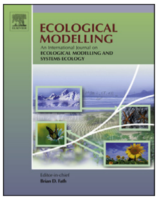
Ecological Modelling 288 (2014) 25–37

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel



Energy analysis of using macroalgae from eutrophic waters as a bioethanol feedstock

Michele Seghetta [a,b,1], Hanne Østergård [a,*], Simone Bastianoni [b]

[a] Department of Chemical and Biochemical Engineering, Technical University of Denmark – DTU, Søltofts Plads, Building 229, 2800 Lyngby, Denmark
[b] Ecodynamics Group, Department of Earth, Environmental and Physical Sciences, University of Siena, Pian dei Mantellini, 44, 53100 Siena, Italy

ARTICLE INFO

Article history:
Received 20 December 2013
Received in revised form 14 May 2014
Accepted 16 May 2014
Available online 18 June 2014

Keywords:
Macroalgae
Emergy
EROI
Bioethanol
Eutrophication
Sustainability

ABSTRACT

Eutrophication is an environmental problem in a majority of shallow water basins all over the world. The undesired macroalgae has been proposed as a biomass resource for bioethanol production and we have analysed the environmental sustainability of two case studies: Orbetello Lagoon (OL), Italy, and Køge Bay (KB), Denmark. Today, macroalgae are collected and stored in landfills to provide a solution for the excess production. An emergy assessment revealed that the main environmental support for macroalgae growth relates to water in both case studies. In OL, rain represents 51% of the emergy use, and in KB runoff from agricultural land constitutes 86%. The environmental support needed for producing one Joule of bioethanol is somewhat more than for a number of other bioethanol feedstocks being 2.12×10^6 solar equivalent Joules (seJ) for OL and 2.56×10^6 seJ for KB. However, a high percentage of the environmental support comes from local renewable flows being 40% for OL and 88% for KB. The difference between the two case studies is partly due to the contribution of energy from waves, which plays an important role in carrying macroalgae towards the coast in Køge Bay. Energy-wise, one J of fossil energy is required directly or indirectly to produce 0.09 J of bioethanol for OL or 0.44 J of bioethanol for KB, i.e. the energy return on (energy) invested (EROI) is less than 1. An alternative scenario was developed in order to investigate improvements of system efficiency. This was analysed with the full-requirement approach as well as with a marginal-requirement approach accounting only what the bioethanol production requires of additional processes, i.e. mainly transportation and conversion of the macroalgae in a biorefinery facility which is assumed to be situated close to an existing industry producing waste heat. Both emergy and EROI analyses showed that only a relatively small amount of resources has to be added to the existing system to produce the bioethanol, e.g. the EROI increased to above 1 in both systems. With the marginal approach, macroalgae may be appreciated as a resource for bioethanol production instead of considered as an environmental problem.

1. Introduction

Eutrophication is an environmental problem which affects many shallow water basins all over the world. It is caused by an increase of nutrients, which creates imbalance in the trophic chain. Micro- and macroalgae are positively influenced by eutrophication due to the availability of otherwise limiting nutrients. This leads to a huge flowering, the so-called “bloom”, which mostly occurs in shallow water basins with a modest exchange of water, where nutrients can easily reach high concentration.

Fast growing macroalgae usually create extensive, thick, unattached mats above seagrass or the sediment surface. These mats are able to change water conditions, such as the concentration of oxygen, nitrogen and the diffusion of light (D’Avanzo and Kremer, 1994; Krause-Jensen et al., 1999). It has been reported that the macroalgae *Ulva lactuca* showed differential growth response when exposed to different nitrogen (i.e. NH_4 and NO_3) sources due to its distinct nitrogen uptake mechanism leading to concentration build-up of slow assimilated nitrogen (i.e. NO_3) in a eutrophic environment where controlling algal growth is crucial (Ale et al., 2011a). The foremost consequence of uncontrolled algal growth is the decline in seagrass population size (Cardoso et al., 2004;

---

* Corresponding author at: Chemical and Biochemical Department, Technical University of Denmark – DTU, Frederiksborgvej 399, 4000 Roskilde, Denmark. Tel.: +45 21326955.

E-mail addresses: mise@dmu.dk (M. Seghetta), haqs@kt.dtu.dk (H. Østergård), bastianoni@unisi.it (S. Bastianoni).

[1] Present address: Department of Environmental Science, Faculty of Science and Technology, Aarhus University, Frederiksborgvej 399, 4000 Roskilde, Denmark.

http://dx.doi.org/10.1016/j.ecolmodel.2014.05.006
0304-3800/© 2014 Elsevier B.V. All rights reserved.

Harlin and Thorne-Miller, 1981; McGlathery, 2001; Sfriso et al., 1992). In spite of the growth promoted by nitrogen uptake of seagrass (Bulthuis et al., 1992), the over proliferation of phytoplankton and floating macroalgae biomasses reduce the light penetration through the water column, and as a consequence the rate of photosynthesis of seagrass is decreased remarkably (McGlathery, 2001). Seagrass is important for aquatic ecosystems due to the high oxygen production that even occurs in the deeper layer of the sediment. The oxygen production is a fundamental condition to effectively decompose the organic matter and create a healthy environment for the benthic community. Ecosystem changes from dominance of seagrass to dominance of macroalgae affect the quality of the sediment surface resulting in a negative impact on the fauna, i.e. limited trophic interactions and reduced numbers of invertebrate and fish species that use seagrass as habitat, food, protective cover, or as a nursery ground.

The lack of oxygen mixing in the deeper layer of the water column, as well as massive decomposition of the large macroalgal population, may lead to anoxic water periods (D'Avanzo and Kremer, 1994). This means insufficient levels of oxygen for the fauna, which leads to massive death of fish, as documented in the Orbetello Lagoon (Innamorati and Melillo, 2004).

Three approaches are often utilized by municipalities to limit the occurrence of macroalgal blooms: (1) Prevent nutrient flows on land from entering river basins; (2) Increase water exchange within the basin; (3) Harvest the macroalgal biomass (Fredenslund et al., 2011; Lenzi et al., 2003; Valiela et al., 1997). The first approach might be the most effective, but it is not always possible, because intensive agriculture is based on the massive use of fertilizer, which is easily drained by rainwater towards the closest river basin. Moreover, a certain amount of nutrients come from municipal wastewaters, which cannot be totally purified. The second solution is only feasible in semi-closed basins, such as lagoons. Clean sea water enters the basin, diluting the eutrophic water and the nutrient-enriched water returns to the sea. The third approach is seldom effective since the amount of nutrients within the biomass is usually much smaller than the amount of nutrients stored in the sediment (Lenzi et al., 2003). Moreover, macroalgal species are fast-growing and can rapidly spread again all over the basin. Harvesting macroalgae, however, reduces the problem of anoxic events.

An additional problem is that rotten macroalgae along the shores prevent people from enjoying the beach due to strong smell. The harvested macroalgal biomass becomes a waste which has to be dealt with, e.g. to be disposed in landfills. This kind of disposal is relatively cheap, but it is still a burden for communities (e.g. the management of the collected macroalgae of Orbetello Lagoon costs around €1 M every year).

As a consequence, uses of macroalgae as a feedstock for different products have been investigated. The commercial utilization of macroalgae for hydrocolloid application (i.e. agar, carrageenan and alginate) in developing countries like Philippines, Indonesia, and Tanzania added value to macroalgal biomass and contributed to economic and livelihood of local farmers in the region. It has been found that some macroalgae contained valuable compounds other than hydrocolloid polysaccharides (Ale et al., 2011b). Fucoidan, an important bio-molecule from macroalgae may have therapeutic properties including immunomodulatory, anti-coagulant as well as anti-proliferative effects on certain types of cancer cells (Ale and Meyer, 2013; Zemke-White and Ohno, 1999). Red macroalgae are being studied in Korea in order to produce paper from their cellulose (Seo et al., 2010). Thanks to their high potassium, nitrogen and phosphorus content, macroalgae can also be utilized as fertilizers or as animal feed (Craigie, 2011; Kenicer et al., 2000; Villares et al., 2007). Only a few studies have considered the utilization of natural macroalgae, e.g. the use of green macroalgae to produce high-tech composite materials (Mihranyan, 2011).

Here we will explore the potential of using macroalgae as feedstock for bioethanol production. At present, more investments are being put into research on developing microalgae-based biofuels compared to investments in the use of macroalgae to produce biofuels (Brennan and Owende, 2010; Wegeberg and Felby, 2010). However, a number of studies and reports are considering the possibility of using macroalgae as a biofuel feedstock (Reith et al., 2009; Roesijadi et al., 2010; Wegeberg and Felby, 2010). Environmental problems related to biofuels from terrestrial energy crops have been demonstrated, such as the availability of feedstock (e.g. Giampietro and Ulgiati, 2005) or the energy return compared to energy invested (Murphy and Hall, 2010; Pimentel and Patzek, 2005), but only few studies are available on aquatic biomass. These are mainly about microalgae (Aresta et al., 2005; Clarens et al., 2010) and just very few papers are on macroalgae (e.g. Bastianoni et al., 2008). Our analysis adds a new feature in feedstock production, by studying macroalgae that are spontaneously blooming due to eutrophication and not farmed in controlled conditions.

The aim of this study is to investigate the potentials of producing bioethanol from macroalgae form eutrophic areas compared with conventional production. The starting point for this evaluation is also the description and identification of structural differences between two aquatic ecosystems. An emergy analysis is chosen to fulfil this scope, due to its capacity to take into account the environmental contribution in making a product or supporting a process.

2. Materials and methods

2.1. Emergy analysis

Emergy accounting is a methodology introduced by Howard T. Odum (see for example Odum, 1996). It considers the total amount of available energy (exergy) of one kind (in particular solar), directly or indirectly required to make a product or to support a process. Emergy flows are expressed in units of solar equivalent joules (seJ) (Sciubba and Ulgiati, 2005).

In order to account for the different transformations of solar energy, a factor called solar transformity (τ) is defined as emergy input per unit of available energy output. Emergy flows and transformities are linked by the following relationship:

$$\mathrm{EM} = \sum_{i=1}^{n} E_i \tau_i$$

where EM is the emergy use (seJ) of a product or a process with n input components, E_i is the available energy (J) in component i and τ_i is the corresponding transformity (seJ J^{-1}). A more complete treatment of the formulas that link emergy flow and transformity can be found in Bastianoni et al. (2011).

Transformities are not the only conversion factors utilized, because inputs can also be expressed in mass units. In this case, the amount of solar energy required to produce a gram of the considered matter is utilized (called the specific emergy). The term “Unit emergy value” (UEV), generally used since Odum (2000), encompasses all the different types of conversion factors. UEVs refer to a planetary solar emergy baseline that represents the annual flow of emergy on Earth. Different baselines have been used. In this study, we refer all UEVs to the 15.83×10^{24} seJ year^{-1} baseline (Odum, 2000).

The total emergy flow is obtained by summing all the emergy flows relative to the inputs, with the exception of sun, rain and wind, since they can be considered as co-products: the maximum of the three inputs is the one taken (Odum, 1996). Inputs are classified in three categories: local renewable (R), local non-renewable (N) and imported (F). In order to calculate the energy flows of wind