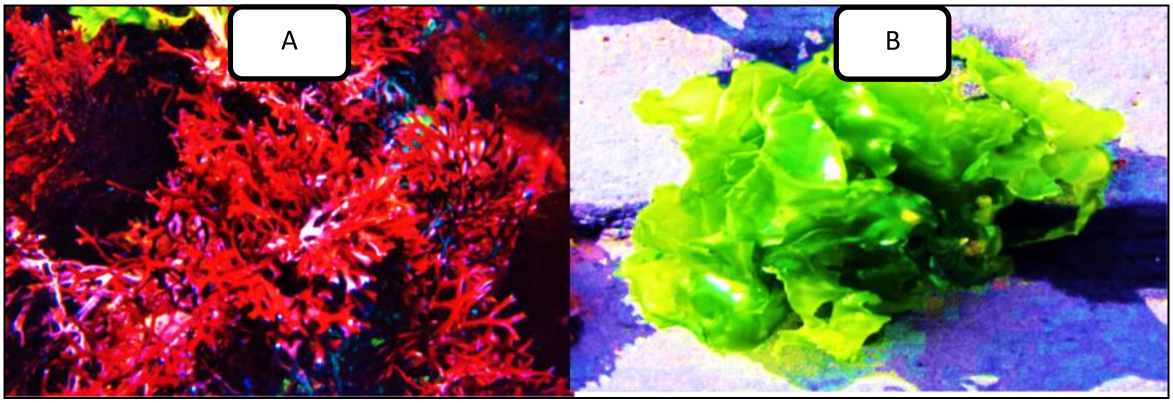


Fig. 5: The common macroalgae used in bioplastic production.
A: the red seaweed; *Gelidium sequipedale,* B: the *green seaweed; Ulva lactuca*
Source: Marques (2017).

They are rich in carbohydrates and selected as sugar sources for Poly-3-Hydroxybutyrate (P3HB) production by bacterial strains. The total biomass of *U. lactuca* and the residues of *G. sesquipedale* recorded 37% and 48% carbohydrate content (dry weight), respectively. Moreover, they were subjected to enzymatic hydrolysis by acid pretreatment assays in order to scale sugar-rich algal hydrolysate production for bacterial usage. The amount of algal substrate used were 43.2g/l and by adding phosphate buffer and enzymatic hydrolysis. The total yield of carbohydrates for the two algae recorded 80 to 90%.

Microalgae

Microalgae are microscopic organisms live in freshwater and marine habitats and they are able to do photosynthesis process (Abu, 2020). They are considered as good source for biofuel production, food and feed to higher organisms, and supplements in various industries (food, cosmetics and pharmaceutical compounds). Microalgae get more attention due to their potential usage in bio-economy (Oh *et al.,* 2018). Table (2) describes the microalgal main components including proteins, carbohydrates, lipids and other elements.

Table (2): The main components of microalgae.

Lipids	Carbohydrates	Proteins	Calcium	Magnesium	Phosphorus	Potassium
7-23%	5-23%	6-52%	0.1-3%	0.3-0.7%	0.7-1.5%	0.7-2.4%
Sodium	Sulfur	Copper	Iron	Manganese	Selenium	Zinc
0.8-2.7%	0.4-1.4%	18-102 ppm	1395-11.101 ppm	45-454 ppm	0-0.5 ppm	28-64 ppm

Source: Chandra and Mohan (2014) for (lipids, carbohydrates and proteins), Tibbetts *et al.,* (2015) for minerals.

The most common microalgae species utilized in bioplastic production (Fig.6) are *Chlorella*, *Spirulina* and others.

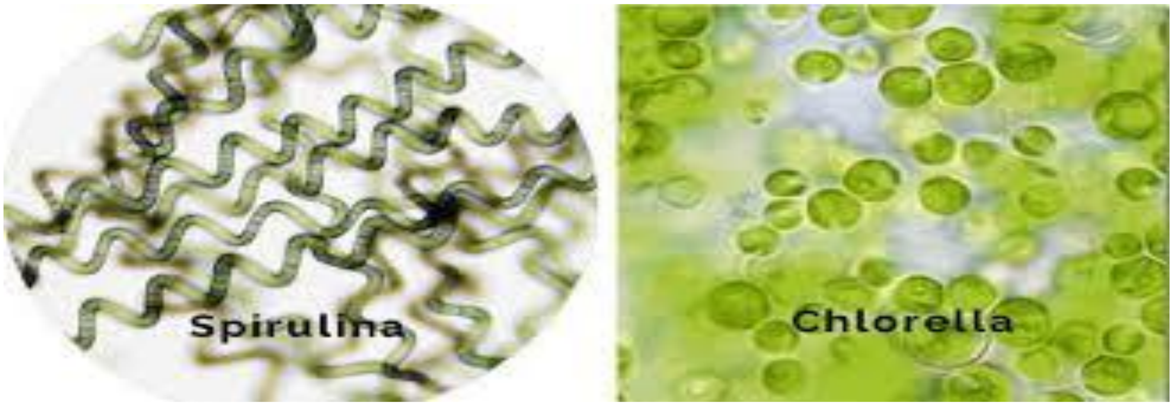


Fig. 6: The most common microalgal genus used for bioplastics production.
Source: Zeller *et al.,* (2013).

Chlorella belongs to green algae and freshwater habitat. It has dense cell wall and higher thermal stability than *Spirulina* (Zeller *et al.*, 2013; Gozan and Noviasari, 2018). *Chlorella* was almost used in biomass-polymer blends. On the other side, *Spirulina* belongs to blue-green algae, spiral filamentous in shape and it is highly adapted to extreme environment (Lupatini *et al*., 2017). *Chlorella* and *Spirulina* contain 58% and 60% (by weight) protein content, respectively (Dianursanti *et al.*, 2019). By comparing the bioplastic produced material from 100% microalgal biomass and other containing blend materials and additives, the results clarified that blending was an essential factor in commercial applications (Zeller *et al.,* 2013). The quality of product produced from *Chlorella* was higher than those produced by *Spirulina* although the latter has better blending characteristics.

Some studies are conducted to measure the product quality from microalgae; Dianursanti (2018) studied the effect of the compatibilizer ratio on the quality of produced PVA (Polyvinylalcohol) by *C. vulgaris* composites. The results showed that the compatibilizer (maleic anhydride) concentration of 6% was the best in the mixture. Another study on *C. sorokiniana* indicated that the microalgae produced starch granules of 1 µm having high gelatinization temperature (110ºC) used in bioplastic, food and chemical industries (Gifuni *et al.*, 2017). Presence of H_2 ions in *Chlorella* allows blends formation without gaps (Zhang *et al.*, 2000). The homogeneity and surface properties of *Chlorella*–PVA blends product could be improved with ultra-sonic homogenization pre-treatment (Sabathini *et al.,* 2018). The study of Otsuki *et al.* (2004) indicated that

Chlorella–PE composites with and without modification of PE (with maleic anhydride) proved that modification of PE positively affected the tensile strength.

Variations in amino acids content between *Chlorella* and *Spirulina* led to different behavior of the two microalgae when blending with PE (Cinar *et al.,* 2020). Compatibilizers addition could improve the product bioplastics of *Chlorella* (Zeller *et al.,* 2013) and adding 6 wt % of a compatilizer to *Spirulina* get higher tensile strength film than ordinary plastic bags and also it increased the elongation ability of the plastic (Zeller *et al.,* 2013) . Other study reinforced *S. platensis* with plasticized wheat gluten (Ciapponi, 2019). Addition of glycerol (15-30%) increased the flexibility of the plastic, adding 30% glycerol produced high flexibility bioplastic bags compared to the commercial plastic bags (Gozan and Noviasari, 2018). Generally, the difference in the compounds blended with the algae affected various product properties (Wang, 2014; Torres *et al.*, 2015; Monshupanee *et al.*, 2016; Zhu *et al.*, 2017). The most microalgal studies to produce bioplastics are performed on *Chlorella* and *Spirulina* but some researchers examined the ability of other microalgal species in bioplastic production as shown in Table (3).

Table (3): Bioplastic production from other microalgae species.

Biomass species	Type of product	Ratio of materials	Characterization
Chlorogloea fritschii	Bioplatsic poly-3-hydroxybutrate	-	PHB levels at 14-17% (w/w DW)
Phaeodactylum tricomutum	Bioplatsic PHB	-	PHB levels of up to 10.6% of algal (DW)
Calothrix scytonemicola, Scenedesmus almeriensis and *Neochloris deoabundans*	Bio-based plastic film	1:2, Carboxymethyle Cellulose (CMC): biomass	-
Calothrix scytonemicola	PHA, plastic film	Product 1: 150 mg pure PH3B and 8 ml of chloroform Product 2: 100 mg of PH3B and 50 mg CMC mixed with 8 ml of CMC Product 3: 100 mg of PH3B and 50 mg sucrose octa acetate in 8 ml of CMC	-
Nannocloropsis gaditana	Bio composite biomass and PBAT	Ratio of biomass 10, 20,30	-

Source: Cinar *et al.*(2020).

Cultivation methods of microalgae

Algal mass production methods aim to produce bio-components to gain biomaterials **(**Chen *et al.,* 2011; Sharma *et al.,* 2012). The economic interest is decreased towards microalgal cultivation for production of food and bioenergy sources. The present interest considered microalgal mass production to produce primary components such as proteins, saccharides, lipids, and secondary components include bioplastics, pigments, vitamins and antioxidants **(**Wijffels *et al.,* 2010).

The microalgae as raw material supplier for various future industrial processes can produce essential organic substances like amino acids, fatty acids, vitamins, and chromophores in high values. The amount and type of the synthetized raw materials mainly depend on the algal type and cultivation conditions (Cinar *et al.,* 2020). Although various systems for algal cultivation but they different in construction and production material and the control process. However, algal mass production for industrial scale is limited (Ugwu *et al.,* 2008). The most accepted common systems are open system (race way) and the closed systems (photobioreactors) as shown in Figure (7).

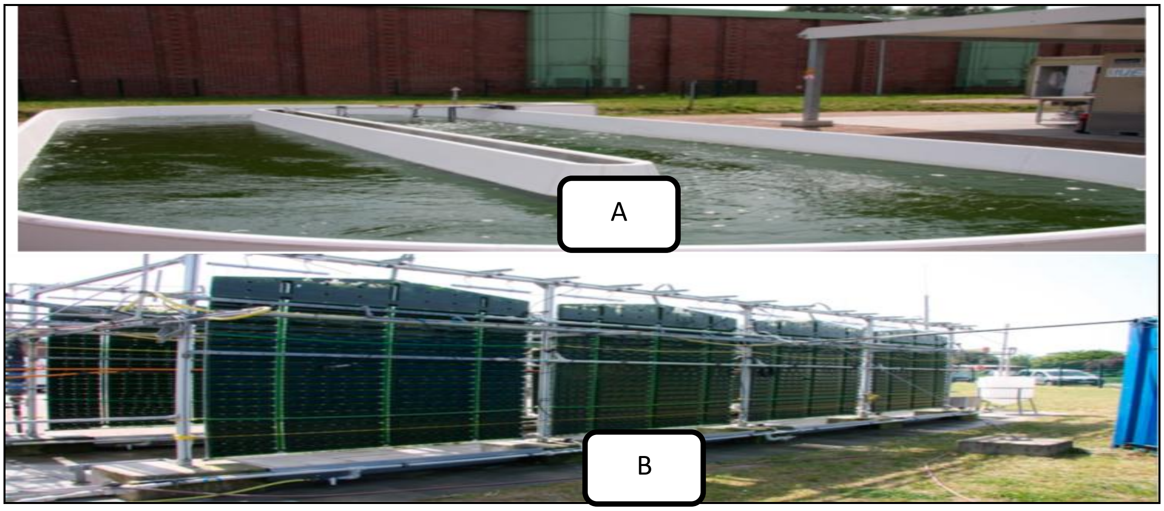


Fig. 7: A- open pond race way system, B- Photobioreactor closed cultivation system.
Source: Cinar *et al.,* (2020).

Harvesting process

This process accounts about 20-30% of production costs (Rawat *et al.,* 2011). Selection of the appropriate harvesting technique depends on morphological characteristics, cell size, density and specific surface charges (Uduman *et al.,* 2010). The most established harvesting methods include filtration, centrifugation, sieving, separation, sedimentation, flocculation, and flotation (Uduman *et al.,* 2010; Chen *et al.,* 2011). Using separator or centrifuge for algal harvesting is the most efficient method. The combination between two methods is possibly efficient and may reduce the cost where the previous methods of harvesting has advantages and disadvantages (Barros *et al.,* 2015).

Methods of microalgae based bioplastic:

Direct use of microalgae biomass

Several compounds (starch, cellulose, PHA, PHB, PLA, PVC and protein polymers) of algae biomass were used to develop bioplastics production (Karan *et al.,* 2019). PHA and PHB polymers were the top recommended in bioplastic production.

Blending process

Blending process improves the physico-chemical properties of the obtained bioplastic and extends the life span caused better mechanical performance. In this process, microalgae can be blended with several materials like cellulose or starch polymers, petroleum plastics. For example study of Otsuki *et al.,* (2004) blended maleic anhydride to modify PE with *Chlorella spp.*, Chiellini *et al.,* (2008) blended Polyvinylalcohol (PVA), and starch with *Ulva armoricanta* while Zeller *et al.,* (2013) examined the thermo mechanical polymerization of *Chlorella spp.* and *Spirulina spp.*, and they indicated that *Chlorella* showed that bioplastic behavior was better than *Spirulina spp.*, and lower blending performance. Jang *et al.,* (2013) compared between brown algae *Laminaria japonica* and the green algae *Enteromorpha crinite* during production of bioenergy to synthesize reinforced PP biocomposites, and they indicated that *E. crinite* showed that thermo mechanical properties were better performance than *L. japonica*. Mathiot *et al.* (2019) used microalgae to synthesize starch- based bioplastics in experiment of ten strains *Chlamydomonas reinhardtii* 11-32 A strain and the obtained plasticization ability showed satisfactory results. Machmud *et al.* (2013) mixed the red algae *Eucheuma cottonii* with latex of *Artocarpus altilis* and *Calostropis gigantean* to substitute use of glycerol as plasticizer. Finally, selection of the blended material is important to choose biodegradable substances avoiding the negative impact on the environment and pollution.

Genetic engineering

The potential of modifying the genes of algal strains to synthesize compounds used in bioplastics production is promising. The synthetized compounds include PHB, thermoplastics and biodegradable polyster produced by bacteria. Using genetic engineering technology by adding PHB of bacteria in microalgae or macro-algae is useful to lowering the cost during bioplastics manufacture (Hempel *et al.,* 2011; Rasul *et al.,* 2017).

Comparing plants, eukaryotic cells and other higher organisms, algae are genetically the simpler one. But the cost of using certain equipment and genetic kits was expensive (this is considered a challenge). Hempel *et al.*, (2011) used the diatom *Phaeodactylum triconutum* and insert on it the bacterial PHB to lowering the cost and gained up to 10.6 % PHB level, accumulated in granule-like form. Chaogang *et al.*, (2010) modified *C. reinnardtii* with two expression vectors containing PHBB and PHBC genes from *R.eutropha* to produce PHB. On the other hand, the genetically engineering algal strains were examined under laboratory conditions but their outdoor large production are critical needs specific conditions; temperature, light intensity, and pH value. Also, it is liable to cause contamination risk and ecosystem risk to human, animals and plants. Some allergic reactions in some people are recorded (Hlavova *et al.,*2015).

Basic common compounds produced by algae for bioplastic production

Figures (8- a, b and c) shows the basic compounds (PHB, PHA and P3HB) produced by algae for bioplastic production.

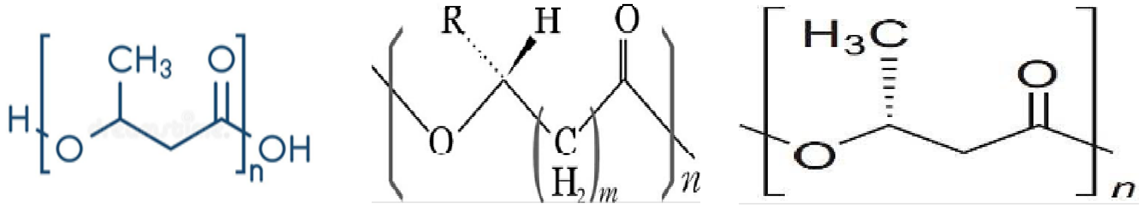
Polyhydroxybutrate (PHB)

PHB compound is a food storage material produced by various types of algae and bacteria (Falcone, 2004). PHB is aliphatic polyester produced by bacteria with thermoplastic characteristic (Suriyamongkol *et al.,* 2007). Algal (PHB) enhances recyclable property of plastic by lower petroleum quantity used in production of plastics. PHB is biodegradable, biocompatible and used in various fields' applications (medical, agricultural and industrial, sensors, audio equipment); due to its piezoelectric property (Mohammed and Aburas, 2016), nano-tubes and nano- complex films (Yun *et al.,* 2008) and pack urea fertilizers (Aguilar and San Rom, 2014). In medical field, PHB was used in nerve injury (Misra *et al.,* 2006), bone plates and as a medium for drugs slow release

(Steinbuchel and Fuchtenbusch, 1998) and tissue engineering applications (Chen, 2009). Abdo and Ali (2019) detected PHB concentrations in *Chrococcus turgidus*, *Microcystis aeruginosa* and *Haematococcus pluvialis* and HRAP different species HRAP *Microcystis spp.* and they found that the latter was the highest one.

Polyhydroxyalkanoates (PHA)

PHAs are thermoplastic polyesters, biodegradable polymers; into monomers after a certain amount of time in soil, compost or marine surroundings. However the degradation becomes more complex when the plastic produced with PHAs and various additives or fillers. The general structure of PHAs is made up of repeating ester units containing a carbon chain, bound to an R-group and two oxygen atoms. Poly-3-hydroxybutyrate (P3HB) is the most common polymer in the PHA family (Raza *et al.,* 2018).



(a) PHB (b) PHA (c) P3HB

Fig. (8): General structure of (a) PHB: Polyhydroxybutyrate, (b) PHA: Polyhydroxyalkanoates and chemical structure of (c) P3HB: Poly-3-hydroxybutyrate
Source: Raza *et al.* (2018).

Starch $C_6H_{10}O_5$) n

Starch is a mixture of two polysaccharides consists of molecule chains of glucose units. It consists of two molecules, the branched amylopectin and the linear and helical amylose (Fig. 9). Starch is produced in most green plants during photosynthesis as a form of energy storage and it's a biodegradable and renewable compound. Therefore, it serves as an ideal raw material substitute for fossil-fuel components in various applications and it used in bioplastics in place of synthetic polymers. Starch based bioplastics with biodegradable plasticizers can be degradable in various environments such as soil, composting and water. Thus, the raw material is highly suitable for applications where the product is likely or at risk to be disposed in the nature such as food and yard waste (Bastioli *et al.,* 2014).

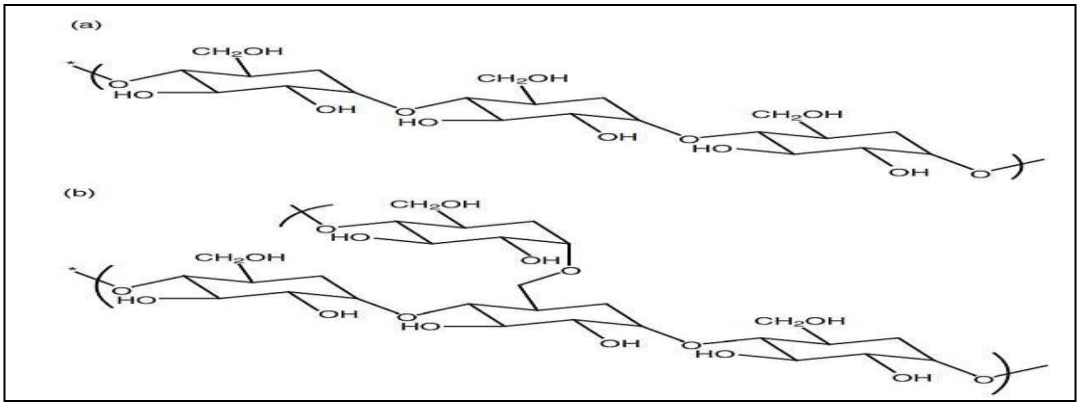


Fig. 9: Chemical structure of (a): amylose, (b): amylopectin,
Source: Starch Europe (2018).

The first attempt to produce bioplastic PHB (Fig.10) in the diatom; *Phaeodactylum tricornutum* and produced up to 10.6 % PHB of the algal (dry weight) thus, microalgae have high potential as novel biotechnology low-cost system. In addition, its high growth rate, easy cultivation with only light and water (Hempel *et al.*, 2011). PHB production in these algae recorded 100 fold higher than synthetized in plants (the known naturally synthesized of Omega-3- fatty acids by *P. tricornatum* discussed by Ramirez *et al.* (2007).

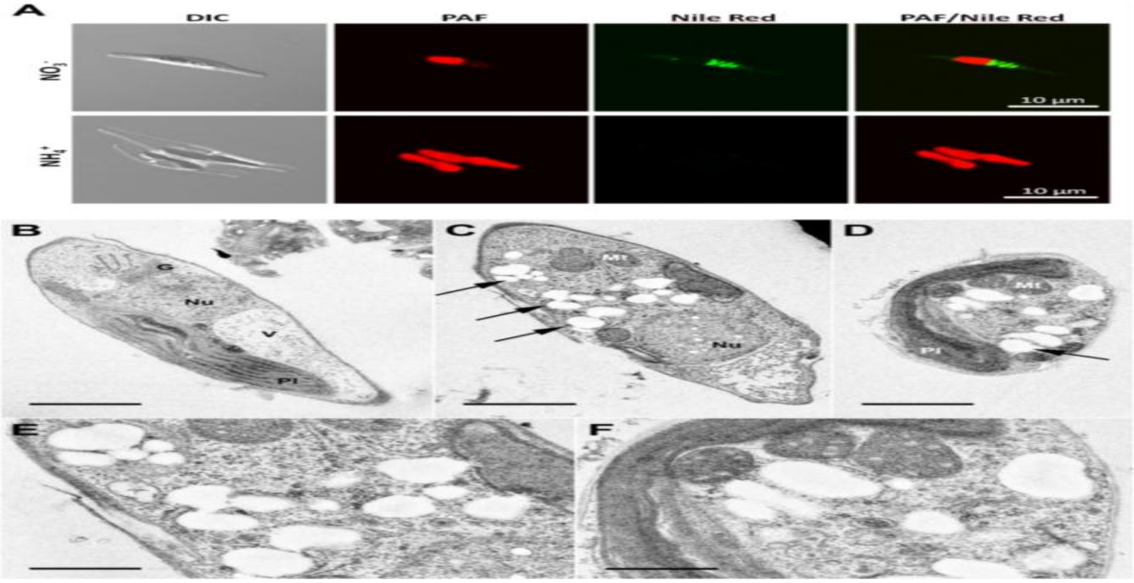


Fig. 10: Fluorescence and electron microscopic analyses on PHB accumulation in *P. tricornutum*. Photos (A-B) the normal cell none induced for PHB accumulation. Photos (C-F) the electron microscope confirm PHB granules formation. , Source: Hempel *et al.* (2011).

Technologies of bioplastic production

The present techniques in production of microalgal bio-composite are still under laboratory conditions and concentrated on the blend design. Further researches are needed to improve the cultivation systems, strains producing biopolymers on genetically basis. To produce microalgae- polymer blends, the following mixture must be formed:

algal biomass, polymers and additives in a mold under elevated temperature (130-160 ºC), pressure (20 KPa to 10 Mpa), for short time (3 to 20 min). The production methods to produce microalgal polymer blend bioplastics were melt mixing (Fabra *et al.,* 2018; Gozan *et al.,* 2018); compression molding (Ciapponi *et al.,* 2019; Fabra *et al.*, 2018); hot molding **(**Dianursanti and Khalis, 2018; Gozan *et al.,* 2018); injection molding **(**Torres *et al.,* 2015); twin screw extrusion (Charlie *et al.,* 2019, Torres *et al.,* 2015); and solvent casting (Zhang *et al.,* 2019).

Life cycle assessment (LCA) of bioplastics

Sustainability of the produced bioplastics is the basic interest for academic and institutional level. The term of LCA means investigation of the benefits and drawbacks of bioplastics used as an alternative of ordinary plastics. LCA is a standardized methodology with ISO 14040 and 14044 which can analyze socio-economic and environmental impacts related to certain goods (Di Bartolo *et al.,* 2021). LCA includes social, SLCA which means raw material, manufacturing, distribution, use and disposal of goods that can cause negative impacts from a social point of view. Life cycle costing (LCC) detects all costs during life cycle of the product (Di Bartolo *et al.*, 2021). Bussa *et al.* (2019) discussed the PLA production from plant –based source and compared this with microalgal source and they found positive results in microalgae. Bishop *et al.* (2021**)** compared between fossile based polymers and bio based polymers and they found lack of data and lack of uncertainly analysis. Most studies ignored additives use and their potential leakage in the environment, biogenic Co_2 in the atmosphere and its impact on fast growing crops, which can be relevant with use of lignocellulosic derived biomass that has long cycle of growth. End of life (EOL) was discussed by Lamberti *et al.* (2020) who covered the recycling routes of several bio-based polymers, and indicated that reuse of plastic as much as possible before recycling was the best then the plastic should be recycled mechanically then chemically. For example PLA should undergo mechanical recycling to gain lower grade polymer which further chemically recycled through alcoholysis to gain value added product (lactide) which can be directly polymerized to high Mn PLA. In general, this review indicated that the gap in the present research on this topic is lack of LCA comparable studies and this will need more in depth researches in the future.

Degradation of bioplastics

The microalgal efficiency in biodegradation of polymers with low degradation energy was proven recently by synthesis of certain enzymes with simpler or multiple toxins systems and involve weaken in polymer chemical ponds. Algae are able to colonize on artificial substrate like polyethelene surface in sewage water and this is the initial step in plastic biodegradation by formation of enzymes namely, ligninolytic and exopolysaccharide (Bhuyar, 2018).

Influence of microplastics on growth of some microalgae were investigated on *Spirulina* (Khoironi and Anggoro, 2019), *Raphidocelis subcapitata* (Canniff and Hoang, 2018) and *Dunaliella salina* (Chae *et al.,* 2019). More studies are recommended to investigate microalgae potential in biodegrading microplastic.

Future prospects and challenges of algal bioplastics

Although algal bioplastics are promising on laboratory scale but large scale production commercially faces some following challenges:

i- Selection of algal species that have ability to produce polymers and also selection of suitable polymer is depending on biodegradability, degradation rate, brittleness feed stock renewability, polymer size, molecular weight and moisture content (Thakur *et al.*, 2018).

ii- The products released from degradation of bioplastics such as CO_2, methane and other harmful gases must be considered for their effect on the environment (Rasul *et al.*, 2017).

iii- Some studies recorded unpleasant odors in bioplastics synthesized from algae (Wang *et al.,* 2016; Beckstrom, 2019).

iv- The cultivation system of algae used in bioplastics either open ponds or photo bioreactors in large mass production, although the costs of open pond was low but it is easily liable to be contaminated and showed low productivity. However, closed photobioreactor (lower contamination) has higher productivity but the scale- up cost is expensive. Based on the available literature, there are some advantages and disadvantages concerning bioplastics (Di Bartolo *et al.,* 2021**)**.

Advantages of bioplastics

1- Reducing reliance on fossil fuels by using renewable resources and replacing current polymers with bio-based alternatives.

2- Possible environmental benefits in terms of global warming reduction

3- Compostable plastics simplify waste management and return carbon to soil as compost in situations where organic contamination is expected.

4- Anaerobic digestion of biodegradable plastics can provide a lot of energy and help to establish a good carbon-to-nitrogen ratio in the process.

5- Biodegradable plastics might be used in lieu of non-biodegradable plastics in items that are prone to leak into the environment, reducing plastic pollution.

Disadvantages of bioplastics

1- Increase cost of production in parallel to low performance compared to common plastics.

2- Inability to process using common standard technology or a lack of expertise.

3- Small bioplastic market size that is not satisfactory to world demands.

4- Potential feedstock competition, mainly the raw materials, with biofuel and food industry.
5- Recycling of biodegradable plastics has risk and lack of research.
6- Emissions of risk gases during landfilling of biodegradable plastics.
7- Decrease in recycling and composting infrastructure.
8- Doubt in biodegradability in open environmental systems.

On the other hand, during organic waste collection in compostable plastic bags, there is no need to separate the bag from the waste, where anaerobic digestion after usage may result in renewable energy. In this field, there are two expressions namely; linear and circular economy. The steps of linear economy begin with resources collection, production of plastic goods, usage, and finally their disposal. The circular economy path adds another 2 steps; repurposing of goods and its recycling, especially with mechanical way, to enlarge the life cycle of the material. World bioplastic industry is relatively recent and small in volume compared to the ordinary plastic industry, so a lot of challenges face this industry and it needs intensive focus scientific research (Di Bartolo *et al.,* 2021).

CONCLUSION

In conclusion, this review focused on the present status of potential use of most algae species for bioplastics production by cultivation systems. Also, it showed the effect of different harvesting processes on biomass and the potential of molding algal genes led to synthesize more compounds. Based on these literatures, *Chlorella* and *Spirulina* have got the better performance and properties of the gained product. Moreover, the algal food storage PHB used in various field applications (medical, agricultural and industrial). Emphasize on the present techniques in microalgal bio-composite and methods of producing microalgal polymer blend bioplastics. The microalgal efficiency in polymers biodegradation by enzymes and colonization on plastic substrata as initial step in plastic biodegradations are considered challenges till now. Although, these criteria are carried out on lab scale and far from commercial production but give promising opportunities.

Finally, this study recommends further studies using genetic engineering and new biotechnology techniques to produce materials needed in bioplastic production. Although some industrial companies could be produced plastics contained 50% algae but plastics derived from 100% algae are still not a reality and require innovative development.

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