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Life cycle assessment of seaweed biomethane, generated from seaweed sourced from integrated multi-trophic aquaculture in temperate oceanic climates

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HIGHLIGHTS

- Seaweed composition is the key factor in decreasing environmental impacts.
- Digestate handling and storage is a large contributor to impacts.
- Proper management of digestate offsets carbon emissions by 3–7 g CO_2 eq/MJ.
- Seaweed farming represents 53% of impacts in production of seaweed biomethane.
- Seaweed biomethane can deliver over 60% carbon savings as compared to fossil fuel.

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ABSTRACT

Biomethane produced from seaweed is a third generation renewable gaseous fuel. The advantage of seaweed for biofuel is that it does not compete directly or indirectly for land with food, feed or fibre production. Furthermore, the integration of seaweed and salmon farming can increase the yield of seaweed per hectare, while reducing the eutrophication from fish farming. So far, full comprehensive life cycle assessment (LCA) studies of seaweed biofuel are scarce in the literature; current studies focus mainly on microalgal biofuels.

The focus of this study is an assessment of the sustainability of seaweed biomethane, with seaweed sourced from an integrated seaweed and salmon farm in a north Atlantic island, namely Ireland. With this goal in mind, an attributional LCA principle was applied to analyse a seaweed biofuel system. The environmental impact categories assessed are: climate change, acidification, and marine, terrestrial and freshwater eutrophication.

The seaweed *Laminaria digitata* is digested to produce biogas upgraded to natural gas standard, before being used as a transport biofuel. The baseline scenario shows high emissions in all impact categories. An optimal seaweed biomethane system can achieve 70% savings in GHG emissions as compared to gasoline with high yields per hectare, optimum seaweed composition and proper digestate management. Seaweed harvested in August proved to have higher methane yield. August seaweed biomethane delivers 22% lower impacts than biomethane from seaweed harvested in October. Seaweed characteristics are more significant for improvement of biomethane sustainability than an increase in seaweed yield per unit area.

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1. Introduction

1.1. Rationale for seaweed biomethane

The EU is committed to achieve at least 20% renewable energy share of gross energy consumption by 2020, rising to 27% by 2030 [1,2]. The Renewable Energy Directive (RED) requires 10% of renewable energy in transport by 2020 [1]. Biofuels have an important role in achieving transport targets but their sustainability must be ensured [1,3]. Land-based biofuels may compete directly or indirectly for land associated with food production [4]. An amendment to the RED sets a cap on first generation (land-based) biofuels to 7% of transport fuel and suggests an indicative target of 0.5% for advanced biofuels, such as algae [3,5]. The algal biofuel sector is immature, but does include for start-up companies and is supported by EU-funded projects [6,7]. Macro-algae (seaweed) do not compete for land and as such seaweed biomethane is considered an advanced (third generation) renewable gaseous fuel, which can be counted at twice its energy content in consideration of 2020 national renewable energy targets [5].

Of the 221 species of seaweed commercially used, 66% of use is for food [8], with the remaining in agrichemicals, fish feed, health and cosmetic sectors [9]. Cultivated seaweed production represents 95% of the seaweed market and produced 24 million tonnes wet weight (wwt) in 2013 [10,11]. The industry has a value of over €6 billion [12]. Farming of seaweed can be integrated with salmon farming in an integrated multi-trophic aquaculture (IMTA) system. This circular economy concept reduces the impacts from nutrient-rich waste released from fish farms, whilst enhancing the growth of seaweed [13–15]. Aquaculture produces over 2 million tonnes live weight each year of Atlantic salmon (*Salmo salar*) [10]. If an average price of €5 per kilogram is assumed [16], this gives a market worth €10 billion. The Food and Agriculture Organization (FAO) estimated that there will be a need to produce an extra 42 million tonnes of farmed seafood to feed the world by 2030, and salmon will play a key role in fulfilling this demand [17]. However, research shows that farmed salmon has a very high environmental footprint [18–21]. Implementation of efficient IMTA has the potential to increase the sustainability of aquaculture systems by minimising the risk of eutrophication in marine environments. Furthermore, the seaweeds become an additional product with additional revenues for the fish farmers [9,22]. The green seaweed *Ulva sp*. and the red seaweed *Gracilaria chilensis* were shown to have enhanced growth levels cultivated close to fish cages than in in control sites [13–15]. *S. latissima* and a red algae, *Palmaria palmata* produced respectively 27% and 63% higher yields when grown close to fish farms than on reference sites [23]. It was also observed that *S. latissima* had a faster growth in an IMTA system than at a reference station [24]. *Saccharina latissima* and *Laminaria digitata* brown seaweeds native to northern Europe, are suitable for IMTA, due to their N uptake capacity and yield improvements in proximity to fish farms [9,25].

Experimental studies indicate the suitability of seaweed substrates for methane production [26–29]. In assessing yields of biomethane from seaweed, the fluctuation in the seaweed supply over the year and the seasonal variation in the chemical composition of seaweed for different species [30] must be assessed.

1.2. Life cycle assessment of seaweed biomethane associated with integrated seaweed and salmon farms

Life cycle assessment (LCA) is accepted as the most suitable tool for the sustainability assessment of algal projects [7,31]. Full comprehensive LCA studies of seaweed biofuels are scarce in the literature; to date algal studies focused mainly on microalgal liquid biofuel systems [6,31,32]. Moreover, the majority of algal LCA papers only examine climate change as the impact category [32].

Taelman et al. [33] compared two off-shore cultivation systems of *S. latissima*; long-line (Ireland) and a raft system (France). The study focused on the assessment of the environmental impacts of seaweed farming (hatchery and deployment at sea) based on the total consumption of resources. Results in Ireland show that about 81% of the impacts are related to transport (between hatchery and sea site) and infrastructure; diesel used for transport contributed 44.3% of impacts, while production of materials used in the processes contributed 36.6%. The impacts of both systems could be lowered if biomass yields per unit area were increased.

The study of Langlois et al. [34] dealt with the environmental impacts of biomethane from the anaerobic digestion (AD) of the whole seaweed (*S. latissima*) and from alginate-extraction residues. Seaweed biomethane has important benefits for marine and freshwater eutrophication as seaweed removes eutrophying pollutants (N and P) from the surrounding seawater during growth. However, the study found that the overall environmental impact of seaweed biomethane could be higher when compared with natural gas, in terms of climate change, ozone depletion and human toxicity. The authors suggested that an optimal system including for ecodesign (materials recycling, heat recovery), technical improvements (increased biomass yield per unit area and lowered fuel consumption), and use of renewable energy (from offshore wind farms) could greatly improve the environmental footprint of seaweed biomethane.

Alvarado-Morales et al. [35] assessed the energy demands and environmental impacts of biofuel produced from *L. digitata* grown on long-lines in Nordic conditions for two seaweed biofuel systems. Biogas production from digestion of seaweed was compared with bioethanol production via saccharification and fermentation. They found that seaweed biogas has the potential to deliver beneficial impacts for climate change (Global Warming Potential), acidification and terrestrial eutrophication. These are related to both the production of electricity from biogas (displacement of coal-based electricity) and use of digestate (displacement of mineral fertilisers). The biogas scenario performed better than bioethanol scenario for all the impacts categories considered. The difference between the two scenarios was linked to the energy consumed for bioethanol downstream and purification process.

In an LCA study of biomethane from *Ulva lactuca* grown in an open pond in southern Italy, seaweed was co-digested with poultry manure and agricultural waste (citrus pulp) [36]. The biomethane produced was used for electricity and heat generation. Compared with a fossil fuel scenario, the seaweed system performed better if total electricity inputs to the systems are supplied by electricity generated from biogas using an onsite CHP system, and digestate is assumed to replace mineral fertilisers.

The gap in the state of the art, and the corresponding innovation in this paper, is that this is the first paper to undertake a full comprehensive water-to-wheel (well-to-wheel[1]) LCA study of gaseous seaweed biofuel associated with an integrated multi-trophic aquaculture system including for consideration of a range of impact factors. The overall sustainability of such systems is unknown and it is essential to assess if this third generation algal biofuel is actually sustainable and how the system could be optimised to ensure sustainability. The systems described are pre-commercial, and as such an extensive sensitivity analysis is undertaken to assess the major sources of impacts and how to maximize sustainability of such systems.

[1] Feedstock is produced at sea; the 'well' is 'water' [61].

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