Chapter

Perspective Chapter: Development of IMTA-Based Bioeconomy Sites in Peatlands; Green Innovation That Promotes Zero-Waste, Zero-Pollution and Climate-Action Principles

Emer A. O'Neill, Marcel A.K. Jansen, Brijesh K. Tiwari,
Antoine Fort, Eoghan Clifford, Julie A. Maguire
and Neil J. Rowan

Abstract

Rewetted peatlands represent emerging environments that combine carbon storage with green innovation supporting rural regeneration and community transitioning to low-carbon economies. This chapter describes the establishment of innovative integrated multi-trophic aquaculture (IMTA) sites in peatlands areas as new bioeconomy demonstrators for viable green innovation that can be replicated globally for strategic sustainable change-of-land-use. Fish aquaculture waste is used by microalgae and duckweed to produce high-value proteins and other added-value ingredients that can be biorefined on-site for human and animal feeds. These peatland-based demonstration sites use organic, zero-pollution, zero-waste and climate-friendly principles. They operate at the vital interface between bottom-up end-user stakeholders and top-down strategic regreening policies. These IMTA bioeconomy peatlands can be digitally transformed for real-time performance monitoring, product development and supply-chain management, and security. The outcome of this novel peatland demonstration site aligns and will contribute to achieving many of the United Nation's Sustainable Development Goals.

Keywords: digital transformation, bioeconomy demonstration, green deal innovation, sustainable and circular innovation, change of land use, policies

1. Introduction

Peatlands are water-saturated ecosystems distinguished by the build-up of partially decomposed organic material, known as peat. Occupying approximately 3% of the

Earth's land surface, they are primarily located in northern Europe, North America, and Southeast Asia [1–3]. Ecologically significant, peatlands store vast amounts of carbon, estimated at twice that of all the world's forests combined, thus playing a contributory role in climate regulation. They support unique biodiversity, provide important water regulation services and serve as critical habitats for various species [3]. However, peatlands are vulnerable to degradation from drainage, agriculture and climate change, necessitating sustainable management practises [4]. Sustainable land use in peatlands is vital to preserve their ecological functions and mitigate climate change. Conventional peatland use, such as drainage for agriculture and forestry, leads to significant carbon emissions, biodiversity loss, and disruption of natural water regulation. Thus, drainage has contributed to environmental degradation and undermined ecosystem services [1]. Green innovation is essential to address this challenge by promoting practises that restore ecological health, but in a manner that is balanced with community resilience [5, 6]. This includes adopting technologies and methods that reverse the environmental impacts of drainage, enhance carbon sequestration, and support biodiversity, thus ensuring the long-term sustainability and resilience of peatland ecosystems [7]. These activities also create prospects for local communities to transition to low-carbon economies and promote rural revitalisation.

Integrated Multi-Trophic Aquaculture (IMTA) is a cutting-edge approach to aquaculture that involves cultivating species from different trophic levels together in a single system (**Figure 1**). By incorporating species like fish and aquatic plants, IMTA establishes a balanced ecosystem where the waste from one species provides nutrients for another [8]. Principles of IMTA include nutrient recycling, enhanced biodiversity, and ecological balance. Benefits include increased productivity, reduced environmental impact, and improved water quality. This innovative, sustainable method supports higher yields and greater economic returns whilst promoting environmental health and resilience in aquaculture systems [9]. This chapter describes the development of a novel IMTA site in peatlands (**Figure 2**) as a bioeconomy demonstration for viable green innovation that can be replicated globally for strategic change-of-land-use.

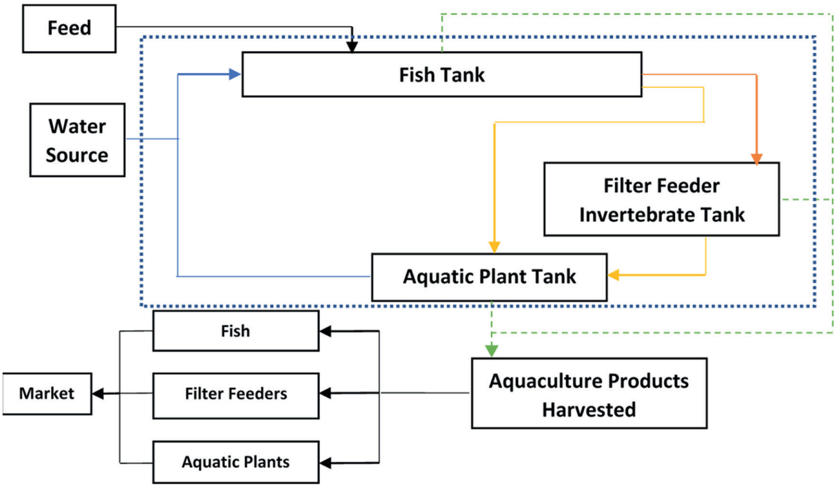

Figure 1.
Schematic of an integrated multi-trophic aquaculture system. Blue arrows indicate the flow of clean water. Orange arrows indicated the flow of water containing particulate organic carbon from fish faecal matter and uneaten feed. Yellow arrows indicate the flow of water containing inorganic nitrogen and phosphorus from fish excretion. Green lines indicate all harvesting processes.

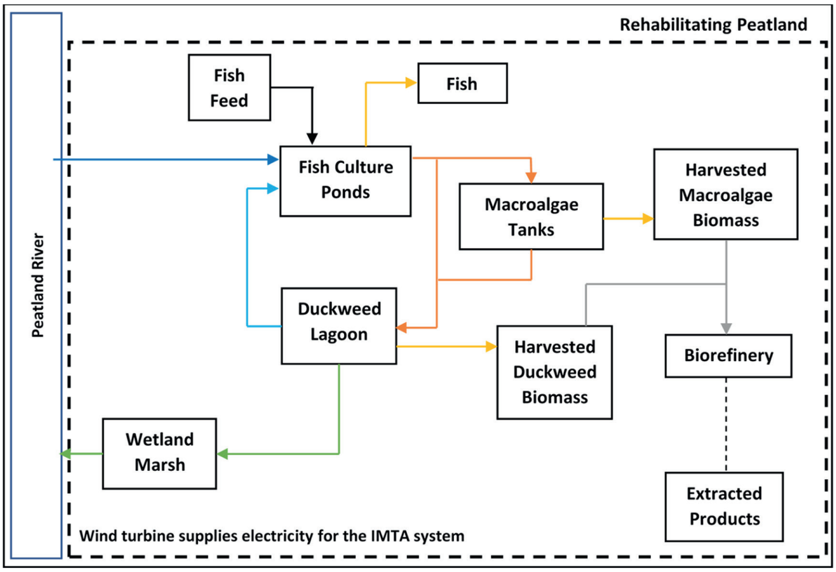

Figure 2.
Schematic of a peatland based integrated multi-trophic aquaculture system (Mount Lucas IMTA system). Dark blue line indicates water intake from adjacent peatland river into system (which only occurs periodically, to compensate for evaporation). Orange line indicates water rich in particulate organic carbon and inorganic nitrogen and phosphorus from fish faeces and uneaten food. Light blue line indicates water returning to fish culture ponds after nutrient removal via macroalgae and duckweed. Yellow line indicates harvesting processes. Grey lines indicate the biorefinery/valorisation process where products are extracted from the duckweed and macroalgae. Green line indicates overflow point in the duckweed lagoon (overflow only occurs during times of excessive rainfall), where water flows into the adjacent wetland marsh before entering back into the peatland river, upstream of the intake point. A wind turbine within the wind farm (number 19), supplies electrical needs for the farm (paddle wheels, airlifts, automatic feeders, etc.*).*

2. Peatlands and the bioeconomy

2.1 Peatlands: Current status and challenges

Peatlands are crucial ecosystems with significant ecological and environmental value. They are vital carbon sinks, storing approximately 550 gigatons of carbon globally, which is more than stored by all the world's forests combined [1, 9–11]. This makes peatlands essential for mitigating climate change by capturing and storing carbon dioxide from the atmosphere. Peatlands also support a rich biodiversity, hosting a range of unique animal and plant species often specifically adapted to these wetland environments [12–14]. Additionally, peatlands are vital for water regulation. They function as natural sponges, absorbing and storing water, which helps reduce flooding and maintain water quality by filtering out pollutants. This water regulation capacity is particularly important in regions susceptible to extreme weather events [2, 3, 15, 16]. Additionally, peatlands contribute to the preservation of archaeological and paleoenvironmental records due to their anoxic conditions, which slow down decomposition [12]. However, despite their importance, peatlands are under threat from drainage, peat extraction, and climate change, highlighting the need for their protection and sustainable management.

For a long time, peatlands have been experiencing significant degradation and land use changes due to human activities. One of the primary threats is drainage for agriculture and forestry, which involves removing water to convert peatlands into arable farming land or timber plantations [2, 17, 18]. This drainage leads to the oxidation of stored peat, releasing carbon dioxide and methane into the atmosphere and contributing to climate change [10, 12]. Nitric oxide emissions are also significant from drained peatlands. Agricultural practises, such as intensive farming and fertiliser use, contribute to the deterioration of these ecosystems by altering their water systems and introducing pollutants [19, 20]. Forestry operations, particularly the planting of non-native tree species, can disrupt the natural water balance and nutrient cycles in peatlands [17, 21]. In addition to these direct impacts, peat extraction for horticultural uses and energy production exacerbates the degradation caused by drainage [22]. The combined effect of these pressures presents significant challenges for conservation, requiring integrated approaches to restore and sustainably manage peatland ecosystems.

Peatlands are relevant for climate regulation due to their ability to sequester and store carbon. However, they are extremely susceptible to climate change [23]. Increased temperatures and changing precipitation patterns can contribute to peatlands drying out, making them susceptible to increased decomposition and subsequent carbon dioxide emission with a reduction in methane emission. This not only diminishes the role of peatlands as carbon sinks but also contributes to a positive feedback loop, exacerbating global warming [3, 4, 10]. Climate change also heightens the risk of peatland fires, which release significant amounts of stored carbon into the atmosphere [3, 15, 24]. Moreover, changing climate conditions can affect the hydrology of peatlands disrupting the delicate hydrological balance required for their maintenance, leading to further degradation [25]. The challenges of preserving peatlands in the face of climate change are considerable. Effective strategies must include protecting existing peatlands from drainage and degradation, restoring degraded peatlands, and implementing sustainable land management practises that enhance their resilience to climate impacts [7, 16]. These are complex issues that require a holistic approach to understanding interactions that will inform impact and solutions for sustainable change. Such approaches can be informed by use of Quintuple Helix Hub that combines academics, policy-makers, industry, regulators and society to inform innovations and policies for change of land use [26]. There is also a dearth of information surrounding the integrated use of Quintuple Helix hubs to model extreme variances in climate change on desirable bioeconomy demonstration site performance and its resilience, which includes sustainable food production and implementing appropriate risk mitigation [26].

2.2 Bioeconomy and green innovation

The bioeconomy involves using biological resources, processes and concepts to sustainably produce goods and services across various economic sectors. At its core, the bioeconomy integrates economic, environmental, and social elements to create a balanced and sustainable system [27, 28]. Economically, it aims to boost growth and create jobs by developing innovative biotechnologies, bio-based products, and bioenergy [16, 26]. Environmentally, the bioeconomy promotes sustainable resource use, reducing fossil fuels dependence, minimising waste, and lowering greenhouse gas (GHG) emissions; thus, contributing to climate action and environmental conservation [26, 29–31]. Socially, the bioeconomy enhances quality of life by promoting healthier ecosystems, nurturing rural development, and ensuring food security through sustainable agricultural practises. Amongst its key principles, bioeconomy includes circular economy approaches, where resources are reused and recycled, and the integration of biodiversity conservation into production processes [7, 26]. By aligning these elements, the bioeconomy supports the just transition to a more sustainable, resilient and inclusive global economy, addressing pressing environmental challenges whilst developing economic and social well-being.

Green innovation strategies are essential for achieving sustainable development goals, focusing on minimising environmental impacts whilst promoting economic and social benefits [26, 32–34]. Central to these strategies are the principles of minimal to aspirations of zero waste and pollution, and climate action [5, 7, 35, 36]. The zero-waste principle emphasises designing production processes and products to eliminate waste, promoting reuse, recycling, and circular economy practises to maximise resource efficiency [37]. Zero-pollution strategies aim to prevent harmful emissions and discharges into air, water and soil by adopting clean technologies, renewable energy sources and eco-friendly materials [38]. These approaches help in maintaining ecosystem health and protecting public health [39]. Climate action principles are integral to green innovation, focusing on reducing GHG emissions, enhancing carbon sequestration, and increasing resilience to climate impacts. This includes the development and distribution of low-carbon technologies, sustainable land-use practises and energy efficiency measures [7, 26, 40, 41]. Together, these strategies foster a sustainable future, addressing urgent environmental challenges whilst supporting economic growth and societal well-being. It is important to understand regional strengths, weaknesses, opportunities and threats for informing key drivers, needs and solutions, such as the use of transnational modelling and risk mitigation [7]. Such concepts are typically supported through inter-regional enterprise and innovation research projects with multiple-actors where shortcomings in some regions can be unlocked through positive experiences gleaned from adjacent regions that delivered on successful green products and solutions [26].

The bioeconomy and green innovation are highly relevant to peatlands, offering sustainable practises and technologies that can transform their management and use [5]. By adopting bioeconomy principles, peatland management can shift towards sustainable resource utilisation, promoting biotechnologies that enhance peatland conservation and restoration [7]. Green innovation introduces zero-waste and zero-pollution approaches, essential for maintaining peatland health [6]. Sustainable practises, such as rewetting and the use of paludiculture (wet agriculture), help restore natural hydrology and carbon sequestration capacity [42, 43]. Technologies like integrated multitrophic aquaculture (IMTA) can also be adapted for peatlands, promoting biodiversity and economic viability simultaneously [7]. Overall, the bioeconomy and green innovation provide pathways for balancing ecological integrity with economic development in peatlands, ensuring these vital ecosystems contribute to climate action and sustainable development goals.

3. Integrated multi-trophic aquaculture

Integrated Multi-Trophic Aquaculture (IMTA) is an innovative approach that combines different species from various trophic levels in one aquaculture system [15, 44–46]. By integrating species such as fish, shellfish and aquatic plants, IMTA leverages their natural relationships to enhance sustainability and productivity [44, 47]. The primary mechanism involves nutrient recycling: waste from higher trophic species (e.g., fish) becomes a resource for lower trophic species (e.g., primary producers and shellfish). Fish excrete nitrogenous wastes, which are absorbed by primary producers, reducing nutrient loads and preventing eutrophication [45]. Shellfish filter and clean the water by feeding on suspended particles and plankton [44, 47]. This creates a balanced, synergistic environment where each species contributes to the health of the system, leading to improved water quality, reduced environmental impact, and increased overall yield [8]. IMTA promotes a more sustainable and resilient aquaculture model by mimicking natural ecosystems' nutrient flows and interspecies relationships.

IMTA relies on careful selection of species, strategic design, and effective management to create a balanced ecosystem. Species are chosen based on their ecological roles and compatibility, typically including fed species like fish, extractive species such as shellfish, and photosynthetic organisms like macro algae [44, 48]. This selection ensures efficient nutrient recycling and minimal environmental impact [48, 49]. The design of an IMTA system involves spatial arrangement to optimise interactions amongst species [48]. Fin fish farms are designed to allow waste to disperse towards shellfish beds and algal growth areas. Proper water flow is crucial to facilitate nutrient exchange and maintain optimal growth conditions for all species [44, 48, 49]. Management practises focus on monitoring water quality, species health, and growth rates, ensuring that each component functions effectively. Regular assessments and adjustments are necessary to maintain balance, prevent disease and enhance productivity [48]. Through meticulous design and proactive management, IMTA systems can achieve sustainable and efficient aquaculture.

IMTA offers significant environmental and economic benefits. Environmentally, IMTA enhances productivity by utilising different species to recycle waste nutrients into value added compounds, reducing the need for external inputs. Waste from fish is absorbed by primary producer species and shellfish, which act as natural biofilters, improving water quality and mitigating eutrophication. This waste reduction minimises the environmental footprint of aquaculture operations [50, 51]. Economically, IMTA increases profitability by diversifying products, spreading risk, and enhancing resilience. Farmers can harvest multiple species e.g., fish and aquatic plants, providing a steady income stream and reducing dependence on a single market [5, 6, 52]. The improved water quality and balanced ecosystem also lead to healthier stock and lower disease rates, further boosting productivity and reducing costs [50]. Additionally, IMTA provides valuable ecosystem services, such as habitat creation and informs carbon sequestration, contributing to biodiversity and climate regulation [8, 53]. Overall, IMTA represents a sustainable and profitable approach, aligning economic growth with environmental stewardship.

3.1 IMTA in peatlands: A novel approach

IMTA in peatlands (**Figure 2**) offers a sustainable solution to land use conflicts and enhances ecosystem services [7]. By combining different aquaculture species that occupy various trophic levels, IMTA maximises resource efficiency and minimises waste [16]. In peatlands, this method can mitigate conflicts between agricultural use and conservation efforts by providing an alternative, low-impact livelihood. Additionally, IMTA will potentially help restore degraded peatlands to their natural state, maintaining their crucial role in carbon sequestration and water regulation [7, 16, 26]. The diversity of species in IMTA systems promotes ecological balance, reducing the need for chemical inputs and enhancing biodiversity. By leveraging the natural filtration capabilities of certain aquaculture species, water quality is improved, benefiting the broader ecosystem [5, 7, 54]. Consequently, IMTA in peatlands not only addresses economic and environmental challenges but also supports sustainable development and conservation goals [6, 15, 16].

Suitable peatland sites should exhibit stable hydrology, appropriate pH levels, and minimal pollution to support diverse aquaculture species [7]. It's crucial to assess water availability and quality, ensuring the site can sustain the species involved [15, 45]. Proximity to markets and infrastructure is also vital for economic viability [6, 7, 26]. In designing IMTA systems, spatial planning must optimise the integration of different trophic levels. This involves strategically placing species that can benefit from each other's presence, such as filter feeders near fish to utilise waste nutrients. Ponds and water channels should be constructed to maintain natural water flow and minimise habitat disruption. Additionally, incorporating native plant species can enhance habitat complexity and stability [55–57]. By aligning design with natural processes, IMTA systems in peatlands can enhance productivity, ecological health and sustainability.

IMTA into peatlands requires harmonising it with existing land uses like agriculture, forestry and conservation. IMTA can coexist with agriculture by utilising water resources efficiently and providing aquaculture products that complement agricultural yields [7]. In forestry, IMTA can be integrated by using forested peatland areas for aquaculture, which can help maintain the natural hydrology and biodiversity of the forest. This integration can also promote agroforestry practises, where trees provide shade and habitat for aquaculture species, whilst aquaculture enhances soil and water quality [8]. For conservation, IMTA supports the preservation of peatland ecosystems by reducing the need for more destructive land uses [44, 58]. By maintaining the natural structure and function of peatlands, IMTA helps protect their role in carbon sequestration, biodiversity, and water regulation, ensuring a balanced and sustainable landscape [7, 16].

3.2 Environmental and socio-economic impacts

IMTA in peatlands offers significant ecological benefits. It enhances biodiversity by creating diverse habitats for various species, supporting both aquatic and terrestrial life [8, 48]. This diversity strengthens ecosystem resilience and stability [8, 44, 47, 48, 50]. IMTA improves water quality through the filtration capabilities of organisms like bivalves and algae and plants which can absorb excess nutrients and pollutants, thus reducing eutrophication and promoting clearer, healthier water bodies [59]. Additionally, peatlands are known for their high carbon sequestration capacity and incorporating IMTA can further enhance this function. The cultivation of plants and algae in IMTA systems absorbs CO_2, whilst the overall health of the peatland ecosystem, supported by increased biodiversity and cleaner water, enhances efficient long-term carbon storage [7, 16]. Thus, IMTA in peatlands serves as a holistic approach to ecological conservation, leveraging natural processes to maintain and enhance these critical environments.

IMTA in peatlands also presents significant economic opportunities. It fosters job creation in both direct aquaculture activities and related sectors such as processing, distribution and research. This diversified employment can stabilise local economies especially in rural areas [8, 51, 52, 60, 61]. IMTA systems produce value-added products including high-quality fish, shellfish, and plant and algal biomass which can be marketed for culinary, pharmaceutical and cosmetic uses. These products command premium prices due to their sustainable production methods, enhancing profitability for producers [7, 26]. Furthermore, IMTA supports sustainable livelihoods by promoting practises that are environmentally responsible and economically viable in the long term [15]. By reducing reliance on single-species aquaculture, IMTA minimises risks associated with market fluctuations and environmental impacts, providing a stable income source [44, 50, 52, 61]. Thus, IMTA in peatlands integrates ecological sustainability with economic resilience, offering a pathway for communities to thrive whilst conserving vital ecosystems.

Community involvement is central to supporting and ensuring IMTA success as local participation ensures the alignment of aquaculture practises with regional needs and values. This is also particularly relevant for European Just Transition Territories where communities are transitioning to low carbon economies [62, 63]. Engaging these communities fosters a sense of ownership and stewardship over natural resources, enhancing cooperative management and resilience [7, 16]. Cultural acceptance is pivotal; IMTA must be tailored to fit local traditions and practises, which can increase its adoption and sustainability e.g., IMTA provides an alternative to turf cutting. This cultural integration often leads to the preservation and revitalisation of traditional knowledge and practises, enriching community identity [7, 26]. Educational outreach is another key aspect, as IMTA projects provide learning opportunities about sustainable practises and environmental safekeeping. Workshops, school programmes and public demonstrations can raise awareness and knowledge, promoting a generation of environmentally conscious citizens [7, 8, 64]. Thus, IMTA in peatlands not only supports ecological and economic goals but also strengthens social cohesion and cultural heritage, ensuring a holistic approach to sustainability. It is apparent that key needs and policies will be supported and enabled by appropriate digital transformation strategies [5, 54]. The appropriate digitisation of data from peatlands that leads to new products and services will help in understanding end-to-end supply chain and process for improvements in efficiency and performance of IMTA system, similar to what has been experienced under Industry 4.0 in agriculture [5].

3.3 Policy and governance framework

Regulatory requirements for IMTA and the bioeconomy are shaped by national and international policies promoting sustainable and efficient resource use including safety. National policies often provide guidelines on environmental impact assessments, licencing and operational standards to ensure IMTA practises minimise ecological footprints and enhance biodiversity [7, 16]. Countries like Canada and Norway have developed specific frameworks supporting IMTA within their broader aquaculture regulations [65, 66]. Internationally, the United Nations' Sustainable Development Goals (UNSDGs), particularly UNSDG 14 (Life Below Water), encourage sustainable aquaculture practises [6]. The European Union's (EU) Blue Growth strategy also supports IMTA by integrating marine resource efficiency into its policy agenda [67]. Additionally, the Food and Agriculture Organisation (FAO) provides global guidelines and best practises for IMTA and bioeconomy initiatives [68, 69]. These policies collectively aim to foster innovation, sustainability, and economic growth within the aquaculture sector, emphasising the importance of cross-border collaboration and adherence to environmental standards.

Incentives and funding for IMTA and the bioeconomy are crucial for fostering innovation and sustainability. Governments and international bodies offer grants, subsidies and investment opportunities to promote this sector. For instance, the EU Horizon Europe programme allocates substantial funding for research and innovation in sustainable aquaculture and the bioeconomy [70]. National governments, such as those in Canada and Norway, provide subsidies and tax incentives to encourage the adoption of IMTA practises amongst local aquaculture businesses [71, 72]. Private investment is also significant, with venture capitalists and impact investors increasingly focusing on sustainable and profitable aquaculture ventures [73]. Additionally, international organisations like the World Bank and the FAO offer financial and technical support to developing countries for bioeconomy projects [74, 75]. These incentives and funding mechanisms aim to reduce financial risks, drive technological advancements, and enhance economic viability, making IMTA and the bioeconomy attractive and sustainable sectors for investment.

Stakeholder engagement is vital for advancing IMTA and the bioeconomy, ensuring sustainable and inclusive growth. Governments play a central role by setting regulatory frameworks, providing funding, and facilitating research and development initiatives. They also create policies that balance economic interests with environmental protection, fostering a favourable environment for IMTA practises [7, 16]. The private sector drives innovation and investment, developing and scaling technologies and practises that enhance efficiency and sustainability. Companies often collaborate with research institutions to pioneer new methods and products, contributing to the bioeconomy's growth [6, 7]. Additionally, Non-Governmental Organisations (NGOs) are crucial advocates, promoting sustainable practises and increasing understanding of the environmental and social advantages of IMTA. They often act as intermediaries, facilitating dialogue between various stakeholders and ensuring community interests are represented [7]. Finally, local communities are integral to successful implementation, as their involvement ensures that practises are culturally appropriate and beneficial to local economies. Their traditional knowledge and their acceptance and buy-in are key to the long-term sustainability of IMTA projects [6, 7, 16]. Collaborative efforts amongst these stakeholders drive the successful integration and expansion of IMTA and the bioeconomy.

3.4 IMTA best practises

IMTA in peatlands leverages the interaction between different species to enhance productivity and sustainability. Successful examples of IMTA can be found across the globe. In the United Kingdom aquaculture incorporates fish farming with reed bed filtration systems, improving water quality and habitat diversity [76]. In Southeast Asia, especially in Indonesia, IMTA integrates shrimp farming with mangrove restoration, reducing erosion and enhancing carbon sequestration [77, 78]. In Canada's Atlantic region, IMTA combines salmon farming with mussel and seaweed cultivation, leading to nutrient recycling and reduced environmental impact [79]. These successful implementations demonstrate how IMTA can be adapted to varied regional contexts, promoting ecological balance, economic viability and environmental stewardship in ecosystems [7]. The adaptability of IMTA to diverse geographical and ecological conditions underscores its potential as a global sustainable aquaculture practise.

Development of IMTA in peatlands has offered valuable lessons in balancing ecological and economic goals. Identified success factors include understanding of local ecological dynamics, ensuring species compatibility and engagement with community stakeholders [7, 8]. Effective water management and monitoring systems are crucial for maintaining water quality and peatland health. Challenges often arise from the complex hydrology of peatlands, potential conflicts between conservation and commercial interests, and the initial costs of setup and research [7, 16, 80, 81]. Adaptive strategies are essential to overcome these challenges. Flexibility in management practises allows for adjustments based on monitoring data and environmental changes. Community involvement ensures that IMTA systems are locally appropriate and supported, fostering stewardship and long-term success. Integration with conservation efforts can enhance ecosystem services such as the capture and storage of carbon, as well as biodiversity [6, 7, 16, 26]. Continuous research and adaptive management are critical to address evolving challenges, optimise productivity and ensure the sustainability of IMTA in peatlands.

Innovative technologies are pivotal for advancing IMTA in peatlands. Biotechnology plays a significant role by enhancing species' resilience and optimising nutrient cycles. For example; breeding/genetic selection can develop fish and plant species better suited to the unique conditions of peatlands [46]. Advanced monitoring systems including; remote sensing and Internet of Things (IoT) sensors which offer real-time inforamtion on water quality, temperature and species health, enable precise and timely management decisions [5]. Digital tools, such as AI-driven analytics and predictive modelling facilitate the optimisation of aquaculture operations by predicting environmental changes and optimising resource use, water flow or nutrient cycling. These technologies can integrate diverse data sources, offering holistic insights into ecosystem health and productivity [5, 7, 54]. Automated feeding systems and drones for monitoring and maintenance further increase efficiency and reduce labour costs [7, 57]. Together, these innovations enhance the sustainability and productivity of IMTA in peatlands, ensuring ecological balance and economic viability.

3.5 Case study: Peatland based IMTA bioeconomy demonstration site

Mount Lucas, located in the midlands of Ireland, is an exemplary site for peatland-based Integrated IMTA, illustrating innovative practises within the bioeconomy [7, 16]. This 5.4 ha. site, originally a peat extraction area, has been repurposed to support sustainable aquaculture (following organic principles), emphasising the multifaceted benefits of IMTA systems in degraded or non-traditional landscapes. A nearby wind turbine contributes to electricity generation and site usage. Water is infrequently introduced to the site (only to offset evaporation) or discharged from it (only during periods of heavy rainfall) [15, 45, 55–57]. The core principle of IMTA at Mount Lucas involves cultivating species from different trophic levels in an interconnected system [6, 15, 16, 45, 46, 82]. This approach not only maximises resource utilisation but also enhances environmental sustainability [15]. The peatland's natural features provide an excellent environment for such integration. The aquaculture system at Mount Lucas includes the farming of rainbow trout (*Oncorhynchus mykis*), brown trout (*Salmo trutta*) and European perch (*Perca fluviatilis*), alongside common duckweed (*Lemna minor*), gibbous duckweed (*Lemna gibba*) and multiple species of macro and microalgae, which contribute to nutrient recycling and water purification [6, 15, 45, 46, 55–57]. The aquatic plants are subsequently used for the generation of protein rich biomass used to produce multiple products such as food and feeds supplements, as well as biofuels using a biorefinery approach [7, 16, 55–57, 82]. The site also provides an opportunity to utilise smart digital technologies to evaluate the effectiveness of peatland-based products and services, supporting a fair and just transition from peat extraction to a low-carbon economy [5, 7, 54].

The transformation of Mount Lucas highlights the significant potential of peatlands in contributing to the bioeconomy [16]. This strongly aligns with G20 initiative on bioeconomy that seeks to promote sustainable development by integrating science, technology and innovation including the simultaneous preservation of biodiversity.

However, the existence of tangible bioeconomy demonstrators are lacking across Europe and internationally. Traditionally, peatlands were exploited for peat extraction in Ireland, leading to ecological degradation [45]. However, their rehabilitation through IMTA practises demonstrates a shift towards more sustainable land use [7]. The aquaculture activities at Mount Lucas help restore the ecological balance of the peatland, improving water quality and fostering biodiversity. Moreover, the site will contribute to the local economy by creating jobs and providing locally sourced products, which aligns with broader bioeconomic goals [6, 16, 26]. The integration of aquaculture in peatlands exemplifies how degraded lands can be converted into productive landscapes, offering ecological, economic, and social benefits. Additionally, research and monitoring at Mount Lucas further support the development of best practises for peatland aquaculture. Studies focus on optimising species combinations, water management and overall system efficiency [15, 57, 82]. The knowledge gained here can be transferred to similar environments globally, promoting the widespread adoption of IMTA in peatlands. Ultimately, the Mount Lucas peatland-based aquaculture site in Ireland serves as a model of how IMTA can be leveraged within the bioeconomy. By transforming a degraded peatland into a thriving aquaculture system, it showcases the potential for sustainable and innovative resource use, aligning environmental restoration with economic development [7, 16, 26].

4. Future directions and research needs

Future promising research on peatland IMTA and the bioeconomy is innovative and promising, especially through integration of genomic, ecosystem modelling and climate adaptation strategies. Genomic technologies can enhance the productivity and resilience of peatland species by identifying traits for improved growth, disease resistance and environmental tolerance [46]. Ecosystem modelling will integrate biological, chemical and physical data to optimise IMTA systems, ensuring sustainable resource use and minimal environmental impact [45, 55–57]. Additionally, climate adaptation strategies are critical, focusing on resilient species and practises that mitigate climate change effects and water management [15]. These approaches will be informed by appropriate use of transregional and national modelling including inclusion of digital technologies to help understand and appreciate compounding factors such as the impact of extreme weather events, climate change and unexpected occurrences [5, 7, 54]. These interdisciplinary approaches will drive the development of sustainable bioeconomy practises, harnessing peatland ecosystems' potential for economic and environmental benefits. By leveraging genomics, advanced modelling and adaptive management, future research will support resilient, productive, scalable and sustainable peatland IMTA systems. Such innovation will also be informed by delivering on appropriate bespoke training and stakeholder workshops at unique IMTA peatland bioeconomy sites in Ireland that can be subsequently replicated internationally in peatlands sites for change of land use.

Scaling up peatland IMTA for the bioeconomy requires strategic pathways for broader adoption and replication in other peatland regions. First, developing standardised guidelines and best practises tailored to diverse peatland ecosystems will ensure consistency and efficiency [6, 7, 16]. Collaboration between academia, industry, stakeholders, local communities, policy makers and government can facilitate knowledge transfer and resource sharing. Additionally, leveraging public and private funding opportunities can support pilot projects and infrastructure development [7, 26].

Establishing demonstration sites will showcase successful models, encouraging adoption by illustrating economic and environmental benefits. Integrating local communities through participatory approaches ensures culturally appropriate and sustainable practises. Advanced training programmes will equip stakeholders with necessary skills and knowledge [6, 7, 26]. Furthermore, incorporating digital technologies for monitoring and management enhances system efficiency and scalability [5, 7, 54]. By engaging with these opportunities, peatland IMTA can expand globally, promoting a sustainable bioeconomy that harnesses the full potential of peatland ecosystems whilst ensuring their conservation and resilience.

Future monitoring and evaluation of peatland IMTA for the Bioeconomy will rely on advanced tools to assess environmental and socio-economic impacts comprehensively. Remote sensing technologies, such as satellite imagery and drone footage, will deliver real-time information on land use changes, water quality and vegetation health, enabling efficient environmental monitoring [5, 7, 54] . Geographic Information Systems (GIS) will enable spatial analysis and visualisation of data, supporting informed decision-making [7, 83]. Environmental DNA (eDNA) sampling will offer insights into biodiversity and ecosystem health with minimal disturbance [84–86]. For socio-economic impacts, participatory tools like community surveys and stakeholder interviews will capture local perceptions and economic benefits. Economic modelling can predict long-term viability and impacts on local economies [7, 87]. Integrating these tools into a unified monitoring framework will ensure a holistic understanding of peatland IMTA systems, guiding sustainable management practises and demonstrating their value to both ecosystems and communities.

5. Conclusion

IMTA in peatlands offers significant benefits and potential. IMTA involves cultivating a range of aquatic species from different trophic levels in a synergistic system, enhancing productivity and environmental sustainability. In peatlands, IMTA can improve water quality by utilising nutrient-rich waters from fish farming, which, in turn, supports the growth of plants and other organisms like shellfish and algae. This approach can reduce nutrient pollution and create diverse, resilient ecosystems [16]. Additionally, IMTA can provide economic benefits by diversifying income sources for local communities and enhancing food security [6, 7, 15]. The potential for carbon sequestration in peatlands also aligns with climate change mitigation goals [15]. However, careful management is essential to maintain peatland integrity and avoid negative impacts on these sensitive ecosystems [45]. Overall, IMTA in peatlands represents a promising strategy for sustainable aquaculture, environmental conservation, and socio-economic development.

The future vision of a peatland IMTA-based bioeconomy holds transformative potential for sustainable land use, enhancing ecological balance and economic viability. This transformation includes supporting and developing on site aquatech innovation encompassing testing of technologies, such as for example exploiting the natural water filtration and nutrient cycling capabilities of peatlands. IMTA can boost biodiversity and productivity, supporting a variety of species, including fish, shellfish, and aquatic plants. This not only mitigates nutrient pollution but also promotes carbon sequestration, contributing to climate change mitigation [16]. Basically, Mount Lucas is a particular case-study where it maybe water self-sufficient—however there are possibly other IMTA scenarios where water input and output might occur. The bioeconomy derived from peatland IMTA can diversify income streams for local communities, fostering sustainable livelihoods and food security. It encourages responsible resource management, ensuring the long-term health of peatland ecosystems. Innovations in biotechnology and aquaculture practises can further optimise these systems, enhancing efficiency and resilience [7]. Ultimately, peatland IMTA-based bioeconomy represents a sustainable land use strategy that aligns environmental conservation with economic development, laying the foundation for a more sustainable and robust future. There is a commensurate scope to develop and test a battery of appropriate organisms representative of different tropic levels in this aquatic (peatland) IMTA system so as of monitor and confirm sustainable preservation of biodiversity. These could also serve as dual indicators for impact of extreme variance of climate and weather on IMTA demo system [15] and to support generation of appropriate evidence-based data for future digital transformation.

To fully harness the potential of peatland-based IMTA for the bioeconomy, a concerted call to action is essential. Possibly achieved in part through the establishment of appropriate Quintuple Helix Hubs to unite regional actors and to provide access to specialist equipment, subject matter expertise and financing. Moreover, multidisciplinary research is crucial to understand and optimise the interactions within these complex ecosystems, ensuring sustainable and efficient practises. Scientists, ecologists, aquaculturists and economists must collaborate to develop innovative solutions that enhance productivity whilst preserving peatland health [26]. Policy support is equally vital. Governments and regulatory bodies should create frameworks that encourage sustainable IMTA practises, offering incentives and clear guidelines for implementation. Policies must balance economic development with ecological conservation, fostering an environment where sustainable aquaculture can thrive [7, 16]. Finally, community engagement is the cornerstone of this vision. Local communities, as primary stakeholders, need to be actively involved in planning and decision-making processes. Education and training programmes can empower them with the knowledge and skills required to manage IMTA systems effectively, ensuring long-term success [7]. Together, these efforts can drive a sustainable, resilient peatland-based bioeconomy.

Acknowledgements

The authors acknowledge funding support from Irelands' Department of Agriculture, Food and Marine (DAFM BioMDJT Scoping Study 2022–2024 and DAFM EU Just Transition Grant 2024 to 2029_Project No. 165) and contributions from MSCA RISE ICHTHYS project.

Conflict of interest

The authors declare no conflict of interest.

Author details

Emer A. O'Neill[1,2], Marcel A.K. Jansen[3], Brijesh K. Tiwari[4], Antoine Fort[1,2], Eoghan Clifford[5], Julie A. Maguire[6] and Neil J. Rowan[1,2]*

1 Technological University of the Shannon, Westmeath, Ireland

2 Empower Eco Sustainability Hub, Midlands Innovation Research Centre, Technological University of the Shannon, Westmeath, Ireland

3 School of Biological, Earth and Environmental Sciences and Environmental Research Institute, University College Cork, Cork, Ireland

4 Teagasc Food Research Centre, Co Cork, Ireland

5 Civil Engineering, School of Engineering, University of Galway, Galway, Ireland

6 Indigo Rock Marine Research Centre, Co Cork, Ireland

*Address all correspondence to: neil.rowan@tus.ie

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