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Explorative environmental life cycle assessment for system design of seaweed cultivation and drying

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ABSTRACT

Seaweeds are presently explored as an alternative source to meet the future protein demand from a growing world population with an increasing welfare level. Present seaweed research largely focuses on agri-technical and economic aspects. This paper explores directions for optimizing the cultivation, harvesting, transport and drying of seaweed from an environmental point of view. An environmental life cycle assessment (LCA) and detailed sensitivity analysis was made for two different system designs. One system design is featuring one layer of cultivation strips (four longlines side by side) interspaced with access corridors. The other system design is featuring a doubling of cultivation strips by dual layers in the water column. Impact profiles and sensitivity analysis showed that the most important impacts came from drying the harvested seaweed, and from the production of the chromium steel chains and polypropylene rope in the infrastructure. This indicates that caution should be used when designing cultivation systems featuring such materials and processes. Furthermore, the high-density productivity of the dual layer system decreases absolute environmental impacts and so found to be a little more environmentally friendly from a life cycle perspective.

1. Introduction

Seaweeds, similar to terrestrial plants, have been used for centuries as a food source. There is evidence of seaweed food products from the 4th and 6th centuries in Japan and China, respectively [1]. Some archaeological digs have suggested their use in agricultural soil management as well in the 2nd Century BC in Cornwall and perhaps even earlier in Estrucian Malta [2]. The use of ***wild*** harvested seaweed for feed, food and fertilizer is known to have evolved in isolation in various parts of the world from Scotland and Ireland to Japan and Peru [3,4]. The development of seaweed ***cultivation***, however, was until recently mostly restricted to Asian societies for local consumption in coastal areas [5]. In Europe, the majority of seaweed production comes from wild harvesting. However due to concerns over environmental impacts, wild harvests have decreased significantly in the last decade and there is a drive to meet the increasing demand by shifting production toward cultivation [6].

Today, both wild harvest and cultivated seaweeds are exploited around the world for many purposes [4]. They still serve as a fertilizer in agriculture and as food and feed [7]. Seaweed are now also increasingly seen as useful ingredients for products in other sectors, notably the pharmaceutical, cosmetic and food industries. Seaweed extracts can be applied as dyes or hydrocolloids [8], i.e. non-crystalline compounds forming jelly-like substances with water. Seaweed dyes and hydrocolloids have a large variety of applications in the food and cosmetic industry [1]. The main application of seaweeds globally, however, remains for human and animal consumption.

Seaweeds contain significant levels of essential nutrients such as carbohydrates, proteins, minerals, vitamins and trace elements like iodine [9,10] as well as antioxidants [11]. This makes some seaweed species highly suitable for both human and animal consumption [12]. The protein content may vary significantly over the different seasons and amongst different species [5,13] but can be up to 47% of the dry mass in a seaweed specie such as *Porphyria* spp. [14]. Their relatively

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high protein content makes seaweed a relevant alternative for animal proteins [15]. Seaweeds furthermore have extraordinary growth capacities, several times higher than for terrestrial energy or food crops such as rapeseed or sugar beets [16], which makes them suitable alternatives for these crops.

Seaweeds are presently explored as an alternative source to meet the future protein demand [17,18] from a growing world population [19] with an increasing per capita welfare level [20]. The cultivation of seaweed is also seen as an opportunity to reduce agricultural land use and related environmental burdens [21] and to remove elevated levels of nitrogen from estuaries and coastal waters [22]. Studies have furthermore suggested that seaweed growth rates can increase while providing bioremediation services to nearby finfish cultivations by absorbing nitrogen [23–26]. Nevertheless, seaweed cultivation may also have negative consequences for the environment and these are likely to be amplified by increasing the scale of operations. Apart from possible direct consequences for marine ecosystems, other and indirect environmental consequences of seaweed cultivation are limited in their description in literature [16]. Indirect environmental consequences refer to upstream production of the means needed in seaweed cultivation, and downstream transport, drying and processing of harvested seaweed into, for example seaweed meal.

The direct and indirect environmental impacts of seaweed cultivation, i.e. the overall environmental performance of the production system for dried seaweed, can be quantified with life cycle assessment (LCA). LCA is a well-established tool to shed light on the environmental performance of product (and production) systems by quantifying their cradle to grave (or gate) contribution to a range of impact categories [27–29]. Some LCA studies have been conducted with a focus on specific aspects of seaweed supply chains, for instance wild harvests and valorisation strategies [30], photobioreactor cultivation and oil extraction [31], macroalgae biorefinery [32,33], and production of biofuels from cultivated seaweed biomass [34]. This study adds to this body of literature by exploring optimal system design for commercial seaweed cultivation and drying. The drying of seaweed reduces biomass weight for transport, it makes it readily suitable for further processing, and is a reliable way of preserving protein and nutritional values [35]. Such future commercially cultivated seaweed is initially expected to be applied in the agri- and aquaculture sectors, as it is considered a sustainable alternative to soy- and fishmeal and a valuable additive to feeds, but may in the long run serve for human purposes in the food industry [36–38].

The LCA in this paper is of an explorative character since commercialised, large-scale seaweed farms are not yet established in Europe. Some small and medium-scale pilots have been established such as in the Oosterschelde estuary, Netherlands, and the Seafarm near Strömstad, Sweden. These pilots provide insight in agri-technically optimal and economically viable seaweed cultivation. However insight is also needed on how to minimise the environmental impacts of the dried seaweed production systems, i.e. of seaweed cultivation and upstream production of means, as well as of its downstream transport and drying. The design of a potential commercial production system for dried seaweed, particularly the design of the cultivation infrastructure sub-system and associated seaweed yield, has not gained much attention to date.

The design of the cultivation infrastructure sub-system might be of great influence to the overall environmental performance of the dried seaweed production system. Two hypothetical infrastructure sub-systems for future seaweed cultivation have been designed, one with single and the other with dual layer longline configurations. First an LCA has been performed for two reference dried seaweed production system designs, one with a reference design for the single layer and the other with a reference design for the dual layer seaweed cultivation infrastructure sub-system. Next an extensive sensitivity analysis was performed, varying the design of the cultivation infrastructure, transport and drying parameters of the two reference dried seaweed production systems. The aim of the LCA in this paper was to explore potential designs of the future dried seaweed production system in order to identify directions for its optimization from an environmental point of view.

2. Methodology

Life Cycle Assessment (LCA) consists of four methodological phases. The first phase, goal and scope definition, specifies why and how a given LCA is performed. The second phase, life cycle inventory, quantifies all environmental inputs and outputs of the production system under consideration. The environmental inputs and outputs are translated in the third phase, life cycle impact assessment, into their contribution to a range of environmental impacts. The fourth phase, interpretation, evaluates the results of life cycle inventory and impact assessment in relation to the defined goal and scope in order to draw conclusions [27–29].

The goal and scope definition basically sets how the other three phases are performed. The goal or aim of the LCA in this paper, as mentioned already in the Introduction, was to identify directions for optimizing the future commercial dried seaweed production system design from an environmental point of view. The scope of the LCA in this paper, i.e. its methodological approach, is further specified here in terms of the software and databases as well as data processing, the functional unit, description of the dried seaweed production system and life cycle inventory, life cycle impact assessment and finally the sensitivity analysis.

2.1. *Softwares, databases and data processing*

The software SimaPro 7.3 is used for life cycle inventory analysis and impact assessment calculations. EcoInvent v3.0, included in the software SimaPro 7.3, is used where relevant as the source for life cycle inventory data (see Table 1). The impact results for the reference systems are presented in stack-diagrams, produced in excel. Impact results for the sensitivity analysis are processed in excel into graphical representations showing the changes in impact resulting from changes in the amount of inputs.

2.2. *Functional unit*

The function of the dried seaweed production system in this LCA is the production of dried seaweed with a protein content of one ton, suitable for further processing. In other words, all LCA results are expressed per ton of protein (and thus not, e.g., per ton dried seaweed). Downstream processing of the dried biomass into commercially available products is not included in the present study.

2.3. *Dried seaweed production system and inventory analysis*

The dried seaweed production system is schematically depicted in Fig. 1. The processes in the grey shaded boxes are included, and the processes in all other boxes are excluded in this LCA. In other words, grey shaded processes are inside and other processes are outside the boundaries of the system. The final product of the system is dried seaweed biomass. Data for sprouting of seeding lines is not available. The materials for production of the service vessel and the diesel used for harvesting are included in seaweed transport. The production of other products used for other harvesting tools, e.g. knives and nets, are excluded in this LCA as they are considered negligible compared to materials used in the boat.

The cultivation of seaweed in a European context still has an experimental character, and only small to medium scale pilots are being implemented to our knowledge. Some pilots are testing different types of cultivation infrastructures, such as those described by Taelman et al. [42]. We have limited information about what large-scale commercial

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