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Seaweed biorefinery concept for sustainable use of marine resources

Karina Balina*, Francesco Romagnoli, Dagnija Blumberga

Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV–1048, Latvia

Abstract

Seaweed, also called marine macroalgae, have a potential to be a valuable feedstock for biorefinery. Depending from seaweed type and species it is possible to extract different fatty acids, oils, natural pigments, antioxidants, high value biological components and other substances which can be potentially used in an industrial production system. The seaweed biorefinery framework presents a conceptual model for high value added product production along with production of biofuels either fluid or gaseous. This in turn reduces the cost of fuel production with maximum utilization of the biomass. The role of seaweed biorefinery concept is analysed in this paper under the perspective of bioeconomy principles and through a SWOT analysis was made to indicate the role biorefinery concept can play to support the development of sustainable bioeconomy.

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Keywords: macroalgae; seaweed; biorefinery; bioeconomy

1. Introduction

Seaweed has been widely used already for centuries, but their role has emerged in last decades when the problem of global population and food amount has been becoming an issue [1]. Similar to algae [2−5], unique composition of seaweeds allows to use them as food, feed and energy source [6]. Seaweeds are used as a feedstock for different kind of materials including biopolymers, cosmetics, agrifood and food supplements with several benefits for health [7, 8]. Algae processing to any kind of products generates leftovers and waste products, which are usually disposed [9].

* Corresponding author.
E-mail address: karina.balina@rtu.lv

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Nowadays we have to focus on sustainable bioeconomy and a production system where no waste flow is created. Biorefinery is a way to decrease negative impact on environment and create products with higher added value to get more economical and environmental benefits.

The integration of different biomass conversion processes to produce energy and value added products into a single facility is called a biorefinery [10]. Advances of biorefinery – combinations of processes and technologies for conversion of biomass to food, feed, energy and other value added products with minimal amount of waste – offers a way to develop sustainable industrial economy and reduce impact on climate change. Biorefinery approach is considered sustainable because the processes produce minimal waste to the environment in fact decreasing the environmental burden and the pressure on ecosystem services. The biorefinery concept is a technical application of this principle in which exploitation of biomass is enhanced beyond bioenergy production. In the biorefinery, available compounds of the biomass ere exploited and every step of value chain is used as a way to add value. If all of the bioresources within the biorefinery structure are efficiently used, including the biological leftovers from a cascade transformation process approach, a nearly zero waste production is achieved.

Biorefinery International Energy Agency (IEA) Bioenergy task 42 has a task devoted to biorefineries. The main goal of the task is to contribute to the development and implementation of sustainable biorefineries – as a part of highly efficient, zero waste value chains – synergistically producing biobased food and non-food products [11]. Since 2007, when the task was set, European and the global view to the task has been changed. In fact the approach has been growing and been developed. Nowadays global biorefinery concept mainly includes terrestrial biomass with plants and forest on top and only small part has recently been devoted to algae [12]. Since mainly first and second generation biomass is used for liquid biofuels production, it is significantly affecting the economy due to the competition for food and energy.

Marine macroalgae or seaweed have a high potential to partly replace terrestrial biomass. With current research going on in this field it is already declared that algae is a 3rd generation bioresource and doesn't compete with food and feed plants, nor is using resources for their growth. Valuable substances that can be found in algae can be a way to promising low-carbon economy. It is necessary to create seaweed biorefinery concept that would display valorization strategy that would display seaweed as a valuable feedstock that can compete with terrestrial biomass. Development of a seaweed biorefinery concept has attracted lot of attention recently and many ongoing research are focused on developing the seaweed biorefinery concept [10, 13–16].

This paper would like to explore the state-of-art of the biorefinery concept implementation in bioeconomy. In fact the paper would like to create a baseline for potential biorefinery concept integration at commercial dimension evaluating where important synergies can be identified among both commercial actors, stakeholders and private investors. Moreover the paper looks toward the identification of prerequisites for better exploitation of local available (and valuable) biorefinery feedstocks within bioeconomy overarching perspective. This will be essential in the direction of reaching the set targets of low-carbon economy, higher sustainability and optimal bioresource use efficiency. This paper review current state of art and display the basic structure of seaweed biorefinery concept and analyse its role in sustainable bioeconomy while focusing on Baltic Sea region.

2. Methodology

2.1. Seaweed biorefinery concept

Seaweed aquaculture is already popular in Asian countries [17], but seaweed natural distribution area is covering all over the world, including Europe and the Baltic Sea [18]. Seaweed cultivation industry and mass production of algae is underdeveloped in Eastern Europe. Seaweed cultivation could represent a promising opportunity to obtain seaweed biomass meanwhile reducing eutrophication problems [19] The opportunities of the marine macroalgae use can thus be wide.

Raw seaweeds and seaweed-based food products in Asian countries have been consumed for centuries [20]. More recently seaweed products as a source of polysaccharides for food and pharmaceutical uses are becoming popular in Europe [21, 22]. The seaweed mineral content is higher than mineral level in terrestrial plants and animal products [23, 24]. High mineral content and low fat content represent a suitable feedstock for food and feed. Macroalgae contain unique composition of carbohydrates, which have different properties than those from terrestrial plants [25]. Laminaran and mannitol are energy storage units in algae, like starch in the plants, but alginates are structural

compounds like cellulose and lignin in plants [26]. Polysaccharides found in seaweeds make them attractive not only to food industry, but also to the pharmaceutical industry. Fucoidans and laminaran found in brown algae exhibit various biological activities with potential health benefits [23, 27]. Marine macroalgae biomass can also be used as a feedstock for energy purposes. They can be transformed in different types of biofuels such as biogas, bioethanol, and biodiesel, replacing a part of fossil fuels [28].

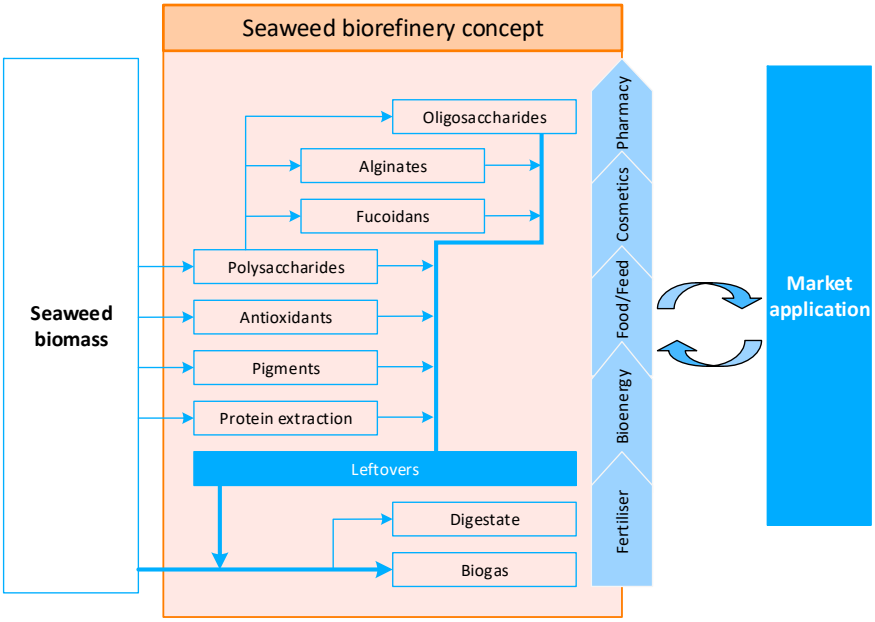

Fig. 1. Seaweed biorefinery concept.

The seaweed biorefinery concept presents a conceptual model for high value added product production along with production of biofuels. Biomass is used with maximum efficiency and expenses related to fuel production are reduced. It is important when planning production process and units, to use capable biorefinery concept where all biomass and energy from production processes would be used to the fullest extent. Conversion processes (physical, chemical, biological and thermal) used in production of products should work in symbiotic way, individually or in system to create economically sustainable products [28]. The various uses of products obtained from algal biorefineries include transport fuels, therapeutics, food additives and biofertilizers [28].

Products derived from feedstock can be separated in products which can be already used in market or they can be used as feedstock for further manufacturing operations to obtain value-added products. The waste and leftovers products obtained after each step of treatment are used as raw material inflows for a parallel production chains on cascading approach (see Fig. 1). Only leftovers which can't be utilized in further production processes with a low quality biomass are used for energy production. This approach allows minimizing the amount of waste produced in seaweed biorefinery concept to a nearly zero waste system. Seaweed biorefinery concept is mainly addressed to use particular seaweed species whose overgrowth, as a result of eutrophication, is causing ecological damages and affects the sustainability of coastal environments. Instead seaweeds can be used for remediation of environment since together with seaweed biomass certain amount of nitrogen and phosphorous is removed from water, nevertheless the identification of the thresholds affecting the overall ecosystem service provide by the depletion of a natural resources is a sensitive issue. Seaweed biorefinery concept can have a major impact by showing different aspects for utilizing seaweed to produce a wide range of value-added products, biofuels, and bioenergy within a concept, rather than focusing in a single product.

When developed and implemented in industry, practical impacts of biorefinery concept can be relevant at different levels: within the seaweed farming and industry, as employment increase in the sectors of the bioeconomy, triggering new investments, unlock incentive and favouring the integration of renewable energy within the overall energy systems [29]. The biorefinery concept used in bioeconomy has the potential for strengthening the global

competitiveness of a broad spectrum of industries. These include agriculture, forestry, and fisheries, as well as strengthening the competitiveness of biobased industries, green platform chemicals, materials and biopolymers, and both new and existing food and feed ingredients and processing industries.

2.2. Strengthening the role of biorefinery under bioeconomy principles

Sustainable development of bioeconomy is dependent not only from economic sectors and properties of the biorefinery end products, but also from different external factors like: financial resources, human resources, climate, environmental, technological, economic and socioeconomically aspects [30]. Bioeconomy key principles has been developed by European Commission to preserve the main goals of bioeconomy – provide food security, guarantee sustainable use of resources, reduce the impact on climate and create jobs and ensure competitiveness [31]. Seaweed biorefinery concept is following these principles and it has a significant role in strengthening the bioeconomy.

2.2.1. Food first

Food safety is set as a first principle and it is focusing on food quality and availability. Seaweed biorefinery concept is matching the aim of this principle. Nutritional value and health benefits of seaweeds are already well known for years. Seaweeds can provide human organism with necessary vitamins, minerals and antioxidants and is a valuable calorie source [32, 33]. Moreover, seaweeds are not competing for land with plants, and land can still be used for agriculture or forestry. Grown in the sea they do not require freshwater and additional nutrients, like terrestrial plants. It is predicted that in 2050, global population will reach 9 billion of people and with current food production it is possible to provide a food only for half of them [34], so it is necessary to find a new food resources or increase food quality. Valuable nutritional value of seaweeds matches with this demand for this additional food base.

2.2.2. Sustainable yields

Sustainable seaweed production currently might be the main challenging, since it is relatively young form of aquaculture. World production has exponentially increased during the last 50 years and it tripled between 1997 and 2012, from 7 million tons to 24 million tons and it is still increasing [35]. Seaweed yield sustainability is dependent of the region. Seaweed farming is rapidly increasing in some countries, while in others it is slowly gaining acceptance [36]. There are still more than 150 countries with coastal area which are not yet considering seaweed cultivation. Reasons are different: seasonality, lack of infrastructure and missing demand from society are the main reasons that hampers the development of the area. Also in Baltic region these are the main reasons that slows down the seaweed cultivation. In addition low level salinity sets some limitations regarding on cultivation species and yield sustainability.

2.2.3. Cascading approach

To ensure sustainable use of biomass, cascading approach has been developed which promotes that product with the highest value is made first, then the second highest is made and so on. The problem is that today large amount of valuable biomass which could be used for high value products is used to produce biofuels and bioenergy [37]. Seaweed biorefinery concept has been developed in a way that products with highest value are made first and products with lower value are made after. Bioenergy and biofuels are made using leftovers from other production processes. This approach increases resource efficiency and adds even higher value to used biomass, which is a part of circular economy. Increased resource efficiency also is saving the raw material supply, because biomass can be used repeatedly. With this principle usually the problem is that leftover biomass has to be transported from one location to another to continue with the next step of production, but biorefinery concept solves this problem since the concept is meant to be implemented in one location.

2.2.4. Circularity

Since cascading approach does not address the waste problem by itself, circularity principle has to be followed. The circular economy is built on tree basic rules: (1) there is no waste, since products are reusable and recyclable; (2) consumed materials should be returnable to the environment without any threats after cascading sequence of use, to provide their stock restoration, but durables should be reusable and upgradeable; and (3) and energy for all processes should be provided from renewable and sustainable sources. The same rules has been used in seaweed biorefinery concept and amount of waste is reduced to minimum and waste energy is used to supply energy to production processes [38].

2.2.5. Diversity

Seaweed biorefinery concept has been made to be diverse and it cover many sectors. Production systems has to be various and produce different outputs using different techniques. A diversity is a key to resilience, and bioeconomy require to develop more innovations to create diversity rather than limit it.

These five main properties does not give a limitation to this seaweed biorefinery concept, instead they are defining guidelines and basic rules biorefinery concept should follow to give the most benefit for bioeconomy. Not only all biorefinery concept together should be based on bioeconomy guidelines, but every step and phase of the concept, starting from input material and production and all life cycle of products they should follow the directions given by bioeconomy principles to give the highest social, environmental and economic benefits.

3. Results and Discussion.

3.1. SWOT analysis

The perspective of a constant evolution of biorefineries will reveal new feedstock and increase their conversion efficiency. It will give opportunity to find new technologies and products. It will positively affect all existing sectors of bioeconomy and develop rural areas. New technologies with high production yield, low use of resources or waste use instead of valuable resources, gives more sustainable approach. Innovative technologies developed for biorefinery increases level of opportunities to all sectors. The creating of a biobased economy has the ability to not only move the world through current challenges on deficiency of biobased resources but will be also give benefits for production meaning reduced impact on environment. Specfically in this section we address the strengths, weaknesses, opportunities and threats of seaweed biorefinery concept and indicate the role biorefinery concept can play to support the development of sustainable bioeconomy within a SWOT analysis of a seaweed-based biorefinery concept.

Table 1. Pros and Cons of seaweed biorefinery concept: SWOT analysis.

	Positive	**Negative**
Internal	**Strengths**	**Weaknesses**
	• Adding value to the biomass; • Development of novel biotechnologies; • Environmentally friendly resource since it is not requiring drinking water and nutrients and it reduces eutrophication • Increase biomass conversion efficiency – reducing raw material requirements • Production of biobased products and bioenergy feeding the full bioeconomy • Circular approach with no waste principle	• Collaboration between representatives of different market sectors (agro, energy, chemical, ...) over full biomass value chain necessary; • Most encouraging biorefinery processes/concepts not clear; • Scientific and technological challenges in not mature technologies; • Studying and concept development instead of real market implementation; • Variability of quality and energy density of biomass.

External	Opportunities	Threats
	• Cascading approach gives more value to biomass • Strengthening of the economic position of numerous bioeconomy sectors (e.g. agriculture, fishery, chemical and energy) • Seaweed biorefinery can give significant input in sustainable bioeconomy • Popularization of sustainable use of seaweed for the production of energy is setting new goals for policy • International agreement that resource should be used as efficiently as possible, develops spreading of biorefinery concept in other sectors • International development of technological aspects of biorefinery concepts.	• Economic change and fluctuation of fossil fuel prices • Competition of other renewable energy technologies satisfying the market needs • Higher quality standards are applied to bioresource and bioenergy than to traditional products • Availability and quality of raw materials (e.g. climate change, policies, logistics) • Difficulties to find investment capital for pilot and demo refineries, and adjusting existing refineries • Changing governmental policies • No market demand for products • Increase of environmental pollution can limit range of products in biorefinery concept

3.1.1. Strenghts and weaknesses

Seaweeds are water organisms and comparing to land plants they do not require drinking water and nutrients. Since additional resource is not needed it reduce cost and energy related to growing. In the same time, since seaweed are consuming nutrients found in environment, eutrophication level can be reduced, meaning that there are both economic and environmental advantages. Seghetta et al. have obtained a reduction in marine eutrophication of 16.3 kg N eq./ha, thanks to bioextraction of nitrogen. It depends from type of seaweed. However seaweed biomass can differ not only in different species and regions, but also from season. That can cause some difficulties regarding to conversion efficiency [39, 40].

It is clear that additional value to biomass gives more economical benefits to involved sides. It is also agreed by Bruton who agrees that adding value to the biomass, which otherwise would be wasted, stimulates economics and raises innovations and investments [41]. Higher economic stability and innovations allows to develop novel biotechnologies. Number of technologies for algae processing has been increased because of growing interest in this field, which has also been reported in State of Technology Review – Algae Bioenergy [28].

Novel technologies and conversion methods allows to increase biomass conversion efficiency using cascading biorefinery approach for coproduction of high-value specialty and commodity chemicals. Huijgen et al. notes, that seaweed is still quite expensive feedstock and cascading approach allows to use biomass in full amount. However lots of concepts/approaches are still theoretical since technologies are not mature and some technical and scientific challenges still exist [13]. To make cascading approach to be the most profitable collaboration between representatives of different market sectors over full biomass value chain is necessary.

3.1.2. Opportunities and threats

Seaweed biorefinery could create a great opportunity to strengthen economic position of numerous bioeconomy sectors (e.g. agriculture, fishery, chemical and energy) if there will be enough political and social support. Valderrama et al. have analysed social and economic dimensions of seaweed farming and processing and they agree on economic profits but also accent that political support is very meaningful, saying that, political instability and insufficient governmental and external-aid-funded support for the sector are further risk factors for the industry's development potential [42].

While political support can be a threat to seaweed biorefinery concept, this concept can also set new political goals, which would promote a sustainable use of seaweed for the production.

Development of the concept would also increase international cooperation in resource management and technological development issues. It would also be necessary to avoid threats like fluctuating oil price and availability of resources that could affect economic feasibility of seaweed biorefinery concept.

4. Conclusions

Within a biotechonomy perspective the sustainable conversion of any biomass is a key aspect moving toward the implementation of novel technologies and integrated concepts in order to reach a sustainable economic growth and market development. This is properly reflected within a seaweed-based biorefinery concept as sustainable and potentially economically viable solution of producing both high value added products and bioenergy. Depending from seaweed types and species it is possible to extract different fatty acids, oils, natural pigments, antioxidants, high value biological components and other substances which can be used in production. This is the reason why seaweed can positively affects several biotechnology areas like biofuels, cosmetics, food and food supplement production and have an impact on aquacultures and pollution removal.

We conclude that seaweed biorefinery concept can make a significant contribution to sustainable development by adding value to the original biobased feedstock but it is crucial to undergo to a more clear understanding of the overall technological processes and pathways. Seaweed conversion into wide spectrum of products using cascade conversion should be adapted to local conditions. This concept allows maximizing the biomass conversion efficiency and reducing the amount of raw material needed within a nearly-zero waste approach. Biorefinery concept is thus merging different bioeconomy sectors to potentially create multi- (and inter-) disciplinary partnerships between stakeholders.

In the same time seaweed biorefinery concept satisfy bioeconomy principles. Seaweed biorefinery is taking care of food availability and quality and uses cascading approach in this way increasing resource efficiency. The described five main properties of biorefinery concept do should not be seen as limitation to this seaweed biorefinery concept itself, instead they are defining guidelines and basic rules on how get the biorefinery concept most beneficial for a more sustainable bioeconomy. Not only all biorefinery concept together should be based on bioeconomy guidelines, but every step and phase of the concept, starting from input material and production and all life cycle of products they should follow the directions given by bioeconomy principles to give the highest social, environmental and economic benefits. Some concerns still exist with the sustainable yield principle. Seaweed availability is dependent on season, climate and nature conditions and this can be challenging factor regarding on sustainability.

Biorefinery concept presents a great way to efficient use of seaweeds. Some barriers like limited technologies and unpredictable amount and quality of seaweed biomass still exist. Once the difficulties are defeated, seaweeds have all necessary properties to significantly contribute to sustainable bioeconomy as a promising biomass.

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