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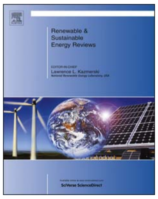

Offshore macroalgae biomass for bioenergy production: Environmental aspects, technological achievements and challenges

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ABSTRACT

Economic and environmental developments in the last decades call for the displacement of fossil fuels to alternative energy sources. Biofuels are considered as a part of the solution for this challenge. Sustainable raw materials for the production of transportation biofuels such as biodiesel, biobutanol and bioethanol, can be obtained from algal biomass. In particular, marine macroalgal biomass is a promising feedstock for transportation biofuels because of (the)its fast growth and its potential cultivation on seawater, avoiding competition of resources with conventional agriculture of terrestrial plants used for food. In addition, dissolved inorganic nutrients like nitrogen, phosphorous and carbon are taken up by macroalgae, helping to alleviate eutrophication in seas and oceans. Using biological, chemical and engineering advances in the last decades, technologies to provide cost efficient cultivation, harvesting, extraction and processing of sustainable biofuels have to be elaborated. This paper provides a review of macroalgae based biorefineries with offshore cultivation and consequent biomass conversion into transportation liquid biofuels. We discuss the methods for offshore cultivation, harvesting, and conversion of macroalgae biomass into liquid transportation biofuels. Based on the current information and global experience, we present local perspectives specific for France, Germany, Norway, the Netherlands and Israel on the potential use of Exclusive Economic Zone for transportation biofuels production. Marketable suggestions for future research need to include all stakeholders of a given site for offshore biorefinery development.

1. Introduction

Sustainable production of food and generation of energy are the major challenges for the world for the next decades [1]. One of the approaches for these challenges is to increase the use and efficiency of the solar energy. Therefore, economically efficient, socially and environmentally sustainable conversion of solar energy into valuable products is a major contemporary challenge for science, governments and businesses worldwide. Transportation fuels, electricity, heating, cooling, drinking water, food, animal feed, chemicals, and materials are all potential products of solar energy conversion. Biorefining is one of the pathways to convert solar energy into these useful products. Biorefinery integrates the capture of solar energy and carbon dioxide (via photosynthesis), biomass harvesting, processing, and distribution of derived chemicals and bioenergy. Design of a sustainable biorefinery, which will generate sustainable food, fuels and chemicals is a complex task and is largely influenced by local raw material supplies, advances in multiple technologies and socio-economic conditions [2].

The choice of raw biomass material is critical to ensure the efficient production of biofuels [1]. The currently used crops and cultivation methods supplied raw biomass for the food and feed sectors for hundreds of years; however, most recently they also started to supply biomass for the production of transportation fuels. First generation liquid biofuel feedstocks includes traditional agriculture crops: cereals, potatoes, sugar beet, rapeseed, wood and dedicated energy crops; while first generation fuel products include ethanol and biodiesel [3]. The second generation biomass feedstocks include animal fat, and dedicated lignocellulosic crops; and produce hydrotreated vegetable oil,

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cellulosic-ethanol, biomass-to-liquids (BtL)-diesel, bio-butanol, and advanced drop-in replacement fuels such as fatty-acid ethyl esters, alkanes, alkenes, terpenes and methyl ketones [4–10]. Recent studies, however, indicate the future of biomass sector development is under high degree of uncertainty mainly due to the limited crops yields and land availability [1,11]. With increasing world population, arable lands will be in full intended to food cultivation. Producing biofuel from the farming of traditional food crops appears awkward regarding food security and freshwater consumption [12,13].

Alternative biomass supply can come from micro- and macroalgae. Because of their remarkably high growth rates compared to most other photosynthetic organisms, the use of marginal land for cultivation, valuable commercial cellular compounds and potential high lipid accumulation, microalgae have been the focus of intense research in the last 50 years [14]. However, cost-effective cultivation, harvesting and dehydration difficulties currently still prevent broad scale, sustainable microalgae technologies implementation for biofuel production [14].

Marine macroalgae, also ranked among the most efficient photosynthetic organisms on earth, bear valuable chemical compounds. Macroalgae must be attached and are, thus, restricted to the seafloor (benthos) or other substrate within the photic zone. In addition to photons to activate the photosynthetic machinery, macroalgae also need nutrients such as nitrogen, phosphorus as well as inorganic carbon to grow. In order for these nutrients to be available and enable algal growth, they need to be dissolved and present in enough concentrations in the seawater medium. Nitrogen can be found in the sediment or in seawater as nitrate or ammonium [15], the latest being the preferred nitrogen source. Dissolved inorganic phosphorus enters seas and oceans from terrestrial sources. The source of inorganic carbon is air-born CO_2 that dissolves into seawater, and due to the generally high seawater pH, creates a significant pool of available HCO_3^- for algal photosynthesis. In addition, certain macroalgae can take up atmospheric CO_2 as well. Overall, these features are of major interest regarding two points. First, since marine macroalgae fix inorganic carbon, they can be used as carbon trap and then as fuel. Second, high levels of nutrients dissolved in seawater (primarily in coastal eutrophic waters) can be recycled through algal growth and subsequent harvesting of the biomass yields. Indeed, an expanding body of evidence has demonstrated that marine macroalgae, which contain very little lignin and do not compete with food crops for arable land [16] or freshwater [17], can provide a sustainable alternative source of biomass for the production of food, fuel and chemicals, such as bio-ethanol and bio-butanol [14,18–24].

Producing sustainable biomass offshore for bioenergy is promising because of its sustainability, but extremely challenging endeavor. Although the concepts of Ocean Farms (Fig. 1) have been introduced decades ago, current macroalgal cultivation is mostly suitable and therefore practiced in protected, near shore areas. The current concepts of offshore marine biomass cultivation include near farm concepts for kelp growth [25], tidal flat farms, floating cultivation [25], ring cultivation [26] and most recently wind-farm integrated systems [27]. Currently, there is no universal definition for offshore cultivation. However, in most cases offshore cultivation means the movement of farm installations from near shore, sheltered environments and facilities to more exposed environments, where then frequent harvests could have additional logistical and cost implications [28,29].

The goal of this article is to provide a comprehensive overview on the available technologies and methods of offshore macroalgal cultivation, and the subsequent conversion of their biomass into transportable biofuels. Hence, this article presents for the first time a comprehensive state of the art of offshore bioenergy production from macroalgae, hoping to provide a solid baseline for future developments aiming at exploring this “old” and “new” source for bioenergy production. There is a strong interest by stakeholders, public and policy in a trusted sustainable infrastructure providing renewable green energy.

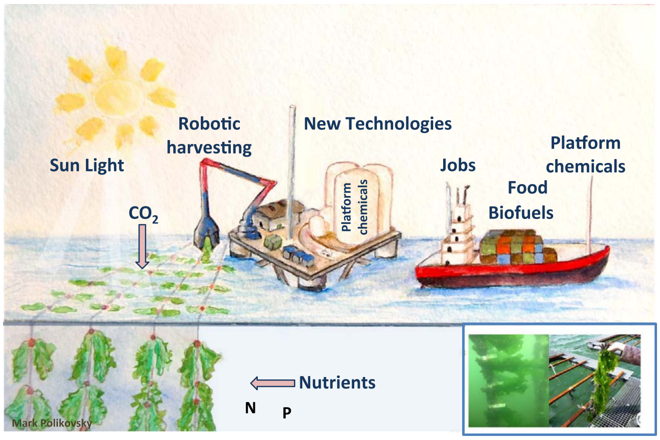

Fig. 1. Conceptual offshore biorefinery system for chemicals, food and energy production. Image adapted with permission from Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability Lehahn Y, Ingle, K.N, Golberg A. Algal Research. 17:150-160,2016.

2. Environmental conditions that predicate macroalgae biorefineries efficiency

Multiple environmental parameters control successful macroalgae cultivation. Water quality, photosynthetic active radiation (PAR), temperature, salinity, concentrations of inorganic nutrients including CO_2, and absence of environmental toxins are required for effective biomass accumulation via photosynthesis [30–32]. These environmental parameters are dynamic and depend on natural and human factors. For example, we can expect temperature and light to vary throughout the day, and during seasons, together with other equally important events such as wind, rainfalls and tides, which will all affect the macroalgal growth [33]. Humans also play a role through landform nutrient enrichment [33,34], aquaculture [35] and wastewaters [36]. Variable environmental conditions also impact the final product since the chemical composition of the macroalgal tissues will strongly be affected by the prevailing growth environment [37]. More recently, global changes occurring in the marine environment are forcing the geographical redistribution of macroalgae on a global scale, for example the retrieval of kelps from warming waters within the North Atlantic shores [38], challenging the prediction and planning of the high-yield areas.

3. Species choice, cultivation and harvesting methods

As benthic organisms macroalgae are typically attached to hard substrates, yet a few species can also grow floating in the upper layers of the seawater surface [53]. Naturally growing macroalgae are harvested in the subtidal zone or at shallow water, and the harvesting methods depend on the species. Several techniques exist ranging from rudimentary ones like hand-picking or cutting subtidal thalli to bulldoze, tractor or boat harvesting [54]. Skimmer boats have been developed to harvest macroalgae easily far from the coast [20,55], such as for *Laminaria digitata* (harvested by a boat with a gear called “Scoubidou” developed in 1960´s and used by e.g. CEVA – Centre d’Etude et de Valorisation des Algues) (Fig. 2). Harvesting naturally growing macroalgae may have severe environmental impacts unless a certain harvesting cycle depending on the macroalgae species is followed to allow recovery [45,56]. Several methods have been used to increase macroalgae growth rate and to ease the harvesting process. Table 1 presents the biomass yields for several types of macroalgae achieved with various offshore cultivation methods.

Attaching seaweeds to ropes, lines or nets is a popular way of cultivation since installation and maintenance costs are very low. The cultivation can be done by attaching the seedlings directly to the ropes