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Natural Biodegradable Promising Polymers From Cellulose Extracted from Water Hyacinth and Seaweed for Bioplastic Production: A Review.

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Abstract

Plastic pollution has become a pressing environmental issue, necessitating the development of innovative solutions to mitigate its adverse impacts. In this study, we investigate the potential of water hyacinth (Eichhornia crassipes) and seaweed as cellulose-based natural polymers for combating plastic pollution. Both water hyacinth and seaweed possess high cellulose content, rendering them promising candidates to produce sustainable alternatives to conventional plastics derived from fossil fuels. By utilizing these aquatic plants and transforming them into useful derivative products, such as bioplastics, we can reduce dependence on traditional plastics and thereby mitigate the environmental consequences of plastic waste. Furthermore, the utilization of water hyacinth and seaweed presents opportunities for a circular economy, promoting resource recycling and repurposing. Through an exploration of the environmental and economic aspects of plastic pollution, this study underscores the potential of water hyacinth and seaweed in effectively addressing plastic pollution and fostering a more sustainable future.

Keywords: Plastic pollution, Bioplastic; Water Hyacinth; Cellulose; Seaweed

1. Introduction

The use of plastic is expected to keep rising for at least the next ten years, as it is expected to increase every year. Only 9% has been recycled of 9 billion tons of plastic produced worldwide (Geyer et al., 2017). 348 million tons of plastic products were produced in 2017 according to (Plastics Europe, 2020). Most of the remainder has found its way into rivers, lakes, oceans, landfills, and other waste sites (Pawar et al., 2016). It was predicted that 52 million tons of mismanaged plastic garbage were generated in Asia, 17 million tons in Africa, and 8 million tons in Latin America in 2015 (Lebreton and Andrady, 2019). Plastic is commonly utilized, especially in the packaging sector, and currently makes up a significant portion of municipal waste due to its excellent heat tolerance, hardness, lightweight, and high flexibility (Awoyera and Adesina, 2020) . Globally, 19–23 million metric tons of poorly managed plastic garbage are dumped into the marine environment each year (Borrelle et al., 2020). Plastics are synthetic or semi-synthetic materials that are typically high molecular mass polymers that are derived from petroleum and natural gas (Rajendran et al., 2012a). Nowadays, petrochemicals made from petrol and fossil fuels account for nearly all the material used to make plastics. Plastics are directly made from petrochemical feedstock, accounting for around 4% of yearly petroleum production (Hopewell et al., 2009). Conventional synthetic polymers, also referred to plastics, such polypropylene and polyethylene, are sourced from non-renewable petrochemicals and are known to have negative environmental effects because they are not biodegradable (Thompson et al., 2009).

Plastic is formed of a long-chain polymer of atoms, which is made up of many repeating molecules, or monomers. Polymers with carbon-carbon backbones make up over 77% of the world's plastic production (Geyer et al., 2017). This molecular structure offers great resistance to degradation by the environment, resulting in durable materials that remain for decades or longer if not destroyed by burning. Since the 1950s, the production of industrial plastic has increased quickly, reaching 368 million tons every year by 2019 (Plastics Europe, 2020). Because these plastics are not biodegradable, it will take a long time for them to be completely degraded. As a result, they accumulate as waste in the environment (Moshood et al., 2022a). Plastic waste has become a serious issue for the environment due to its disadvantages (Kibria et al., 2023). Disposing of plastics requires the release of toxic chemicals like dioxins, which may contribute to global warming(Verma et al., 2016).

Recycling these plastics is also challenge and it must be recycled using different process (Tulasi and Bhai, 2013). Plastic waste exacts a harmful effect on terrestrial and aquatic environments, with far-reaching consequences for ecosystems and human health (Verma et al., 2016). Plastic pollution imposes multifaceted risks on human health and ecosystems, extending beyond visible littering (Kumar et al., 2021).If animals are poisoned by toxic materials found in plastic waste and plastic products, it could have a negative impact on human food sources (Proshad et al., 2017). In fact, reports of the harm that the massive amounts of plastic waste that are entering the world's oceans pose to the survival of huge marine creatures have been documented (Okunola A et al., 2019).When plastic waste that was landfilled finally dissolves down, carbon dioxide and methane are released into the air (Borra, 2002).Pollutants such dioxins, heavy metals, PCBs, and furans are released when plastics and plastic items are burned openly. These pollutants can be harmful to human health, particularly respiratory conditions. Birds' digestive systems can get physically obstructed and damaged by ingesting plastic wastes, which can lower

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the system's capacity to digest food and ultimately result in malnutrition and death (Okunola A et al., 2019).In the intestines and stomachs of dead animals, large amounts of plastic waste were found which encourage the development of cancer cells (Kurniawan et al., 2021). Most additives found in plastics have the potential to cause cancer and disturb hormone balance. The plastic polymers that are most frequently used are polyethylene,polyethylene terephthalate (PET),polyvinyl chloride (PVC), and polypropylene(PP).Plastics and microplastics (particles less than 5 mm)have a significant negative effect on human health and economy.The negative effects of plastics involve the blockages of canals and sewers,the development of mosquito breeding grounds, the obstruction of animal airways and stomachs,and contaminated beaches, lakes, and rivers(Tekman et al., 2022). Additionally, because microplastics have been found in human food, the air, and drinking water, they could be threats to the health of people, animals, and ecosystems (Josiane Nikiema et al., 2020). Egypt is the largest producer of plastic pollution in the Arab world, producing 5.4 million tons of plastic annually (Gomaa et al., 2022). According to a recent assessment by the Worldwide Fund for Nature (WWF), Egypt is the main contributor to the Mediterranean's plastic pollution, contributing 250,000 tons annually (Abdel Ghani et al., 2022). Because of this, it is crucial to utilize biodegradable plastics that are made of natural sources and have the same characteristics as plasticizers in order to maintain human health and the environment (Aragão and Turan, 2022). The benefits that humans receive from the sea are predicted to decrease by 1–5% as a result of plastic pollution (Beaumont et al., 2019). Therefore, individuals are searching for a substitute that may reduce the problems caused by plastics, such as development of "bioplastic," which is a plastic derived from renewable biological sources like plants, bacteria, and algae that can be broken down by microorganisms that live in the soil like fungi and bacteria without producing any pollutants (Lomartire et al., 2022; Thiruchelvi et al., 2020).

Plastic pollution disrupts marine ecosystems in a variety of ways, including by directly affecting the health of marine life caused by organisms hitchhiking and having negative effects on fisheries, in addition to damage to ecosystem services (Carney Almroth and Eggert, 2019). Additionally, the accumulation of microplastics has complicated impacts on individual organisms and ecosystems (Thushari and Senevirathna, 2020). As a result, the global concern about plastic pollution has increased. Figure 1 shows one form of plastic pollution. Plastic pollution is complicated and requires effective management using a variety of strategies (Aare et al., 2024). This could be achieved by preventing plastic waste from ending up in the environment and by recycling it (Aare et al., 2024). So, studies investigated and concerned bioplastic production to overcome these problems. The definition of "bioplastic" is a material that made from renewable resources (Ezgi Bezirhan Arikan and Havva Duygu Ozsoy, 2015).

Fig. 1 one form of environmental plastic pollution

The definition of "bioplastic" is a material that made from renewable resources(Ezgi Bezirhan Arikan and Havva Duygu Ozsoy, 2015). Bioplastics have many benefits over petroleum-based plastics, including non-toxic chemicals, ease of recycling, a reduction in the use of fossil fuels, lower cost requirements, and a lower consumption of energy to produce renewable and environmentally friendly materials (Thiruchelvi et al., 2020).

It is not a new concept to use bioplastics; at first, they were primarily used to wrap candies in the early 19th century (Ogwu et al., 2024). They derive from biological origins, hence they are very important (Paxman et al., 2008; Thiruchelvi et al., 2020). A promising solution to the world's current plastic-related challenges is bioplastics (Porta, 2019). Agriculture waste (AW) was utilized by Roopesh Jain et al. as an inexpensive, renewable substrate for bacterial fermentation to produce bioplastics (Jain and Tiwari, 2015). Blending the bioplastic sheet with cellulose acetate butyrate (CAB) has also been shown to improve its tensile qualities (Jain and Tiwari, 2015). Yug et al. (Saraswat et al., 2014) produced bioplastic based on starch, explain how to form bioplastic films using different types of starch and discuss the role of plasticizers (especially glycerol and sorbitol) in generating them. Also studied its properties and importance to bring this technology to India (Saraswat et al., 2014). Akshaya Krishnamurthy and Amritkumar (Krishnamurthy and Amritkumar, 2019) were formed three composite bioplastic films using starch mix with lemon extract and water.

The formulated films' physical, chemical, mechanical, and biological parameters were studied. Biodegradability of films was demonstrated through soil burial method and culturing of pure cultures of microorganisms in minimal media by providing the film as carbon source. Bioplastic films developed in this study using low-cost plant starch sources have displayed properties with potential application in food packaging industry (Krishnamurthy and Amritkumar, 2019). Bioplastics can come from a variety of sources, including plants, animals, and microorganisms, but they are limited in several ways, including the inability to obtain large biomass and the challenges associated with cultivation(Bhatia et al., 2021). In these situations, seaweed can be used as an option for producing bioplastics due to their high biomass, adaptability to a variety of conditions, and natural cultivation(Rajendran et al., 2012b). This contrasts with other microbiological sources which demand a particular setting to grow. It has been observed that seaweed-derived bioplastics are less brittle, more durable, and resistant to microwave radiation. It is predicted that significant advances in the bioplastics sectors will enable the development of technologies for seaweed-based bioplastics, which are currently in the research phase and could eventually become a reality (Rajendran et al., 2020). This review focuses on investigating approaches that can be used to reduce weed waste and plastic pollution in aquatic systems. This review also focuses on producing environmentally biodegradable plastic based on cellulose extracted from water hyacinth and seaweed. So, earlier and future research concentrated their efforts depend on this concept.

2. Bioplastic

Bioplastics were first produced in the 1950s and then came back in the 1980s (Endres, 2019; Folino et al., 2020) but have only recently acquired the necessary attention (Endres, 2019; Yang et al., 2010)specifically, their industrial-scale production started in the 2000s (Song et al., 2009). The concept of "bioplastics" represents both bio-based plastics, including those produced from biogenic components, and biodegradable plastics, including those made of petrochemicals. However, not all bio-based plastics degrade easily (De Gisi et al., 2022). On the other hand, some biodegradable plastics might have petrochemical roots (Anstey et al., 2014; Penkhrue et al., 2015). Therefore, a bioplastic is one that is either bio-based, biodegradable, or both (De Gisi et al., 2022). A decrease in the number of carbonyl groups during degradation is a good indicator of microbial growth (Montazer et al., 2020). The final products of the degradation of these smaller polyolefins are water and carbon dioxide (Montazer et al., 2020). Pro degradant additives may also be added to these polymers to accelerate their rate of degradation and usually include metal salts (Nandakumar et al., 2021). The search for alternatives has become possible because of the environmental issues raised by synthetic polymers (Atiwesh et al., 2021). In 2019, The quantity produced was 2.11 million tons of plastic, of which 55.5% were biodegradable plastics and 44.5% were bio-based plastics (Bioplastics 2020). Additionally, it is predicted that in 2024, the generation of bioplastics will grow nearly 2.43 million tons (Kuddus and Roohi, 2021). Bioplastics promise to be the best alternative to traditional plastics (Accinelli et al., 2012; Karamanlioglu et al., 2017), as they might have the same application. Bio plastics are an appropriate solution for sustainability in the environment (Rosenboom et al., 2022; Ryan et al., 2017) because they are both biodegradable (Mihai et al., 2014; Rosenboom et al., 2022) and the utilization of biogenic raw materials in their production. Both aspects support the objectives of the circular economy (Sharma et al., 2019). Since using bio-based polymers instead of traditional plastics would only require about 0.02% of the planet's total arable land for agricultural production, the ability to manufacture bioplastics from waste is of greatest significance (Bioplastics and 2020). According to estimates, this percentage will rise by more than 50% by 2050, raising the serious question of whether land could be utilized for growing food crops or as a storage facility for plastic, as had happened with first-generation biofuel, which needs substantial land-based crops (Sharma et al., 2019). Agricultural crop-based feed stocks (carbohydrates and plant materials) are still used to make a significant amount of bioplastics (Karan et al., 2019) which increases water use and decreases food production (Lima, n.d.). According to this perspective, the adoption of new technologies to produce bioplastics will accelerate the transition from a civilization reliant on fossil fuels with inefficient waste management to one reliant on renewable resources with reduced fossil fuel use and efficient waste management focused on reuse (Ford, 2016). Recent environmental, economic, and societal difficulties have contributed to the development of environmentally friendly materials (Peelman et al., 2013b). Future global production and use of bioplastics will rise. As a result, these materials need to be carefully evaluated for sustainability and waste management (Ezgi Bezirhan Arikan and Havva Duygu Ozsoy, 2015).

2.1. Sources of Bioplastic

Bio plastics are manufactured from bacterial, algal, and plant sources (Rajendran et al., 2012a). It produced from different sources as follows;

2.1.1. Plant source

A biodegradable plastic based on natural sources is of great interest as it is cost-effective, renewable, and used for various applications (Moshood et al., 2022b). The term "biodegradability" refers to an end-of-life solution that uses the power of microorganisms found in the disposal site to quickly, safely, and effectively remove all plastic items intended for biodegradability from the environment through the microbial food chain (Rujni, 2020). Natural plant derivatives can be used to generate bioplastic (Mooney, 2009). Many naturally occurring polymers produced by plants, such as starch or cellulose, have been exploited to produce plastics (Mooney, 2009). The numerous plant sources include starch-based ones such as corn starch, wheat, rice, sweet potatoes, barley, sorghum, and derivatives of cellulose, which account for more than 80% of the market for bioplastics (Rajendran et al., 2012a). A number of bioplastic typologies have been introduced in recent years; the most significant ones are based on starch derivatives (Tokiwa and Calabia, 2014; Vasile, n.d.). The chemical and physical structure of bioplastics has significant effects on their biodegradability (Emadian et al., 2017). On the other hand, their biodegradation is greatly influenced by their surrounding environment (Emadian et al., 2017).

Previous study (Emadian et al., 2017) focused on the degree of biodegradation, environmental factors, and the biodegradation of bioplastics in a variety of environments. It also identified the microorganisms from various microbial communities that are capable of breaking down bioplastics (Emadian et al., 2017). Enzymatic breakdown of bioplastics is caused by either extracellular or intracellular enzymes (Urbanek et al., 2020). Enzymes have a major role in the biodegradation of bioplastics, therefore depolymerases, which can be derived from microorganisms capable of breaking down bioplastics, were investigated (Chua et al., 2013). This paper discussed the production of bioplastic from plants that have many drawbacks for the environment, like water hyacinth, as follows;

Water hyacinth (WH)

Water hyacinth is an invasive alien species that damages aquatic ecosystems (Téllez et al., 2008). Although it originated in the Amazon basin in South America, it has since expanded all over the world. Due to its quick proliferation, it can be regarded as the world's most dangerous aquatic weed. It has been estimated that two plants may multiply into 1,200 plants in just 120 days (Rezania et al., 2015). The plant can quickly cover significant water areas due to its rapid growth (Ajithram et al., 2021). The propagation of WH and its spread to new places can also be accelerated by strong winds or excessive waves. The spread of the invasive WH plant can cause problems in the agricultural, ecological, economic, and public health fields. To stop its spread, several types of strategies have been used, but little substantial progress has been made. There has been very little research dealing with systematic methods for WH control (Karouach et al., 2022). The biological, mechanical, environmental, and chemical methods are the types that are most frequently employed to manage and control the growth of WH (Carvalho and Cerveira Junior, 2019). Each of these management techniques has benefits and drawbacks, which will be discussed in more detail in the next part of this article. WH has certain disadvantages, but it also has a lot of beneficial applications. WH is a free-floating aquatic plant with large, thick, glossy, and oval leaves, as shown in figure 2 (El-Chaghaby et al., 2022). WH may grow up to one meter (3 feet) above the water's surface. The stem with the leaves is 10–20 cm (4–8 inches) broad and floats above the water's surface due to buoyant nodules that look like bulbs. They have bulbous, long, spongy stalks. The purple-black roots hang freely and fluffily. A single spike of 8–15 strikingly beautiful flowers, most of which are lavender to pink and have six petals, is supported by an erect stem. WH develops when the water is between 28°C and 30°C, with high levels of nitrogen, phosphate, and potassium. Under ideal circumstances, water hyacinths grow very quickly in fresh water (El-Chaghaby et al., 2022). In ideal circumstances, WH surface can expand by up to 60 meters each month, and its seed can remain dormant on the bottom of the invaded water body for a period of up to twenty years (Auchterlonie et al., 2021). WH come in seven different kinds, including E. crassipes, the common water hyacinth; E. azurea, the anchored water hyacinth; E. paniculata, the Brazilian water hyacinth; and E. diversifolia, the variable leaf water hyacinth (Rezania et al., 2015).

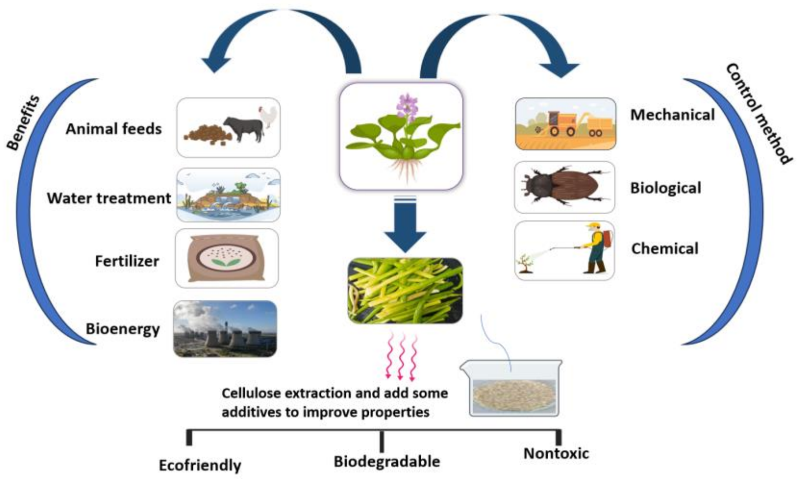


Fig. 2 Water hyacinth control methods and benefits

The most popular strategies that are utilized for control involve mechanical, biological, and environmental techniques (El-Chaghaby et al., 2022), as shown in Figure 2. Each of these management strategies has benefits and drawbacks. Chemical control is reasonably affordable, but it is unlikely to be utilized as a long-term solution given its negative impact on the environment (Auchterlonie et al., 2021; Ilo et al., 2020). An effective substitute for the use of herbicides is the mechanical harvesting or shredding of water hyacinth shoots, but this method requires expensive equipment. Although it has potential, it is quite expensive because of the high cost of mechanical equipment, manpower, and initial investment, as well as because it takes a lot of time. Environmental management techniques include restricting the amount of shallow water and sunshine to prevent plants from producing enough food; however, this approach is ineffective once the plants start to slant towards the water's surface (Joshi et al., 2019). Biological control, which is commonly regarded as a hopeful strategy that includes the use of biological control agents, is one of the best ways to reduce water hyacinth populations. Eight different kinds of biological agents for pest control have been introduced globally (El-Chaghaby et al., 2022).

Bioplastic production from WH

It is true that WH suffered significant economic loss, which almost hides the advantages of using this plant and reaping its benefits. Due to its high cellulose content (25%), hemicelluloses (33%), and lignin (10%) (Setyaningsih et al., 2019), water hyacinth is suitable as a raw material for cellulose base polymers, which are more economically valuable than the materials they are currently using.

According to an earlier study by Thiripura and Ramesh (Thiripura Sundari and Ramesh, 2012), cellulose is considered as a natural polymer that has been employed in a variety of applications owing to its particular advantages, for instance, being easily accessible, biocompatible, hydrophilic, non-toxic, and biodegradable. Cellulose is formed by β-1,4-glucosidic bond. Cellulose is the most abundant organic chemical formed from cellulosic biomass, the most common natural polysaccharide, and the oldest substance utilized on Earth. Cellulose serves as a structural component in flora. Cellulose has special benefits and characteristics, including biodegradability, relatively high resistivity, biocompatibility, renewability, and rigidity, among others (Arbelaiz et al., 2005; Eichhorn et al., 2010; Johar et al., 2012). Naturally, cellulose is found as an assembly chain of cellulose that repeats a semi-crystalline structure, not as a single isolated molecule, so it is creating microfibrils in the plant cell wall. Typically, a hydrogen bond network connects about 36 individual cellulose molecule assemblies to form massive structures called elementary fibrils (Habibi et al., 2010). Many different polymers with distinct structural characteristics and carbon reserves are produced spontaneously by plants. Polysaccharides constitute around 70% of all organic matter, according to estimations. The most common macromolecule on earth is cellulose, which accounts for about 15–25% of the lignin and 40% of all organic matter in a typical woody plant. Additionally, a large portion of biomass globally is made up of starch. It has been hypothesized that the capacity to digest starchy meals played a part in the development of humans and their ability to exert dominance over other forms of life (Perry et al., 2007). Today's most prevalent forms are those based on starch, followed by those made of poly-3-hydroxybutyrate (PHB), polyamide 11, organic polyethylene (PE), and polylactic acid (PLA) (Satti and Shah, 2020). Despite the benefits of bioplastics made from plants, there are certain drawbacks, such as decreased biomass, an effect on the human food chain, and a longer production time (Rajendran et al., 2012a). Most common plastics made from petroleum, such as polystyrene, polypropylene, polyethylene, and PVC, are not biodegradable, but adding starch to polyethylene enables polymer breakdown in composting environments. Plastic that can be broken down through the action of naturally occurring microorganisms, including fungi, algae, and bacteria, is known as biodegradable plastic (Mooney, 2009). Plastics' resilience and strength typically directly conflict with how easily they can degrade biologically. It is challenging for biological catalysts (enzymes) to degrade the polymer because of the chemical composition of plastics. Section provides more details on these components as well as others (Tokiwa et al., 2009). Thermoplastic starch made from materials like rice and corn has generated a lot of interest among the variety of bioplastics now on the market because of its good processing ability, abundance, and low cost (Nguyen et al., 2024). In comparison with conventional synthetic polymers, it has a variety of shortcomings, including retrogradation during storage, low mechanical performance, and considerable hygroscopicity (Nguyen et al., 2024). In this regard, it has been demonstrated that the use of fillers is an effective strategy for enhancing the characteristics of bio-derived polymers and composite materials that are competing for their intended uses (Darder et al., 2007; Peelman et al., 2013a).

2.1.2. Algae Sources

Autotrophic organisms that can be found in both single- and multicellular forms are called algae (Bonito, 2024). Depending on their size and appearance, algae are classified as microalgae or macroalgae (Jalilian et al., 2020). Additionally, differing ecosystems like freshwater or marine environments, specifically freshwater microalgae or marine macroalgae, contribute to their diversity (Cheng et al., 2022). Microalgae are typically unicellular, less than 1000 m in maximum size, rapidly growing organisms with high production (Dolganyuk et al., 2020). Microalgae are found in diverse aquatic environments and play important roles in wastewater treatment, industrial pollutant removal, and various industries (Hala et al., 2021). They have rapid reproduction rates and can convert sunlight and carbon dioxide into biomass through photosynthesis. Microalgae cultivation can be integrated with wastewater treatment to remove pollutants and produce biomass for bioplastics (Hala et al., 2021) . Their biomass contains valuable compounds for bioplastic production, and their composition can be manipulated for desired properties. It is difficult to harvest, unlike Spirulina dregs, which are used to make bioplastics (Chisti, 2007; Thiruchelvi et al., 2020). Seaweed and other macroalgae have greater potential than the sources already mentioned because of their large biomass, low cost, ease of cultivation in a natural setting, ability to thrive in a variety of conditions, and year-round harvest ability (Abdul Khalil et al., 2017a).

Seaweeds

Multicellular photosynthetic organisms known as marine macroalgae (seaweeds) live in all aquatic habitats (Lee and Ho, 2022). They offer a lot of benefits and are known to be a source of several important bioactive materials (Rashad and El-Chaghaby, 2020). In the domains of biotechnology, microbiology, food technology, and medicine, seaweed is frequently used. They are also currently used in the plastics business. The evolution of seaweed production and processing on a global scale over the previous 20 years was examined, and the most recent developments in seaweed farming technology were presented as shown in Figure 3 (Zhang et al., 2022). Pollution from plastic poses a hazard to the world's marine ecology (Mirpoor et al., 2020). There are new challenges as well as existing environmental problems, such as the dwindling supply of raw materials needed to produce plastic (Sheldon and Norton, 2020). Because natural gas and petroleum are utilized to produce traditional plastic raw materials (Duruin et al., 2022). Pollution from plastic poses a hazard to the world's marine ecology (Mirpoor et al., 2020). There are new challenges as well as existing environmental problems, such as the dwindling supply of raw materials needed to produce plastic (Sheldon and Norton, 2020). Because natural gas and petroleum are utilized to produce traditional plastic raw materials (Duruin et al., 2022). Pollution from plastic poses a hazard to the world's marine ecology (Mirpoor et al., 2020). There are new challenges as well as existing environmental problems, such as the dwindling supply of raw materials needed to produce plastic (Sheldon and Norton, 2020). Because natural gas and petroleum are utilized to produce traditional plastic raw materials (Duruin et al., 2022). In the modern world, seaweed is employed as a novel and bioplastic alternative source due to its special qualities, which include being toxic-free, environmentally beneficial, and inexpensive (Thiruchelvi et al., 2020). Pollution from plastic poses a hazard to the world's marine ecology (Mirpoor et al., 2020). There are new challenges as well as existing environmental problems, such as the dwindling supply of raw materials needed to produce plastic (Sheldon and Norton, 2020). Because natural gas and petroleum are utilized to produce traditional plastic raw materials (Duruin et al., 2022). In the modern world, seaweed is employed as a novel and bioplastic alternative source due to its special qualities, which include being toxic-free, environmentally beneficial, and inexpensive (Thiruchelvi et al., 2020). In addition, their chemical resistance and tensile strength are comparable to those of other bioplastics (Thiruchelvi et al., 2020). In addition to being affordable, widely accessible, and sustainable, seaweeds may absorb CO_2 through photosynthesis to slow global warming and lessen ocean acidity (Duarte et al., 2017). Oxygenated air is a byproduct of photosynthesis. In the soil, seaweed bioplastics decompose within four to six weeks (Lim et al., 2021).

Seaweed types

Seaweeds are plant-like organisms that generally live around coastlines and cling to rocks or other hard surfaces (Batcha and No, 1986). They are also referred to as marine macroalgae. Seaweeds can be divided into three major groupings based on their color, which is induced by the pigments' presence: brown (Phaeophyta), green (Chlorophyta), and red (Rhodophyta), as shown in Figure 4 (Aryee et al., 2018; Haugan and Liaaen-Jensen, 1994; Seely et al., 1972). Brown and red seaweed originate almost entirely in the ocean, as opposed to green algae, which is often found in habitats of freshwater like rivers and lakes in addition to on land (Green and Elmberg, 2014). A clear health benefit of seaweed is their high concentration of vitamins and minerals (Rajapakse and Kim, 2011). They can be consumed raw in salads, soups, pastries, dinners, and condiments because they are palatable and packed with healthy nutrients (Hamed et al., 2015). The amount of protein content varies by species even though all seaweed species share a similar chemical composition (Abdul Khalil et al., 2017b; El-Said and El-Sikaily, 2013). As indicated in Table 1, brown seaweed has a protein concentration of 3-15 %, but green and red seaweeds have protein concentrations of 10-47% (Abdul Khalil et al., 2017b; El-Said and El-Sikaily, 2013).

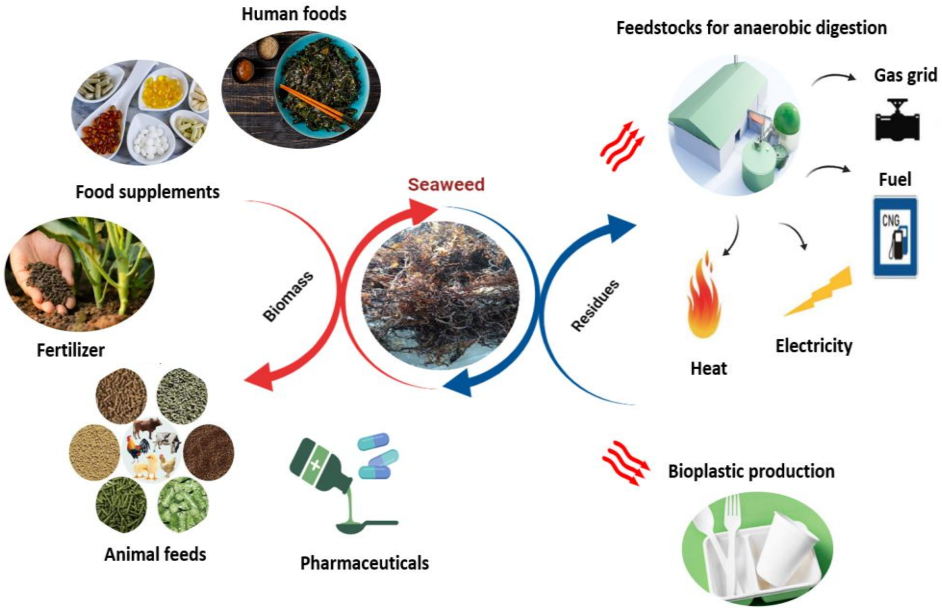


Fig. 3 Overview of the applications of seaweed

Seaweeds are unquestionably superior to other biomaterials because they can thrive without freshwater, soil, or pesticides (Ditchburn and Carballeira, 2019).

Along with the value of seaweed as a food in its natural form, its high carbohydrate content has encouraged the industrial use of seaweed species as a source of hydrocolloids (seaweed derivatives), such as alginate, carrageen, and agar, in the fields of microbiology, food technology, medicine, biotechnology, and the plastics industry (Table 2) (Abdul Khalil et al., 2017b; Gade et al., 2013). These hydrocolloids are hydrophilic polymers with long chains (polysaccharides) that can create gels and/or viscous dispersions when detached from water (Gade et al., 2013). As a result, they are frequently used as gelling agents or thickeners to regulate the functional characteristics of aqueous solutions (Gade et al., 2013). Each phylum of seaweed has polysaccharides that vary not just in their chemical makeup but also in how they function (Gade et al., 2013). The origin, species, growing locations, and extraction techniques are only a few of the variables that might impact the composition and characteristics of seaweed. In numerous applications, including the production of plastic, derivatives of seaweed like carrageenan agar and alginate are frequently used because they have a low lignin content and unique film-forming capabilities (Kadar et al., 2021). Diverse seaweed types can be used or merged with other materials to increase their performances and qualities, despite their flaws, including mechanical strength and low water vapor barrier properties (Porta, 2019).

Fig. 4 Three main groups of seaweeds according to their color

Table 1 Seaweeds chemical composition (Abdul Khalil et al., 2017b; El-Said and El-Sikaily, 2013)

Components	Compositions
Water	80-90%
Protein	Red or Green seaweed:10-47% dry weight Brown seaweed: 3-15% dry weight.
Carbohydrates	50% dry weight
Lipids	1-3% dry weight
Minerals	7-38% dry weight

Table 2 Available polysaccharides in brown, red and green seaweeds (El-Said and El-Sikaily, 2013)

Polysaccharides	Red seaweed	Brown seaweed	Green seaweed
Agar	✓	-	-
Carrageenan	✓		
Alginate	-	✓	-
Floridean Starch(α-1,4-bindingglucan)	✓	-	-
Cellulose	✓	✓	✓
Mannitol	-	✓	-
Fucoidan(sulphateedfucose)	-	✓	-
Mannan	✓		-
Laminarin(β-1,3 glucan)	-	✓	-
Sagrassam	-	✓	-
Sulphatedgalactans	✓	-	-
Porphyran	✓		-
Xylans	✓	-	✓
Sulphuric acid polysaccharides	-	-	✓

Alginate, carrageenan, and agar are the seaweed-derived biological substances best suited to create biofilms or bioplastics (Abdul Khalil et al., 2017a; Kanmani and Rhim, 2014). Jang et al. (Jang et al., 2013) synthesized seaweed-reinforced polypropylene (PP) bio composites using two kinds of seaweed, namely brown algae Laminaria japonica and green algae Enteromorpha crinite, which were collected from the waste materials utilized to produce bioenergy. The investigation revealed that E. crinite was a more suitable option for reinforcing bio composites than L. japonica because it demonstrated stability at high temperatures. The strength and thermomechanical properties of green algae-reinforced PP bio composites were found to be satisfactory when compared to brown algae-reinforced PP bio composites (Hun et al., 2013). Microalgae were employed in a study by Mathiot et al. (Mathiot et al., 2019) to produce starch-based bioplastics. It was discovered that the starch-based bioplastics have a good plasticization potential (Arora et al., 2023). The mechanical properties of composites decreased as the percentage of algae concentration increased, except for E. crinite composites, which showed high particle sizes. It was shown that the mechanical properties of the composites were influenced by the size of the algae particles, with larger particles exhibiting superior mechanical properties. Further investigation ought to focus on enhancing the bond between the matrix and filler, thereby customizing the kind of algae and particle size to maximize the composite's efficiency (Bulota and Budtova, 2015). Machmud and coworkers (Machmud et al., 2013) employed *Eucheuma cottonii*, a red alga, as a raw material for the filtration method of plastics production. Because the increasing concentration of glycerol decreased the thickness and density of the bioplastics, red algae were mixed individually with the latex of Artocarpus altilis and Calostropis gigantea to generate bioplastics instead of using glycerol as a plasticizer. The room-temperature tensile test showed that glycerol decreased the bioplastics' tensile strength and energy absorption while having no effect on their ductility (Machmud et al., 2013)

a. ***Alginate***

Alginate has been observed to have the ability to create edible films and is the most prevalent polysaccharide inside brown seaweed, accounting for up to 40% of its dry weight(Abdul Khalil et al., 2017b). It is a polysaccharide that derived from alginic acid, its salts and derivatives (Abdul Khalil et al., 2018b). Figure 5 shows how they are made of alginic acid polymers with 1,4 linkages between the monomer units of -D-mannuronic acid (M) and -L-guluronic acid (G) (Setyawidati et al., 2018). The alginate gel's mechanical and physicochemical properties vary based basically on the length of the structure and the M/G ratio; therefore, a high guluronic acid content results in a more elastic gel and stronger gelling properties (Ramdhan et al., 2020).

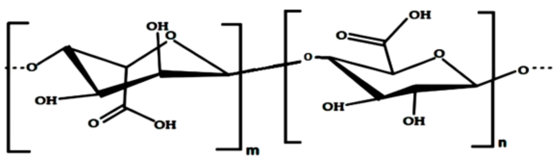
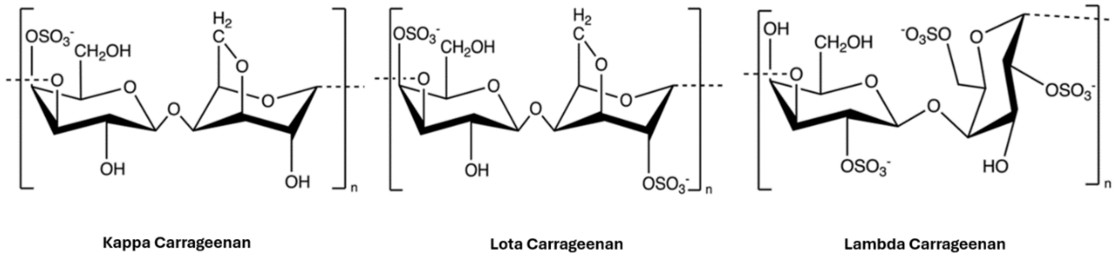


Fig. 5 Alginic acid chemical structure (Setyawidati et al., 2018)

Low M/G ratios, on the other hand, produce strong, brittle gels with outstanding heat stability, although they exhibit syneresis upon freeze-thaw processing (Abdul Khalil et al., 2018b). Alginate is frequently used in food and medicine due to its strong stabilizing and thickening characteristics (Abdul Khalil et al., 2018b; Lim et al., 2018; Oussalah et al., 2007). Alginates are very hydrophilic, thus it's crucial to combine the matrix with additional components to increase resistance when it comes in touch with water (Lomartire et al., 2022). Alginates' solubility is also influenced by ions, and the sort of cation bonds they make determines whether they can gel (Abdul Khalil et al., 2018b). The addition of calcium to the alginate matrix will increase the membrane's resistance and stability, which might be a fascinating breakthrough for biodegradable materials with non-toxic packaging and antibacterial capabilities (Lim et al., 2018; Oussalah et al., 2007).

b. Carrageenan

A linear chain of partly sulfonated galactans makes up the water-soluble polymer known as carrageenan (Campo et al., 2009). Using a diluted alkaline solution, these sulfonated polysaccharides are extracted from red seaweed (Premarathna et al., 2024). After extraction, the dilute extracts (1–2% carrageenan) are concentrated, filtered, and finally isopropanol is used to precipitate them, creating a fibrous coagulum (Premarathna et al., 2024).The coagulum is then rinsed and squeezed to remove the solvent. Finally, it is then dried and milled to an appropriate particle size (Tavassoli-Kafrani et al., 2016). Carrageenan has considerable promise as a gel-forming substance since it can create a gel by ionotropic gelation in conjunction with a method



that comprises the formation of a helix after cooling and cross-linking in potassium or calcium ions presence (Thivya et al., 2024). Carrageenan is typically used as a gel to boost the viscosity of dishes like sweetened condensed milk, sauces, and ice cream (Shit and Shah, 2014). Carrageenan comes in three varieties, each with unique chemical compositions and gelation characteristics (Roberts and Quemener, 1999) (Figure 6). In contrast to iota-carrageenan, which creates softer, elastic, and cohesive gels, lambda-carrageenan does not make gels. These discrepancies can be due to the distinct sulphate groups and an hydro bridges in these materials, which can be used by various production processes to produce polymer particles (Campo et al., 2009; Joye and McClements, 2014).

c. Agar

D-galactose and 3, 6-anhydro-L-galactose repeating units, with a few modifications, are the primary chemical components of agar, which also has a modest ester sulphate level (Araki, 1956) as shown in Figure 7. It consists of two groups of polysaccharides: agar pectin, a simplistic term for the charged polysaccharide, and agarose, a neutral polysaccharide (Araki, 1956).

Fig. 6 Chemical structure of three types of carrageenan

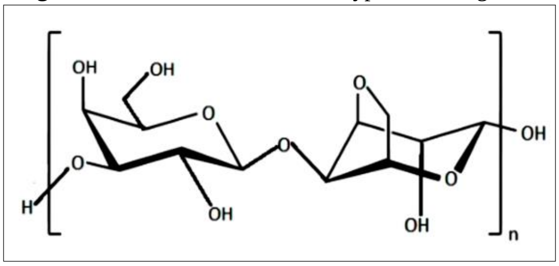


Fig. 7 Chemical structure of agarose polymer

Agar's ability to gel is due to agarose, which also gives it exceptional film qualities and makes it particularly useful in skin care, herbal remedies, and medicinal uses (Rhim, 2011). Owing to their capacity to serve as thickening agents, emulsifiers, and stabilizers, agar and carrageenan are extensively used in the commercial food processing sector (Kokkuvayil Ramadas et al., 2024). In gel-based foods like sweets, jams, jellies, and baked goods, both are already present. Agar-based gels are typically lucid and tight, but sugar's addition strengthens them (Bixler and Porse, 2011). Agar films can also easily be combined with different bioactive compounds and/or plasticizers to help produce elastic and soft gels because they are physiologically inert.

Agar has minimal hygroscopicity, which is advantageous in the production of packaging (Martínez-Sanz et al., 2019; Mostafavi and Zaeim, 2020).

Sustainable techniques for making seaweed bioplastics:

The typical techniques for extracting commercial seaweed hydrocolloids are shown in Figure 8. Cleaning the seaweed to get rid of epiphytes, pollutants, sand, debris, salts, and toxins is crucial before extraction (Lomartire and Gonçalves, 2022). Alkali pre-treatment is applied to agar and carrageenan to enhance the gelling characteristics by converting unstable sulphate molecules into 3,6-anhydro-L-galactopyranose (3,6-AG) (Abdul Khalil et al., 2018b). In order to reduce the colour pigments in the seaweed tissue and increase alginate yield, alginate is first pre-treated with formaldehyde. It is then pre-treated with hydrochloric acid (HCl) in order to "clarify" the phenolic compounds and formaldehyde residue and to encourage the conversion of insoluble alginate salts (calcium, magnesium, etc.) into soluble salts (Bertagnolli et al., 2014). To obtain compounds with desired properties and functionalities through the manipulation of many parameters, such as temperature, time, pH, solvent concentration, etc., hot water extraction is conducted for agar and carrageenan, followed by alkali extraction. Only alkali extraction is carried out for alginate. All three compounds are then further neutralized by removing extra chemicals and solvents; following this, residuals are removed and the pure compound is obtained through precipitation and filtration; the final steps include drying and milling to produce dry and purified final products suitable for commercial use

(Abdul Khalil et al., 2018b). Hydrocolloid seaweed is often harvested and processed into films to make seaweed bioplastics. However, it is not practical to produce bioplastics using the usual techniques. This is since, when compared to polymers made from petroleum, they have a lower yield and require more money, effort, and energy. The amount of water utilized in the production process, the reactant, and the chemicals all contribute to the high cost. In addition, the reactant and chemicals need to be managed properly as waste because they are toxic (Abdul Khalil et al., 2018a; Lim et al., 2021). Additionally, the film might be harmed by the traditional extraction technique. In comparison to untreated agar film, alkali-treated agar film has been shown to have reduced elasticity, water vapour permeability qualities, and viscosity, making untreated agar film a more affordable and environmentally responsible choice (Mostafavi and Zaeim, 2020).

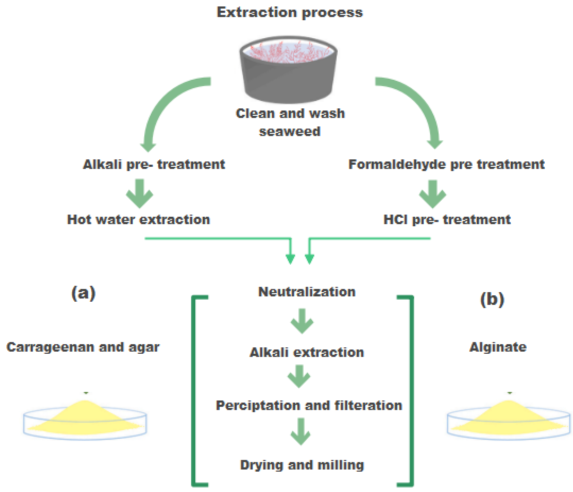


Fig. 8 Common commercial seaweed hydrocolloids extraction process: (a) carrageenan and agar, (b) alginate

Regarding the replacement of polymers derived from petroleum, seaweed bioplastics with environmentally friendly production techniques offer a lot of potential and viability (Kammler et al., 2024). In addition to being affordable, biodegradable, renewable, and sustainable, the materials can be synthesized without using chemicals or hazardous waste (Novak et al., 2020). Seaweeds can be extracted using a variety of environmentally friendly techniques, including supercritical fluid extraction (SPE), enzyme-assisted extraction (EAE), pressurized solvent extraction (PSE), microwave-assisted extraction (MAE), photo bleaching, and reactive extrusion processes (Gomez et al., 2020). It is important to conduct experiments to evaluate the physical, mechanical, optical, thermal, antibacterial, and antioxidant properties, in addition to the biodegradability, of dried and pure phycocolloids that demonstrate their appropriateness for bioplastics production (Pangestuti and Kim, 2015). While biodegradability is often assessed using a soil burial test, antimicrobial qualities are evaluated by the inhibitory effects of the purified phycocolloids against bacteria including Listeria monocytogenes, Salmonella Typhimurium, and Escherichia coli. Seaweed bioplastics are useful in applications relating to human health, such as food or drug packaging, because they decompose quickly in soil and don't release any plastic residues into the environment (Lomartire et al., 2022). If the phycocolloids' quality is good enough to manufacture biofilms, the phycocolloids' matrix can be enriched with additional hydrophobic substances, polymers, and/or nanoparticles to create a hybrid material with water barrier qualities and the mechanical strength necessary for durable, seaweed-based packaging (Hasan et al., 2019).

Advantages and drawbacks of bioplastic

Some plastics break down quickly in the ocean, releasing extremely dangerous chemicals into the water that damage plants, animals, and humans by entering the food chain (Hassan and ul Haq, 2019). Plastics that decompose into biomass are completely harmless and contain no chemicals or contaminants (Dey et al., 2024). This plastic decomposes harmlessly and is absorbed by the earth (Witt et al., 2001). On the other hand, bioplastic takes less time to degrade, and the time needed to degrade completely is significantly less. This reduces the vast pressure on our prevailing landfills (Pathak et al., 2016). The advantage of using bioplastics is that they are made from renewable resources (Brodin et al., 2017). However, to increase production, biomass extraction requires significant amounts of water, appropriate locations, and intensive farming (Brodin et al., 2017).

Therefore, the manufacturing of bioplastics may need the use of herbicides and pesticides in crops throughout the transformation processes, which might be avoided by using environmentally friendly synthesis (Ezgi Bezirhan Arikan and Havva Duygu Ozsoy, 2015). Efficiency of energy as production of bioplastic needs less energy compared to traditional plastics (Ezgi Bezirhan Arikan and Havva Duygu Ozsoy, 2015). Environmental safety; additionally, bioplastic emits fewer greenhouse gases and is free of toxins, on the other hand the drawback of bioplastic may be represented in High costs(Yu and Chen, 2008). It is widely known that the cost of bioplastics is double that of traditional plastics. However, it is expected that if reductions in costs are put in place there will be an increased amount of large-scale industrial manufacturing of bioplastics, which will become more common (Lagaron and Lopez-Rubio, 2011).

Applications of bioplastic based on cellulose

After discussing bioplastics, their eco-friendly characteristics, and their manufacturing from a variety of renewable sources, it is possible to improve their characteristics based on the study findings to generate high-quality materials that are suitable for the desired applications. Bioplastic will be produced in the future for a variety of uses in daily life, including flexible and rigid applications (Bulla et al., 2024).

Bioplastics production has increased considerably compared to usual plastics (Serrano-Aguirre and Prieto, 2024). These products can benefit the environment by minimizing greenhouse gas emissions, the requirement for landfill space, the marine pollution risk, and the impact on human health (Comaniţă et al., 2015). The viability of using biobased materials for food packaging, particularly in comparison to conventional packaging materials, was the focus of a lot of research. Biobased packaging is superior to conventional packaging as it can even benefit the food product (Yin and Woo, 2024).

Films made of cellulose may provide an alternative for some food product packaging, according to studies on this issue (Peelman et al., 2013a). Lignin, cellulose, and hemicelluloses, which are sugar molecules generated from water hyacinths, can be transformed into polyhydroxy butyrate (PHB), a polymer which is a basic ingredient for producing biodegradable plastic. PHB and polypropylene are quite similar, which are both widely utilized in a variety of industries for products like packaging, ropes, bank notes, and automotive components (Reddy et al., 2013).Cellulose-based biopolymers are receiving scores of interest owing to their biodegradability, great durability, strength, and stiffness. Reinforced composites made of cellulose are non-abrasive, low-density, and cost-effective. In cellulose-based bioplastics, the faraway fragile molecules are formed up of a weak hydrogen bond that causes rapid disintegration (Nanda et al., 2022). Because they degrade naturally, bioplastics are frequently used in the packaging sector (Rajendran et al., 2012a).

So, bioplastic used for various applications, e.g., packaging and bags, medical instruments, pharmaceuticals (capsules including antibiotics), electronic, and industrial applications, as follows: Numerous specialty materials, such as eyeglass frames, films, food packaging, and other items, are frequently made from cellulose-based bioplastics, such as cellulose acetate (Ahmad et al., 2024). Due to its demand in the production of electronic products including screen shields, wearable devices, transparent dialers, headphones, cosmetic cases, and vehicle interior components, the cellulose-based bioplastic industry is growing (Nanda et al., 2022).

Additionally, cellulose and its derivatives have applications in biomedicine, pharmacology, and three-dimensional printing (Nanda et al., 2022). The benefit of employing water hyacinth as a raw material is that it is always freely available. Applications for bio-plastics include the biomedical industry, clothing fibers, compost bags, fast food paper coatings, and single-use goods including plates, cutlery, cups, and film wrapped plastic bottles (Reddy et al., 2013). According to Popa and Belc's study, the most often used sustainable packaging materials nowadays are board and paper made of cellulose (Popa and Belc, 2007). There are several cellulose derivatives that are commercially accessible, but cellulose acetate is the one that is most frequently utilized for a lot of applications (Peelman et al., 2013a), including textiles, plastic films, and packaging (Yadav and Hakkarainen, 2021). It is an eco-friendly material sourced from cellulose in wood or cotton linters through acetic acid reaction (Yadav and Hakkarainen, 2021). According to Abdelhamid et al. (Abdelhamid et al., 2023) marine algae incorporated with cellulose acetate polymer can be used in the removal of Cd^{2+} and Zn^{2+} from contaminated aqueous medium. The material exhibits exceptionally good compaction capabilities when bioplastics are combined with additional pharmaceutical excipients, enabling the drug-loaded tablets to form dense matrices suitable for oral medication administration. The rate of tablet disintegration and medication release can be altered by tablet coating or microparticle inclusion when using crystalline nanocellulose's cutting-edge pelleting procedures (Jackson et al., 2011).

Conclusion

This review focuses on producing environmentally biodegradable plastic based on cellulose extracted from water hyacinth and seaweed. Water hyacinth has harmful effects on the environment, on the other hand there is a benefit from it and preserves the environment from pollution. Seaweed is a promising bioplastic alternative due to its toxic-free, environmentally friendly, and cost-effective nature, as well as its comparable chemical resistance and tensile strength to other bioplastics. The formed biodegradable plastic from these natural sources will be ecofriendly and nontoxic compared with synthetic plastic based on petroleum products. These problems can be addressed, and promising solutions can be found through further research to manufacture bio plastic product material with optimum properties. Therefore, it is developed by researchers to obtain the best results and high quality of biodegradable plastic at a lower cost and use the available environmental resources in the right direction.

Challenges and future scope

As biodegradable polymeric materials are the strongest competitor to beat petrochemical-based plastic in the future, more research can be done to investigate the use of more bioplastic materials to improve community lifestyle and reduce recycling costs. This could lead to new applications in fields such as agriculture and medicine (Thakur et al., 2018). The widespread use of the Green Design Principle will serve as a preventive matrix to pinpoint process leverage points. It is founded on the ideas of green chemistry, which attempts to lessen the use of hazardous materials and the creation of chemical products along the path of a life cycle (Kishna et al., 2016). The current control methods for water hyacinth are insufficient to stop its antagonistic propagation due to its high rate of proliferation and the high cost of eradicating it. As a result, empirical research is being done to find alternative mitigation strategies that take advantage of the aquatic weed's untapped potential (Ilo et al., 2020). The industrial production of bioplastic from waste is still regarded as a premature process because of the challenges associated with waste handling, transportation, pretreatment needs, and the lack of efficient and affordable conversion technologies in comparison to petroleum-based synthetic plastic (Bhatia et al., 2021). Although biodegradable plastics are expected to benefit the environment, there are certain instances in which they can harm the natural world.

At landfills, there is a significant release of greenhouse gases during their degradation, such as carbon dioxide and methane. This can be managed by creating plastics that decompose gradually or by collecting the released methane and using it as fuel in other places (Pathak et al., 2016). Due to the valuable importance of bioplastic researchers condensed their efforts to produce it with optimum properties and utilizing natural resources that have a harmful effect on the environment. All of this aims to create a clean environment and management of waste.

Conflict of interest

There are no conflicts to declare.

Authors' contributions

N. M. Salatein: Conceptualization, Writing – original draft, Writing – review & editing. B.M. Elmowafy: Conceptualization, Writing – original draft, Writing – review & editing. I.S. Fahim: review & editing, Supervision. All authors have read and agreed to the published version of the manuscript.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

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