Seaweed Functionality: Sustainable Bio-Based Material

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Sustainable development is an integrated approach to tackle ongoing global challenges such as resource depletion, environmental degradation, and climate change. However, a paradigm shift from a fossil-based economy to a bio-based economy must accomplish the circularity principles in order to be sustainable as a solution. The exploration of new feedstock possibilities has potential to unlock the bio-based economy's true potential, wherein a cascading approach would maximize value creation.

Keywords: sustainable development goals ; bio-based economy ; seaweed functionality

1. Introduction

The world's population is expected to reach 9 billion by 2050, putting prodigious pressure on environmental resources [1]. Focusing on reducing our dependency on the fossil-based economy and shifting toward a bio-based economy could help in tackling these situations, as well as for achieving sustainable development goals (SDG's) The accomplishment of a bio-based economy is entirely dependent on the utilization of renewable resources, especially biomass, to produce multi-functional applications, including food, animal feed, bio-based materials, energy, and pharmaceuticals. Recently, much focus has been given to either producing novel bio-based materials, or replacing the existing fossil-based products by the scientific community and start-up industries [2].

The circular economy is the most discussed and promoted concept, wherein the life cycle of materials, products, and resources are extended as much as possible to extract their economic benefits [1]. The European Union (EU) has made considerable efforts in making the bio-economy sustainable by establishing a European bio-based industries-joint undertaking (BBI-JU) fund worth 3.7 billion euros via public-private partnership (PPP) Moreover, the EU has established initiatives to encourage and help the bio-based industry to interlink within new value chains. It is estimated [3] that the bio-based industry generated nearly 2.3 trillion euros worth of turnover in 2015, wherein, 50% was contributed by food and beverage related industries, ~17% was accompanied by the agricultural industry ~8% by the paper industry [4].

approximately 950 Mt comes from the agricultural sector and 150 Mt from the forestry sector. It was also estimated that out of 1 billion tons of available biomass, the EU utilizes roughly 60% of it in the food sector, 20% in the bio-based energy sector, and 19% in the novel bio-based material sector [4]. The EU chemical sector used 77.7 Mt of organic raw material, with 10% of its share coming from renewable material [5]. The prospects for the bio-based economy look promising; however, the cost associated with the development of bio-based materials is significantly dependent upon the availability and efficacy of feedstock [1].

From an industrial point of view, such biomass has potential application in various fields, including pharmaceutical, food, feed, cosmetics, bioenergy, etc. A sufficient equilibrium between social, environmental, and economic performances can set up a benchmark for future sustainable development, and newly established industries can benefit from these astonishing consequences. However, most of such industries are inceptive, and even institutional research is rudimentary. Therefore, it is valuable to cumulate the recent progress, coherent potential value chains, and subsequent sustainability impacts in a comprehensive overview.

According to Scopus, nearly 7000 articles related to seaweed applications were published in 2020 alone, wherein, a significant focus was placed upon agricultural and medicinal applications. Subsequently, >5000 reviews in total have been published so far; however, ~70% of such articles discuss a seaweed strain. It is essential to understand that seaweed's application suitability has not been evaluated in every case. Moreover, the economic, social, and environmental aspects of seaweed's value chains are discussed collectively in just one article [6]; despite this, the entire value chain's inclusiveness is lacking.

The primary aim of the present manuscript is to assess whether seaweed biomass can deal with ongoing sustainability issues, and to identify routes of potential improvement. First, the manuscript discusses the current seaweed market and seaweed characteristics. Later, this manuscript discusses the aspects surrounding sustainability, including environmental and economic perspectives. In this review, the latest information on seaweed functionality and its sustainability proceedings is collected, which may help policymakers, industries, and researchers to further develop a bio-based economy.

2. Sustainability in Seaweed Cultivation

Environmental sustainability can be assessed using life cycle assessment (LCA), which evaluates both the benefits and burdens associated with the whole life cycle of seaweed, from seaweed production to the application and the end-of-life stages. The LCA methodology considers the life cycle starting from extraction of raw materials, manufacturing a product, transport, distribution, use, and end-of-life, including waste collection, segregation, treatment, recycling, and disposal [7]. However, very few studies are available in the literature that solely focuses on the seaweed cultivation's life cycle assessment.

The life cycle for seaweed cultivation started with the seed line production and development of lines, which is the juvenile plant cultivation process mentioned previously. The development of lines and seaweed harvesting is considered inside the system boundary by most available studies [7][8]. The inventories required for developing the LCA model of seaweed cultivation processes include electricity, water, seashore land required, nutrients, such as phosphorus (P), magnesium (Mg), zinc (Zn), nitrogen (N). Researchers have found that carbon dioxide is required to grow juvenile seaweed, which means that seaweed utilizes the oceanic carbon from the water column directly for their growth, and reduces oceanic carbon content [8].

At present, most seaweed cultivation activities are carried out in limited coastal locations; therefore, it is estimated that a maximum of 2.48 million tons of carbon have been extracted from the ocean, which is nearly 0.4% of the total expected oceanic carbon. The agricultural sector is expected to produce nearly 30% of the total global warming gases; seaweed has a great potential to reduce these emissions due to its efficient carbon sequestration. After the cultivation and harvesting process, seaweed is partially dried and transported to the next facility to produce intermediates and products.

It has been consistently observed that the electricity required throughout the cultivation system has contributed to significant impacts in all the impact categories and resulted in resource depletion, global warming potential, and increased toxicity potential. The use of renewable energy to replace traditional energy may improve the overall environmental performance of the system. The cultivation of only economically feasible seaweed species, such as Palmaria palmate, requires fewer nutrients and a high carbon sequestration rate. The impact of raw materials consumed, including chemicals and minerals, is not discussed extensively in the literature; however, the carbon absorption has reportedly affected the environment by reducing the overall impacts, especially in terms of global warming.

3. Sustainable Seaweed Applications

However, even though world seaweed production has been increased three times in the past 50 years, the sustainability of seaweed functionality is still a challenging concern [9]. Sustainability is a relative concept, especially in seaweed cultivation, and depends on the production region. Similarly, Jard et al., 2013 observed a 25% higher biomethane yield when Saccharina latissimi seaweed was cultivated and harvested in August, compared to the winter or summer [10]. Therefore, seaweed sustainability must be discussed and assessed to identify the sustainability benefits and drawbacks in relation to seaweed functionality.

Conversion of seaweed biomass has typically been presented as having strong potential for biorefinement in the present literature, wherein its composition, treatment technologies, and value chains are discussed, similar to that of microalgae. Moreover, the sustainability and thorough analysis of a value chain in the biorefinery process is still lacking in the literature. Sustainability is often a vaguely used term in literature on seaweed cultivation, focusing on ecology and the environment. Nonetheless, with an increase in the number of reports on seaweed functionality, it is necessary to implement sustainability assessments comprehensively, which could also support finding improved seaweed economics and social acceptance.

Task 42 aimed to implement sustainable biorefineries with a zero-waste value chain and the production of both bio-based food and non-food-based value chains [11]. With additional economic value given to seaweed processing, several technologies have increased along with interest in this field, as reported by Laurens et al., 2017 [12]. Since seaweed is still an expensive feedstock (~USD Figure 4 depicts the potential biorefinery approaches in seaweed processing through different systems.

This system has been established in Asian countries, where seaweed is consumed as a food in various cuisines, including Furikake, Jerky, Sea-chi (kimchi), pickle, salsa, tea, etc. Seaweed-based food companies such as Cargill, Acadian seaplants, DuPont de Nemours, Irish seaweed, Mara seaweed, and Beijing Leili had nearly USD 5 billion/year collective trade in the last decade [13]. System 3 depicts another biorefinery route for seaweed processing, wherein the seaweed extracts are used as active biological ingredients in food, pharma, and cosmetics industries, as discussed previously. Ltd. (Tianjin, China), etc., have been developing an entire range of cosmetic products based on seaweed extracts.

The LCA's quantitative and qualitative analysis can exploit the benefits of the seaweed value chain. The literature on the LCA of the seaweed value chain is limited, with most papers focusing on biofuels. The European Directives embraced the LCA methodology in 2009 to evaluate the environmental impacts generated by biofuels during their entire life cycle, and created an objective to reduce the GHG emissions by 50% in the next decade [14].

In the non-fuel applications of seaweed, LCA studies indicate that seaweed cultivation plays a significant role in imposing environmental impacts throughout the cradle-to-gate scenario. Technology usage was different in every study, starting from the seaweed cultivation until the intended application production. Due to the presence of reactive nitrogen in nutrients and the anoxic conditions that occurred during seaweed cultivation, nitrogen emission (N2O, NH3, etc.) Similarly, the CO2 fixation at the cultivation step and CO2 emission during the user phase (especially combustion in biofuel applications) need to be considered.

4. Techno-Economic Assessment

Apart from technological glitches, seaweed is at the center of attention for its potential to substitute fossil-based products and positive environmental impacts, such as nutrients recovery. It was reported that the seaweed harvesting cost would vary from USD 200–900/ton of dry mass, based on the type of seaweed cultivation [15]. , 2010 suggested the optimization of seaweed farming by expanding the current production line and producing value-added products or selling wet seaweed at a higher price (USD 2/kg) to have profitable farming [16]. The UK government has taken an initiative to subsidize the electricity production from seaweed anaerobic digestion, by which the failure in time price of the electricity has been set to 147 GBP/MWh for small-scaled units [17].

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