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MORALITY BEFORE KNOWLEDGE

Integrating natural resource potential and technological innovation: An interdisciplinary study on the development of seaweed-based bioplastics in Indonesia as an alternative to conventional plastics

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ABSTRACT

Background: Plastic usage has become an integral part of modern life, spanning applications from food packaging and single-use bags to large-scale industrial uses. With plastic waste ranking as the second largest type of waste in Indonesia—and with Indonesia identified by a Nature journal (9 September 2024) as the world's third largest contributor of plastic pollution at 3.4 million metric tons per year—the environmental impact is significant, especially considering plastic's persistence for hundreds to thousands of years. **Methods**: This research employs a qualitative approach, analyzing relevant literature, policy documents, and industry reports to assess the opportunities and challenges in developing bioplastics made from seaweed in Indonesia. **Findings:** he study finds that seaweed-based bioplastics, which are naturally degradable within four to six weeks and even edible, offer a promising alternative to conventional plastics. Indonesia's position as the second-largest seaweed producer globally presents a unique opportunity to harness social, economic, and environmental benefits. However, challenges remain in scaling sustainable seaweed aquaculture, adopting efficient technologies, and formulating supportive policies, with international cooperation in knowledge and technology transfer deemed essential. **Conclusion**: The development of seaweed-based bioplastics in Indonesia could serve as a sustainable solution to the plastic waste crisis, provided that targeted research, policy reforms, and industry collaborations are implemented. **Novelty/Originality of this article:** This research uniquely integrates environmental, economic, and social perspectives to advance the emerging field of seaweed-based bioplastics, highlighting the potential for international partnerships to drive sustainable innovation in Indonesia.

KEYWORDS: bioplastic; challenge; opportunity; plastic; seaweed.

1. Introduction

Indonesia is the fourth biggest population country in the world with total of 281,562,465 as of July 2024 (U.S Census Bureau, 2024). This big amount ironically reflected in its big number of waste generation which reached 38,621,127.90 tons per year in 2023. Plastic waste was in the second place with 19.23% (Ministry of Environment and Forestry, 2023). Globally, plastic waste is 12% of Municipal Solid Waste's composition. In addition, globally only 9% of plastic waste was recycled, 19% was incinerated, 50% went to landfills, and 22% was mismanaged. Furthermore, unlike organic waste that can decompose naturally, plastics can take hundreds to thousands of years to be degraded in nature (Zahrah

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et al., 2024). Several types of plastics which are commonly used are Polyethylene Terephthalate (PET), High Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low Density Polyethylene (LDPE), Polypropylene (PP) and Polystyrene (PS) (Prasetyo et al., 2024).

Currently, Indonesia has several regulations on national waste management. Such as Law Number 8 year 2008 on Waste Management as an umbrella for national waste policy, Law Number 32 year 2009 on Environmental Protection and Management and other specific laws regulation the waste type and technical implementation. Furthermore, in 2018 Directorate of Solid Waste Management, Director General for Solid Waste, Hazardous Waste and Hazardous Substance Management, Ministry of Environment and Forestry, Republic of Indonesia along with Sustainable Waste Indonesia (SWI) and the IGES Centre Collaborating with UNEP on Environmental Technologies (CCET) issued the National Plastic Waste Reduction Strategic Actions for Indonesia. These strategy and actions are intended to serve as one of the national references for how Indonesia can fulfill its national solid waste management targets, to reduce solid waste from its source by 30%, to properly handle 70% of solid waste by 2025, 70% of marine plastic litter by 2025. In addition, Indonesia also issued the Presidential Decree number 83/2018 on Marine Debris Management (Ministry of Environment and Forestry, 2020).

Nevertheless, plastic waste is still a critical issue in Indonesia. Almost every product is packaged using plastic because it is indeed practical, lightweight and able to protect products. Food products rely on plastic packaging for hygienic reasons and quality. Home care, body care and cosmetic products are also packaged using plastic materials (Burhani et al., 2023). No wonder Indonesia is still in high dependence on landfills even causing repeated landfill closures due to overload and fires (Zahrah et al., 2024). The COVID-19 pandemic has also immensely contributed to ongoing plastic pollution, driving the big production and use of single-use plastics such as masks, gloves and face shields. The pandemic has also led to increase the trend of online purchases and food deliveries impacting the increasing number of plastic packaging and disposable takeaway container (Ghasemlou et al., 2024).

Urban residents undoubtedly tend to use more plastic bags than the residents in rural areas. Many argues that residents' lifestyle in urban areas is one of the primary sources of plastic pollution in the environment. Studies have found that the concentration of plastic debris in urban river flow has increased compared to the concentration of plastic in rural rivers areas. Additionally, almost 92% of the total waste collected from water streams in urban areas eventually ends in marine ecosystem (Ridwan et al., 2023). In the marine environment, plastic will degrade into microplastic by the action of wind, waves and sunlight. The presence of microplastics has been found in about 100 aquatic species from fish, shrimp, mussels and finally to our dinner plates (Jayakumar et al., 2023). Some studies even found the contamination of microplastics in branded and traditionally produced salt (Amqam et al., 2024).

The reduction of plastic waste requires proper management and cooperation from all sectors not only by limiting the plastic bags, but also reducing the all-other plastic products. Some plastic bottle wastes are being recycled into various voided concrete slabs and others, but its efficiency and environmental impacts are still issues. Therefore, the development of eco-friendly plastics is a promising solution to achieve the environmental sustainability. Bioplastics are one of such categories which are obtained from renewable sources, biodegradable, sustainable and also biocompatible (Jayakumar et al., 2023).

Bioplastic is defined as all polymer products come from biomass or plastic which is naturally degradable (Muljana, 2019). The environmental benefit from bioplastic is lowering dependence on fossil fuels, reducing the greenhouse gases emissions, reducing the accumulation of plastic wastes, better end-of-life care management and preservation of marine ecosystems (Kumar et al., 2024).

Bioplastic initially developed to substitute ivory and casein-based plastics in 19th century, however at that time it did not really attract the world's attention since there was still low awareness of the dangers of plastic. Moreover, the costs were still very high to

implement. Currently, bioplastics has been developed because they come from plants, animals, and microbes which have several superior benefits compared to the conventional plastics, as well as providing less pollution in the degradation process. Bioplastics from plants such as corn is also considered effective but it has certain consequence which requiring large areas of land only for plastic production itself, while they are also food source in the other hand. Bacteria and other organism sources can also be used for bioplastics production, but their application will be limited due to the complexity of the process, required conditions and equipment. Therefore, seaweed will be the best alternative to overcome these limitations because of its capacity to survive in various environmental conditions and does not require special planting techniques (Yong et al., 2022).

In general, seaweed or algae is considered as an alternative resource to produce biofuels, biochemicals and food. Due to the seaweeds' high biomass, it is used as one of the alternatives for development of bioplastics (Consebit et al., 2021). Ecologically and commercially consideration, seaweed plays a vital role in aquatic food chain, producing up to 50% of Earth's oxygen and is a raw material for humans to develop pharmaceuticals, cosmetics and food (Dang et al., 2022). The development of bioplastics can make a significant contribution in supporting Sustainable Development Goals (SDG) number 12 on responsible production and consumption, and number 13 on climate action (Basnur et al., 2024).

The industry of seaweed aquaculture has remarkably increased. In 2020, global mariculture output reaching 51.4% of total global mariculture surpassing other key aquaculture production species such as Mollusca (25.8%), finfish (12.3%), crustaceans (9.9%) and other aquatic animals (0.7%) (Yong et al., 2024a). The seaweed production is concentrated in the five main continents, which Asia being the dominant contributor with 97.38% of the total. According to FAO in 2021, global seaweed production, China holds the top position globally in aquaculture production accounting for 56.82%, followed by Indonesia with 28.6% and South Korea with 5.09% of the world's aquaculture production (Kajla et al., 2024).

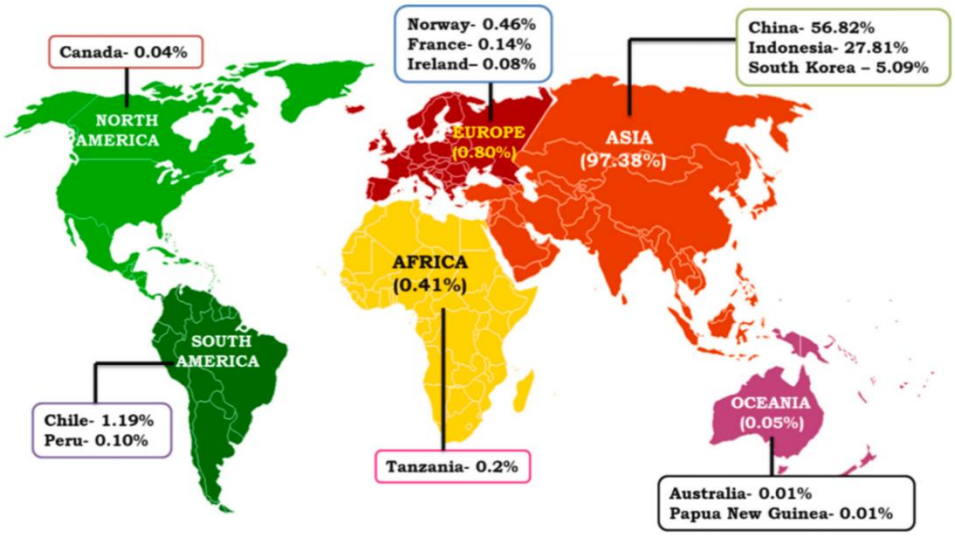

Fig. 1. Global Seaweed Production
(Kajla, 2024)

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As the previous explanation, Indonesia needs to find the alternative solution on tackling the plastics waste by lowering the dependance on plastics waste which conventionally produced from fossil fuel. This can be achieved by the development of bioplastics made from environmentally friendly raw materials or known as bioplastic. The bioplastic can be made from seaweed where Indonesia has great potential on it. One of the senior researchers in National Research and Innovation Agency (Badan Riset dan Inovasi Nasional), Yeyen Nurhamiyah, also explained that seaweed is highly potential for bioplastic development since Indonesia is the second biggest producer in the world. Compared with other biomaterials, seaweeds are clear winner as they do not require any fresh water, pesticide and land to grow because they even grow in waste water too (Kumar et al., 2024). Therefore, this research will analyze the opportunities and challenges faced by Indonesia in the development of bioplastics from seaweed.

2. Methods

The study was carried out by gathering secondary data from related research or journals and interviewing experts on the field of seaweed development from bioplastic. The interviewee come from National Research Agency as the key informant who has researched and technically involved in the related development.

The interview with the key informant was conducted on 15 October 2024 through zoom application with one of senior researchers in National Research and Innovation Agency (Badan Riset dan Inovasi Nasional), Yeyen Nurhamiyah. Yeyen has conducted some related research for more than 10 years and has great concern in bioplastic development especially from seaweed. In addition, from 2022 she has also conducted joint research with one of the bioplastic industries made from seaweed in one company located in Cikarang, West Java. Yeyen has researched and developed the technology on bioplastic sheet products development made from carrageenan (seaweed) for environmentally friendly spices packaging.

The main purpose of the interview was to analyze the opportunities and challenges in bioplastic development from seaweed, the market trend of bioplastics in Indonesia, and to gain perspective on what the government has done in terms of policy or regulation on the seaweed development. Furthermore, also to discuss the future prospects and recommendations for researchers, governments or businessman in bioplastics development from seaweed in Indonesia.

The literature review was performed from beginning of September 2024 until December 2024 to find information on various research and study related to the seaweed development. The first step is data collection from primary database of Scopus and Google Scholar. The second step involves in selecting keywords both in English and Bahasa Indonesia using the advanced search feature of Scopus consisting the data of plastic waste globally and domestically as the background of the research, then "The seaweed bioplastic development" starting in the global, regional and domestic level of Indonesia.

The third step is establishing the chosen research year interval of 2019-2024 considering the 5 years period will be enough insightful sources of related research and study. The articles should include the discussion on bioplastics development especially from seaweed and also the explanation on the opportunities and challenges of the bioplastic's development.

3. Results and Discussion

The role of seaweed in bioplastic development can be a huge potential for Indonesia to create a more sustainable plastic industry. Besides having good impacts on environment by

reducing the undegradable plastic waste, the number of seaweeds cultivated in Indonesia is also huge. Nevertheless, the development still faces some challenges. In further discussion, the opportunities and challenges of bioplastic development from seaweed in Indonesia will be classified into three categories which are environmental, economic and social aspects.

3.1 Opportunities

3.1.1 Environmental aspect

Seaweeds are low-level plants that can grow quickly up to 60 m in fresh or salt water (Meirinawati & Wahyudi, 2023). Seaweeds play a significant role in the aquatic ecosystem, representing approximately 50% of the planet's primary productivity. Seaweed has emerged as a promising industry with tremendous growth potential and its ability to address the long-term challenge of environmental sustainability (Kajla et al., 2024). Seaweed can absorb nutrients from the water to protect coastal areas and sequester carbon which help tackling the issues on water pollution, ocean acidification and global warming (Waqas et al., 2024). Furthermore, some seaweed species possess inherent antimicrobial properties which means bioplastics with built-in resistance to bacteria and mold growth (Nesic et al., 2024). Studies also show that macroalgae or seaweed can also trap the microplastics through twining, attachment, embedment and wrapping, which could partially decrease the influence of microplastics on marine ecosystem (Zhang et al., 2024). Furthermore, even the seaweed craft waste can be used to develop bioplastics (Tarigan & Cahyonugroho, 2024).

Indonesia is the second largest seaweed producer in the world, contributing 38% of the global seaweed market. In 2021, according to Ministry of Marine Affairs and Fisheries (MMAF), it is estimated that the seaweed production reached 9.05 million tons (live weight). Seaweed production in Indonesia is spread across the provinces, where Sulawesi Selatan, Nusa Tenggara Timur, Kalimantan Timur, Sulawesi Tengah and Nusa Tenggara Barat as five seaweed-producing provinces (Basyuni et al., 2024).

Seaweeds are mainly divided into three main groups according to their color pigments which are brown seaweeds (phylum Ochrophyta, class Phaeophycaeae) with abundance of pigments that vary from yellow to dark brown, red seaweeds (phylum Rhodophyta) which contain high amounts of carotenoids, chlorophyll, phycoerythrin, phycocyanin and allophycocyanin and green seaweeds process mainly chlorophyll, which has a key role in photosynthesis (Lomartire et al., 2022). Indonesia is the largest global producer of the red seaweeds Kappaphycus alvarezii and Eucheuma denticalatum which are used to produce carrageenan, and Gracilaria species which are used to produce agar (Rimmer et al., 2021). Carrageenan is one of hydrocolloid's type which can be made to produce bioplastic (Eri et al., 2018). Seaweeds have higher ability to produce bioplastic than animals, plants and other sources because they have higher biomass (Kumar et al., 2024).

Fig. 2 Different types of seaweed
(Nesic et al., 2024)

Indonesia has rich biodiversity spreading in 24 provinces. There are 325 species consist of 103 Chlorophyceae (green algae), 167 Rhodophyceae (red algae) and 55 Phaeophyceae (brown algae). Tropical seaweed species are found in habitats such as coral reefs and mangrove forests. The study identified 166 seaweed distribution sites in 24 provinces in Indonesia namely Aceh, Bali, Banten, Bengkulu, Central Java, Central Sulawesi, East Java, East Kalimantan, East Nusa Tenggara, Gorontalo, Jakarta, Lampung, Maluku, East Kalimantan, North Maluku, North Sumatera, Riau Archipelago, South Kalimantan, South Sulawesi, Southeast Selawesi, West Java, West Nusa Tenggara, West Sulawesi and Yogyakarta. There were 10 sites which have a high number of seaweed species (one site more than 40 species) namely Air Island, Kotok Besar Island, Semak Daun Island, Tidung Besar Island, Tidung Kecil Island, Kotok Kecil Island in Jakarta (261 species), Spermonde Archipelago, South Sulawesi (146 species), Butong and Hutumuri, Ambon Provinsi Maluku (80 species) and Mantehage Island, North Sulawesi (44 species) (Basyuni et al., 2024).

3.1.2 Economic aspect

The Gross Domestic Product (GDP) growth would impact plastics demand as people traditionally use much more plastics as their average incomes grow (Moshood et al., 2021). The food packaging industry is mainly responsible for the global plastic crisis. Therefore, to gradually phase out conventional plastics, the massive production and use of bioplastics is now a top priority for food manufacturers. According to European Bioplastics, the production capacity of bioplastics in 2023 was around 2.18 million tons which 43% of the production were destined to the packaging market. The packaging market was the biggest market segment within the bioplastics industry. Furthermore, it is estimated that the production capacity to increase around 7.43 million tons by 2028 (Ghasemlou et al., 2024). The seaweed-based bioplastic products still primarily used in the form of biofilms, with its current volume is still too small for precise market sizing, the global bioplastic market is valued at 11.5 billion USD. The projections indicate a 20% of Compound Annual Growth Rate (CAGR) between 2022 and 2030, envisioning a seaweed-based bioplastic market potential of 733 million USD in 2030 (Yong et al., 2024a).

Referring to former Coordinating Minister of Maritime and Investment Affairs, currently the seaweed aquaculture process only covers 102 thousand ha or approximately 0.8% of the total area. More than 60% of seaweed are exported in raw materials or in dried form. By implementing the large scale of seaweed aquaculture in 100 ha area with supported by proper technology and method, it will generate the large economy profit such as investment of USD 2-2.5 million, creating new job opportunities and improving the seaweed production in wet seaweed of 10-15 thousand ton per year. Therefore, the government is currently trying to encourage the down streaming (hilirisasi) of seaweed production to accelerate the integration of both upstream and downstream by conducting the pilot projects of seaweed aquaculture in several areas in Indonesia (Kemenko Bidang Kemaritiman dan Investasi, 2024).

Based on the research by Tarigan (2024), the biodegradable plastic can also be produced from seaweed craft waste. After mixing the seaweed craft waste extract with chitosan and sorbitol, it resulted the potential for biodegradable plastic production. The addition of chitosan tends to strengthen mechanical properties and inhibit biodegradation and water absorption, while the sorbitol tends to weaken the mechanical properties and increase water absorption. Sorbitol as a plasticizer provides a medium for microbes, hence it accelerates the degradation process. It also meets the American Standard Testing and Material (ASTM) 5336 standard with degradation time of 60 days in total (Tarigan & Cahyonugroho, 2024). The seaweed waste poses a significant environmental and aesthetic concern, especially in a region that thrives on tourism. Therefore, besides helping the environment on tackling the waste issue, the recycling process can also catalyze the economic opportunity on innovative industries, fostering job creation in both the recycling and manufacturing sectors (Rizal et al., n.d.).

Bioplastic industry development requires proper technology to support the business capacity and to meet market needs. There are several different machines options with particular merits. In addition, there are currently some renewable machines for bioplastic production with relatively affordable price. This will be a good opportunity for novice bioplastic businessmen. The renewable bioplastic machines will also help reducing production cost, times and labors (Khadija, 2023).

3.1.3 Social aspect

Currently, national policy makers and multilateral agencies are increasingly aware that sustainable growth problems cannot be separated from the environmental concerns (Moshood et al., 2021). The awareness from people has also grown higher for choosing the sustainable business and products. This increased awareness affects the increasing demand on sustainable products will open the opportunity in market of bioplastic development (Jayakumar et al., 2023).

In addition, based on the research by Wigati et al., (2023) the bioplastic production by algae or seaweed in Tual, Maluku province can be used as a unique branding destination supporting its beautiful coastal landscape. Tual is known as the high-quality seaweed producer area. The bioplastic development involving the local community empowerment, is not only aims to preserve the environment but also to encourage tourist attraction while educating the wider community on reducing single-use plastics and promoting biodegradable plastics use (Wigati & Mihardja, 2023).

Business has shifted their policy by implementing a more sustainable concept. Some multinational companies have joint partnership in order to become leading providers of renewable bio-based materials and plastics, such as Nestle and IKEA. The companies also invited others to join their projects in other to utilize their resources in the growing of the market of bio-based products. Nestle has developed a way of producing renewable plastics identical to the functions of the conventional fossil plastics. This collaboration aims to produce plastics similar to presently used ones, while replacing fossil feedstock with renewable, recycled or residual raw materials. Nestle also intends to revolutionize the bio-plastic market in the near future to reduce dependency on fossil as well as carbon footprint, while IKEA aims to increase the use of plastics manufactured from recycled or renewable raw material (Emeka, 2018).

The growing interest in seaweed packaging has been leading to increased research and development efforts, and more startup companies exploring new technologies and applications for seaweed-based materials. As the industry continues to progress, seaweed packaging is expected to become a more prominent and sustainable solution in the packaging market (Nesic et al., 2024).

Some of Indonesian companies has also developed the bioplastic products from seaweed such as Evoware and Biopac. Evoware was established in 2016 and introduced their first product “Edible Seaweed Cup”. They gradually expanded their products with seaweed-based packaging, cassava bag, rice straw, sugarcane food container, wooden cutlery and bamboo cutlery. Evoware has also exported their products to Australia and Middle East countries. In their company Sustainability Report 2019-2022, Evoware has collaborated with 45 Non-Governmental Organizations (NGO) and other business partners. Their products have been impactful as substituting 4,970,679 plastic straws, 1,785,300 plastic bags, 33,258 plastic sachets, 76,588 plastic containers, 191,803 plastic cutleries, 12,992 plastic cups in 56 countries. It is estimated that total carbon of 85.8 ton carbon reduced from that plastic replacement involving 33,803 people.

Biopac is a women-led company established in 2019. Biopac emphasizing its products as user friendly, environmentally friendly and sustainable along the supply chain. Their products ranging from pouch, hang tag, drawstring bag, griphole bag, seaweed-based ink and pet waste bag.

Table 1. The opportunities of seaweed-based bioplastics development in Indonesia in summary

No.	Environment	Economy	Social
1	Indonesia is the second biggest seaweed producer in the world with rich biodiversity.	Increasing demand of bioplastic products especially in food packaging industry.	Rising awareness from consumer on conventional plastic threats and the shifting willingness to consume environmentally-friendly products.
2	The promising sustainable industry by offering ecological benefits of seaweed aquaculture such as carbon absorption, primary producer, reducing water pollution and ocean acidification.	Fostering job creation in innovative recycling and manufacturing sectors.	Bioplastics can be transformed into a new branding image for tourism
3	Seaweed (carrageenan) craft waste reduction.	Renewable machines with affordable price are currently available	Business players have shifted their policy into a more sustainable business

3.2 Environmental aspect

As around 70% of the surface of the earth is covered with water, it has great availability of seaweed that can be used as raw material for bioplastic development. However, it is crucial to consider the ecological implications of massive seaweed harvesting (Santana et al., 2024). Based on research by (Ayala et al., 2024), the cultivation of seaweed is associated to the carbon uptake during the process. It suggests that the upscaling of seaweed-based bioplastic production could lead to a significant reduction in greenhouse gas emissions compared to pilot-scale production (Ayala et al., 2024). The seaweed farming which is located above the seagrass beds may cause the shading effects making the temperature warmer and impacting the growth and vitality of seagrass. Seaweeds, especially the brown seaweeds also tend to accumulate heavy metals such as arsenic, cadmium, lead and mercury. Hence, it needs further research in preventing the potential negative side effects on human health (Waqas et al., 2024). Excessive collection can alter marine ecosystems, affecting biodiversity and ecological functions. In addition, it may reduce the habitat of various marine species and cause changes in ecosystem structure. Therefore, it is important to emphasize the implementation of sustainable harvesting practices to prevent the side effect (Santana et al., 2024).

Furthermore, the challenge in seaweed aquaculture comes from the pests and diseases. The prevalence of pests and diseases greatly affects aquaculture production since it may slow down the seaweed growth by taking the nutrients in it. The diseases can be caused by water quality and season. The seawater temperature change can also cause thallus bleaching or known as ice-ice disease (Ardiansyah et al., 2024).

Despite seaweed has many benefits compared to the conventional plastic which is made from fossil fuel, the commercial of bioplastic in Indonesia has some limitations. One of the limitations come from the natural character of seaweed itself. Bioplastic made from seaweed has low impact strength or material resistance to sudden force and lower elongation at break. Apart from that, its melt strength and low flow ability can only be used in low to medium temperature work because it is easily degraded thermally. The extraction of seaweed polymers may involve the use of chemicals sometimes that can cause environmental problems, not all seaweed polymers are suitable for natural degradation and the impact of seaweed polymer microplastics is still unknown. These further negative impacts on marine ecosystem can be minimized by employing farming practices by utilizing native seaweed varieties (Zhang et al., 2024).

In addition, seaweed-based packaging offers a wide range of versality. The choice of seaweed packaging material depends on the specific product requirements, including its

shelf life and necessary barrier properties. Different seaweed species have a varying moisture content, different distribution of proteins and bioactive components (Nesic et al., 2024). Their yields also depend largely on the extraction conditions which also affect the properties of the final bioplastic. Therefore, the identification and selection of the most suitable species and optimum conditions, and the appropriate polymer content are critical. More research must be conducted to overcome these limitations before commercialization (Tennakoon et al., 2023).

3.3 Economic aspect

The market dynamics of bioplastic are predominantly influenced by factors including cost and accessibility of raw feedstocks, high production and distribution costs, consumer demand, fluctuations in crude oil prices, as well as regional bans and restrictions on conventional plastics (Parveen et al., 2024). Indonesian seaweed market price has not been significantly intervened by government policies or regulations. As a matter of fact, farmers and business players are exposed to typical business risk and must cope the range of adversities such as extreme weather events and loses. Many farmers are not aware yet of the importance of insurance protection even though the government has issued Law No. 7/2016 related business insurance covered by the government (Permani et al., 2024).

Generally, domestic seaweed industry still faces various challenges, especially at the cultivation and processing industry levels. For example, the quality of produced seaweed is generally still too low due to inappropriate cultivation techniques hence the final product does not meet the international quality standards. In addition, the processing industry does not have a guaranteed supply of seaweed raw materials in the proper quality. Usually, because seaweed is mostly sold in dry form, and the price of seaweed is often irrational for industry players. This is due to no coordination on trading system with reference to industry norms as many raw material speculators (Kartika, 2020).

Even though the marine raw materials are quite accessible, the cultivation techniques, pre-treatment requirements, extraction processes and bioplastic conversion technologies required for bioplastic production are still under development. Therefore, the production of bioplastics from marine materials continues to be less cost-effective and efficient compared to synthetic plastics. The conventional seaweed hydrocolloid extraction processes are not cost-efficient as they require the use of high amounts of chemical and water, and the production method is time-consuming (Tennakoon et al., 2023).

Among the various markets for seaweed, bioplastics are considered one of the lowest-ranked target markets. The potential for the current production to shift towards bioplastic market is limited because using biomass for bioplastics is not as economically profitable in the short term as higher-value applications such as food, feed, pharmaceuticals, cosmetics, fertilizers and alginate market (Ayala et al., 2024). Currently, Indonesian seaweed industry is likely to be oriented to the production of carrageenan for some time. However, much of the attention of the Presidential Roadmap is concerned with the development of non-carrageenan products as the diverse benefits of seaweed. However, many of technologies and applications are in the early stages of developments and face logistic or commercial challenges. Further development should not be based only on technological development but should be subject to a full cost-benefit analysis to ascertain economic viability (Waldron et al., 2023).

In addition, Yeyen argues that the key obstacle in bioplastic development comes from the price of seaweed as raw materials is still relatively high compared to the raw material of conventional plastics. Therefore, the cost production borne by the company or industry will be much higher. This will eventually affect the price of product in consumer's hand, hence it will limit the consumers target as their purchase power. The supply chain market of seaweed industry is also relatively long. The producer area has limited logistic and transportation accessibility. This also causes the increased operational cost and inefficiency of production and marketing. Almost all national seaweed industry centralized in big cities

such as Jakarta and Surabaya. Meanwhile, the aquaculture cultivated as the raw material found across eastern Indonesia starting from Sulawesi, East Nusa Tenggara, West Nusa Tenggara and Maluku (Saefulloh et al., 2021). The cheapest biodegradable bioplastics are seen to be twice as expensive as traditional polymers which could limit their large-scale application and demand (Parveen et al., 2024).

3.4 Social aspect

Despite the promising potential of marine source-derived bioplastics as an alternative to synthetic plastics and prevailing bioplastics, fully replacing synthetic plastics will take many years. Further research needs to be conducted on novel cultivation techniques, extraction methods, optimal environmental conditions and degradation ability to overcome the challenges. Moreover, there are technical issues such as clinical rules and regulations preventing these bioplastics from reaching global market production, and their properties must be optimized for specific applications (Tennakoon et al., 2023). Until today, the overall production volume for bioplastics is still low compared to the fossil plastics, which has been researched and developed over several decades to improve its product quality and efficiency. Biological plastics remain in the testing process for many decades or so. Due to comparatively low price of crude oil, it was challenging to create a bio-built plastics on the market. There is no international funding trend for bioplastics, except that there has been widespread exposure to the niche strategy of banking single-use carry bags. These niche policies would not encourage large-scale production and consumer uptake investment than biofuels' main policies (Moshood et al., 2021).

As the research and development of bioplastics from seaweed continue to advance, it is crucial to address several challenges such as optimizing extraction and manufacturing processes, improving mechanical properties and evaluating the biodegradability and environmental toxicity of bioplastics production. Furthermore, the collaboration between stakeholders such as industry, academia and policy makers are essential to foster the adoption and commercialization of bioplastic development from seaweed (Santana et al., 2024). The effectivity of warehouse receipt system (WRS) which has been implemented by Ministry of Trade remains low since the difficulty of finding professional warehouse management and farmers' low awareness of the system and its benefits (Permani et al., 2024).

Table 2. The challenges of seaweed-based bioplastics development in Indonesia in summary

No.	Environment	Economy	Social
1	Excessive seaweed harvesting may alter marine ecosystems affecting biodiversity and ecological functions	The encouraging regulations or incentive on bioplastic development are necessary to attract the market players	Replacing the conventional plastic requires stakeholders' coordination and supportive regulations
2	The potential of pest and diseases in seaweed aquaculture	The operational challenges in domestic seaweed industry (low quality seaweeds with no supply guarantee, inconsistent price)	Further joint research will be fundamental
3	The challenging natural characteristics of seaweeds as raw materials in bioplastic development	The overall production cost of seaweed-based bioplastics is still higher than biofuel plastic	The strict law enforcement of conventional plastic reduction and bioplastic development are highly required
4	-	Domestic seaweed orientation still dominated by carrageenan production, and bioplastic is one of the lowest-ranked target in seaweed market	

Indonesia has issued the Decree of Minister of Industry Republic of Indonesia number 55 year 2020 on Standardization of Green Industry for Plastic Bag or Packaging and Bioplastic. The decree regulates on the technical requirement and management for green industry, even though there are no specific raw materials mentioned. Therefore, basically there is no certain regulation or incentive from government related to the development of bioplastic made from seaweed in Indonesia. Policies and regulations at the national level reasonably covered many aspects of solid wasta management. But only 99 out of 514 local governments have regulations on a single-use plastic bag (Arifin et al., 2023). The strict law enforcement on conventional plastic reduction and bioplastic development policy are essential to encourage the industry development in Indonesia. Furthermore, the transformative journey requires collaboration between stakeholders such as researchers, industry and policy makers in realizing the full potential of seaweed as a game changer (Yong et al., 2024b).

4. Conclusions

The opportunities and challenges in seaweed-based bioplastics development in Indonesia can be analyzed through the categorization of social, economic and environmental aspects. The opportunities come from the vital role of seaweed and its abundance resources, the high demand of bioplastic production and the raising awareness of the plastic negative impact and the willing to shift from a fuel-based plastics to degradable materials based such as seaweed from consumer, producer and governments as policy makers. These huge potentials encourage a promising industry with many benefits in supporting the sustainable environment especially in achieving the SDG number 12 on responsible production and consumption, and number 13 on climate action. Nevertheless, some challenges such as the negative impact on massive seaweed harvesting may disturb the marine ecosystem balance. In addition, Indonesia also needs to improve the quality of raw seaweed materials and provide the price regulation to ensure the sustainable market to business players. Further research on sustainable seaweed aquaculture supported by the efficient technology and encouraging collaborative policy are required on the development of seaweed-based bioplastics industry in Indonesia. International cooperation on knowledge and technology transfers, as well as funding assistant will also boost the bioplastic development in Indonesia.

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