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Case Report

Development of a novel recirculatory multitrophic peatland system for the production of high-value bio-based products at scale embracing zero waste and pollution principles to unlock sustainable development goals

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A R T I C L E I N F O

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A B S T R A C T

This case study describes the novel development and demonstration of commercial, green, bio-based products using a peatland based recirculating integrated multi-trophic aquaculture (IMTA) system in the Irish Midlands. This site enables the transition from traditional peat harvesting for energy generation towards alternative sustainable employment. The system effectively addresses sustainable in-land freshwater aquaculture development. It also demonstrates value-chain products at scale for new feeds arising from the fish waste-stream by exploiting cascades from the fish culture waste-stream (bio-fertiliser) for cultivating duckweed and macroalgae. These plants can then be bio-refined and valorised to produce new products. The system also provides a circular demonstrator site that will facilitate industry and entrepreneurs to develop and test new innovations and ideas. By providing this open-access site to support companies in testing, financial constraints such as access to specialist equipment and technical expertise will be off-set thus enabling entrepreneurs and industry to develop new commercial products at scale. Additionally, the outputs from this system will help address and inform several United Nations sustainable development goals.

1. Introduction

The steady growth in global population coupled with the commensurate demand for edible protein has contributed to an agricultural intensification that presents challenges for the sustainability of livestock farming [1]. Specifically, there is a need to reduce the production and release of agriculture waste products to protect our fragile environment [2]. Conversely, new opportunities are arising to valorise agricultural waste, for example; through the co-production of different bio-based products from raw materials (biomass) that can be used for the production of food, feed and biofuels [3]. Such a circular bioeconomy is aligned with a renewed focus on rural resilience and regional development across Europe [1] that seeks to promote zero-carbon changes in land use, including rewetting peatland [4]. The bioeconomy offers new sustainable and climate-resilient pathways for economic development aiding a fair and just transition (JT) from a fossil fuel driven economy [5]. However, there remains pressing technical and financial challenges that includes scalability and delivering clear messaging where solutions can be met through pilot commercial demonstration activities. Consequently, this case study describes the use of a peatland-based, recirculating integrated multi-trophic aquaculture (IMTA) system in the Irish JT Territory to overcome some of these hurdles through organic fish-production and culturing duckweed as a protein crop. This does not just include technical advances, but also

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embraces, for example, multi-actor stakeholder engagement using a quadruple helix approach [6,7] that integrates industry, policy-makers, society and academics.

2. IMTA process at Mount Lucas wind farm in Irish peatlands

The IMTA site at Mount Lucas in the Irish midlands is a former commercial peat-harvesting site that has operated several years as a successful organic fish farm using the principle of integrated multi-tropic aquaculture i.e., where two or more organisms are cultured or farmed together [8]. Building on that core principle, this case study describes the development and future trajectory of the site. Ziegler et al. [9] reported that key challenges affecting the development of peatland-based innovation include the lack of shared systems of data generation for meta-analysis, corporate strategy, risk-mitigation and business disruption. In Ireland, there is nearly 100,000 ha. degraded peatland used for commercial peat cutting thus presenting scope to develop and demonstrate an IMTA approach to deliver solutions at scale for the bioeconomy. The IMTA farm is located in the Irish Midlands on a wind farm (53°17′3″ N – 7°11′45″ W) and is a cut-away rewetted glacial till site, from which peat was previously extracted [9,10]. Four split (pill) aquaculture ponds were dug-out on the infertile cut-away substrate and used for culturing of rainbow trout (*Oncorhynchus mykiss*) and European perch (*Perca fluviatilis*) [10]. The system is circulatory and fishponds are connected by means of channels to an algae and duckweed lagoon that serves as a natural fish effluent waste treatment system (see Fig. 1). Energy is locally generated by wind turbines. Water is rarely taken into (only done so to compensate for evaporation) or released from (only during times of excessive rainfall, the system to a nearby bog river.

3. Use of freshwater macroalgae for nutrient recycling and biomass production

Early studies have revealed the presence of a large variety of algae in the IMTA system at Mount Lucas [11]. As part of the IMTA process, the fish cultivation waste stream will be used to cultivate macroalgae in land-based tanks. Freshwater macroalgae, unlike their marine counterparts, are a relatively overlooked group of plants that, to date, have not been fully harnessed at scale for their nutrient removal potential or their biomass composition in aquaculture systems. Several species have been shown to be indicators for eutrophication through their sustained growth in nutrient-rich freshwater bodies [12]. Such characteristics will be leveraged in Mount Lucas to efficiently recycle the fish effluent (which mostly contains ammonium and phosphates) into useable biomass. Macroalgae have distinct advantages over freshwater microalgae, namely their containment within the site, ease of harvest, and higher resistance to bacterial contamination in the environment [13].

Determining the diversity and performance of local freshwater macroalgae species under high nutrient load and/or a seasonal pattern has yet to be characterized. Screening for growth and nutrient removal potential of Irish freshwater macroalgal species, particularly Chlorophyta such as *Cladophora*, *Oedogonium*, *Monostroma*, *Pithophora* and freshwater *Ulva* genera will advance system performance [8]. Some species of these genera have been shown to grow in freshwater at very low to no salinity conditions and sustain high growth in high-nutrient environments [14,15]. Growth and nutrient uptake kinetics will be interpreted in the context of continuous monitoring of nutrient levels using sensors. An on-site nursery informing production of fresh macroalgae biomass in land-based tanks will be deployed with focus on determining seasonality of species to ensure an all year-round process. Harvested macroalgae will be bio-refined for bioactives such as proteins, carbohydrates, lipids and antioxidants. For example; it has already been shown that *Oedogonium* represents a high-quality source of proteins for animal feed [16], while *Cladophora* biomass has been shown to possess a wide range of possible applications from feed, nutraceuticals and composites to bio-stimulants [17].

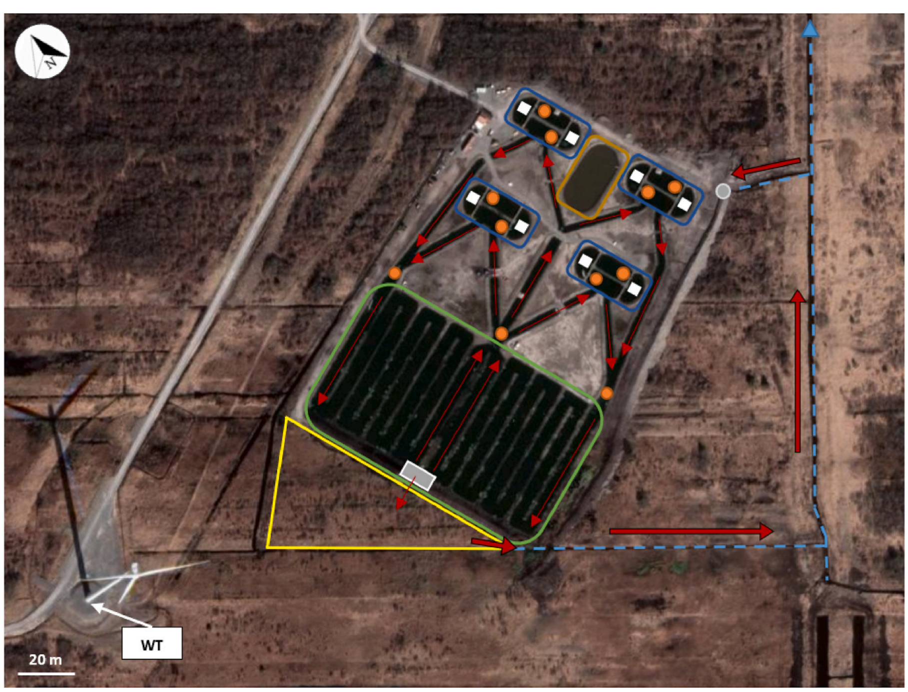

Fig. 1. Aerial view of the full IMTA system. Culture ponds (blue squares), reservoir (orange square), treatment lagoon (green square) and neighbouring wetland (yellow triangle) are visible. Airlift (white squares) and paddlewheel (orange circles) locations have been indicated. Peatland/bog river (blue dashed lines) has been included along with the intake point (grey circle) and overflow point (grey rectangle). Red arrows indicate water flow in and around the system. Wind turbine (WT) 19 which provides all electrical needs for the farm can be seen in the bottom left-hand corner. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Duckweed for sustainable valorisation of aquaculture wastewater

Duckweed (*Lemnaceae*) species have gained considerable attention as a sustainable source of high-quality nutrition, biofuels, and pharmaceuticals, as well as effective organisms for the phytoremediation of wastewaters [18]. A protein content of up to 45 % makes duckweed biomass nutritionally interesting as an ingredient for animal feeds, or for human use [18]. Previous work conducted on the pilot IMTA site at Mount Lucas has demonstrated the potential to generate high biomass yields from duckweed, with yields in excess of 30 tonnes [19] containing some ten tonnes of protein. Such yields are substantial in comparison with those of traditional crops such as soybean that rarely exceed five tonnes per year. The duckweed protein content was found to range between 20 % and 25 % [19], but there is scope to increase the protein content to about 40 % [20], through an increase in nitrogen in the water column. Thus, integrated management involving fish-husbandry, nutrient monitoring and duckweed manipulation can increase the economic case for the cultivation of duckweed as a novel protein crop. The strength of the IMTA is that it comprises of an integrated system in which fish, duckweed and algae species engage in mutually beneficial, as well as antagonistic interactions which need to be aligned with stakeholder interests (i.e., protein extraction technology) in accordance with priorities for a JT.

Moreover, outdoor duckweed cultivation has gained in popularity in recent decades, but it can be challenging to optimise, to control operationally and to integrate into a more comprehensive system such as an IMTA. Substantial challenges remain with respect to scaling up small-scale systems (up to several m^2) to semi-commercial, large-scale systems. This includes understanding the relevant importance of the diffusion and mixing processes in facilitating plant nutrient supply to the thin surface layer of the floating duckweed plant. Optimising recirculating flow through technology, as described in this IMTA peatland model, coupled with sensor supports systems with artificial intelligence (AI) and machine-learning growth models, and monitoring of growth using an UAV, can maximise biomass yields. The duckweed performance data will be used to infer performance modelling of the farm and identify positive and negative drivers of duckweed growth *in-situ* (e.g., nutrient levels, flow rates, weather conditions), but also to calculate the capacity of the duckweed system to manage water nutrient levels that are safe for diverse fish species. Furthermore, such monitoring will facilitate accurate timing of autonomous harvesting, optimised to maximise yield. To avoid harvesting becoming a bottleneck to commercial exploitation, a SWOT analysis of key activities, including biomass cultivation, harvesting, biomass pre-treatment and protein extraction, will be undertaken.

5. Conversion systems, bio-refinery and valorisation

Bio-refinery concepts comprise of an integration of processes to make high-value-added products such as food or feed ingredients (e.g., proteins, fibres), biomaterials, nutraceuticals (e.g., bioactives), and lower-value-market products (e.g., biogas). The Mount Lucas IMTA system addresses production of macroalgal and duckweed with a biorefinery approach that will yield marketable products without producing unused waste or side streams (Fig. 2). The key challenges associated with the development of sustainable zero-waste value chains are; (1) post-harvest interventions for biomass; (2) on-site preservation; (3) pre-treatment technologies; and (4) robust, energy-efficient conversion systems (Fig. 3). For industry, two aspects of biomass processing methods can be considered. One is on-site preservation using ensiling. The more preferred but energy-intensive method currently employed is hot air drying. Currently, most large-scale biomass drying is carried out using conventional hot air dying (10–15 h. at 50^{o}C) without pre-treatments. Macroalgal and duckweed biomass will need to be intensively dried post-harvest in order to reduce their moisture content from 70-80 % to

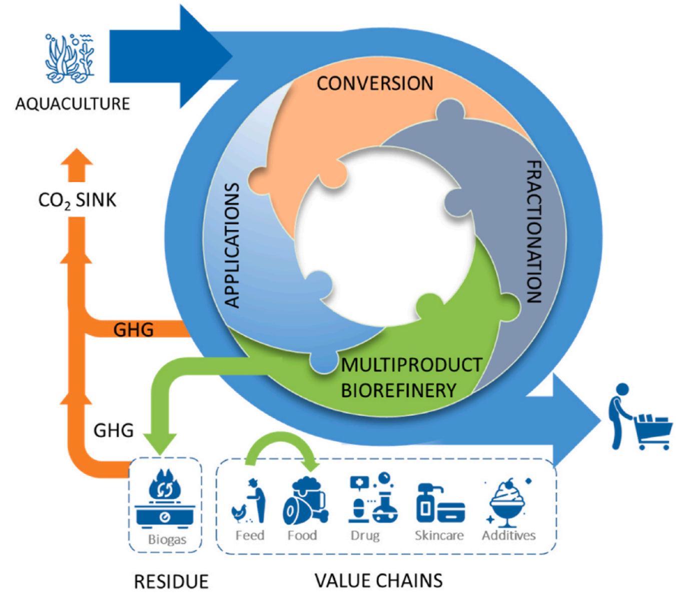

Fig. 2. Zero waste approach for Biorefineries'.

8–10 % ahead of further fractionation. From a cost perspective, it is preferable to avoid processing such as intensive drying, which is expensive to run, especially when drying large volumes of biomass that has a very high moisture content (>70 %), such as macroalgal and duckweed biomass. However, the application of alternative novel drying techniques, such as microwave-assisted and ultrasound-assisted drying, can improve drying efficiencies and product quality. Alternatively, establishing bio-refineries from fresh biomass will limit the degradation of valuable unstable bioactive compounds such as polyphenols; however, this puts a strain on the producer, as transporting fresh biomass is logistically challenging, expensive and inefficient. In an ideal situation, the bio-refinery processing plant would be located close to the biomass production site, as is the vision for the IMTA system.

One of the key bottlenecks of bio-refinery has been the separation of some fractions without wasting other fractions through simple, cost-effective and scalable processes with low-energy requirements [21]. Hence, key steps in establishing a zero-waste bio-refinery for the Mount Lucas site can be adapted from IEA Bioenergy (https://www.ieabioenergyreview.org/) (Table 1). Novel extraction and processing technologies play an important role in establishing energy-efficient bio-refineries by reducing dependencies on solvents and improving extraction efficiencies while preserving desired functional properties. The application of a range of new technologies for valorisation of biomass has been reviewed extensively [22]. Table 2 outlines the key features of novel technologies for the extraction of compounds of interest. One of the best strategies for improving extraction efficiencies is to develop a combination of sequential extraction technologies to maximise the synergies [23]. Such sequential extraction of ingredients (proteins, fibres and bioactives) has been established for macroalgae [24]. The zero-waste potential of macroalgal bio-refinery has been realised in the production of several products for food and pharmaceutical applications [25], and the potential to integrate advances in bio-refinery technologies with a commercially viable business has been highlighted [26].

6. From innovation to sustainable business ideas

The pilot IMTA demonstrator site will facilitate industry and entrepreneurs to develop and test innovations and ideas matching business canvas model. Environmental sustainability (including risks, threats and bottlenecks) of new products and value chains, demonstrated on-site, will be determined using life cycle assessment (LCA). Appropriate LCA

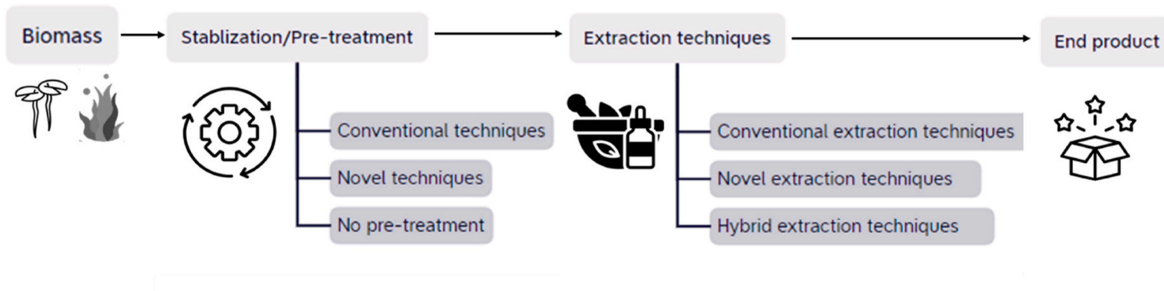

Fig. 3. Valorisation of biomass.

Table 1
Key steps for developing energy efficient zero waste biorefineries.

1	Determining chemical composition and physicochemical properties of target biomass (e.g., macroalgae, duckweed)
2	Define the target bio-products and physicochemical properties required for potential applications (e.g., agri-food, nutraceuticals, energy)
3	Develop an inventory of technologies or any interventions required to produce targeted bio-products (*e.g.*, pre-treatments, processing technologies, solvents)
4	Inventory of input materials (*e.g.*, solvents, energy, biomass)
5	Data collection for each unit operation (*e.g.*, conversion, fractionation, processing
6	Determine the chemical compounds to be transformed via pre-treatment/processes (e.g., side streams generated)
7	Carry out cost-benefit analysis (LCA/LCCA) to meet targets (*e.g.*, economic, environmental and social indicators)

Table 2
Comparison of selected extraction techniques.

	Hydrodynamic Cavitation	Ultrasound cavitation	Microwave	Pulsed electric field	High pressure processing	Enzymatic processes	Chemical processes
Scalability	Medium	Low	Medium	Medium	High	Low	Medium
Operating cost	Medium	Medium	Medium	Medium	High	High	Low
Efficiency	High	Medium	Medium	Medium	High	Medium	Medium
Energy requirement	Low	Low	Medium	Medium	High	Low	Low
Residue					Particulates	Enzymatic residue	Chemical residue
Harsh condition			High temperature		High pressure		
Selectivity	Low	Low	Low	High	Low	High	High

and life-cycle costing analysis (LLCA) will be conducted for value chains across the IMTA, supporting optimal engagement with stakeholders/beneficiaries with a commercial market orientation [27]. Ecological and ecotoxicological assessments that also embrace the impact of weather variance and climate change will be conducted in accordance with the methods of O'Neill et al. [28]. A go-to-market strategy will assist the transition from pilot ideas to market-ready innovations using appropriate business analysis and modelling tools (e.g., SWOT, PESTELE, PM-CANVAS). Innovation studies thus far at this IMTA site (such as aquaculture and protein harvesting from duckweed) [8,18,28,29] have implemented proven methodologies such as the 'innovation sweet-spot' i.e., the optimal intersection at which feasibility (what is technically possible), viability (what can be sustainable for a business) and desirability (what users or customers need and want) converge, leading to successful and impactful innovations [30].

7. Summary

The development of a fully monitored and characterised IMTA site in the peatland at Mount Lucas presents a timely opportunity to demonstrate high-value bio-based products at scale. This peatland recirculatory site will be informed by an integrated multi-actor stakeholder approach that will help identify and overcome technical and economic challenges for viable new products and services that embrace appropriate change of land use. The value stream generated from the fish culture waste stream presents many exciting business opportunities that will be balanced by conducting an appropriate environmental LCA. Fish production (freshwater aquaculture) in the rewetted peatland is an important activity for food security. However, an on-site hatchery and mesocosm are needed to increase nutrients in the waste stream so that sufficient amounts of biomass are produced for duckweed and macroalgae bio-refinery activities, leading to high-value products and services. This IMTA model provides an open-access site for supporting companies in the testing and development of new green products. Additionally, financial constraints in terms of access to specialist equipment and technical expertise are off-set. This IMTA site will operate at the critical interface between top-down government policies (and strategies) for informing effective bioeconomy activities to meet end-user/beneficiary needs and addressing a fair and JT for communities pivoting to low-carbon economies. Current and future outputs from this IMTA site will help address and inform several Unite Nations Sustainable Development Goals (UNSDGs) including; No Poverty (SDG 1), Zero Hunger (SDG 2), Good Health and Wellbeing (SDG 3), Responsible Consumption and Production (SDG 12), and Life Below Water (SDG 14).

CRediT authorship contribution statement

Neil J. Rowan: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Conceptualization. **Antoine Fort:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Emer A. O'Neill:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Eoghan Clifford:** Writing – review & editing, Writing – original draft, Methodology. **Marcel Jansen:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Markus Helfert:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition. **Damien Toner:** Writing – review & editing, Writing – original draft, Methodology. **Julie Maguire:** Writing – review & editing, Writing – original draft, Methodology. **Brijesh Tiwari:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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