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Effects of climate and environmental variance on the performance of a novel peatland-based integrated multi-trophic aquaculture (IMTA) system: Implications and opportunities for advancing research and disruptive innovation post COVID-19 era

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HIGHLIGHTS

- Integrated multi-trophic (IMTA) aquaculture offers a sustainable food process.
- IMTA can be affected by extremes in weather/climate events.
- IMTA balance can be disrupted by emergence of toxigenic algae.
- Future need for in-farm real-time monitoring of IMTA systems

GRAPHICAL ABSTRACT

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ABSTRACT

Advancing wet peatland 'paludiculture' innovation present enormous potential to sustain carbon-cycles, reduce greenhouse-gas (GHG) gas emissions and to transition communities to low-carbon economies; however, there is limited scientific-evidence to support and enable direct commercial viability of eco-friendly products and services. This timely study reports on a novel, paludiculture-based, integrated-multi-trophic-aquaculture (IMTA) system for sustainable food production in the Irish midlands. This freshwater IMTA process relies on a naturally occurring ecosystem of microalgae, bacteria and duckweed in ponds for managing waste and water quality that is powered by wind turbines; however, as it is recirculating, it does not rely upon end-of-pipe solutions and does not discharge effluent to receiving waters. This constitutes the first report on the effects of extreme weather events on the performance of this IMTA system that produces European perch (*Perca fluviatilis*), rainbow trout (*Oncorhynchus mykiis*) during Spring 2020. Sampling coincided with lockdown periods of worker mobility restriction due to COVID-19 pandemic. Observations revealed that the frequency and intensity of storms generated high levels of rainfall that disrupted the algal and bacterial ecosystem in the IMTA leading to the emergence and predominance of toxic cyanobacteria that caused fish mortality. There is a pressing need for international agreement on standardized set of environmental indicators to advance paludiculture innovation that addresses climate-change and sustainability. This study describes important technical parameters for advancing freshwater aquaculture (IMTA), which can be future refined using real-time monitoring-tools at farm level to inform management decision-making based on evaluating environmental indicators and weather data. The relevance of these findings to informing global sustaining and disruptive research and innovation in

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paludiculture is presented, along with alignment with UN Sustainable Development goals. This study also addresses global challenges and opportunities highlighting a commensurate need for international agreement on resilient indicators encompassing linked ecological, societal, cultural, economic and cultural domains.

1. Introduction

Unlocking the challenges of climate-orientated peatland management will enable conservation of their important carbon stocks (Wichmaan et al., 2016; Ziegler et al., 2021). However, some 15% of peatlands globally are degraded due to drainage-base agriculture and forestry that are key contributors to greenhouse gas emissions (GHG) (Uràk et al., 2017; Ziegler et al., 2021). The controlled rewetting of peatlands offers solutions to preventing GHG emissions and biodiversity loss (Ziegler et al., 2021), and presents opportunities for farming and innovative use of these rewetted peatlands that is termed 'paludiculture' (O'Neill et al., 2019; Ziegler et al., 2021). There is strong interest in developing commercial paludiculture activities including fuel, horticulture, aquaculture, and construction material; however, there is a need to address knowledge gaps that will influence the economic viability of paludiculture-derived products and services (Ziegler et al., 2021; O'Neill and Rowan, 2022). Factors affecting effective deployment of paludiculture are complex as fostering sustainable green innovation requires a holistic strategic response that can be effectively facilitated through the 'quadruple helix' approach of industry, academia, government and society (Rowan and Casey, 2021; Tan et al., 2021).

Key challenges affecting the development of paludiculture-based innovation include the lack of shared real-time systems of data generation for met-analysis, corporate strategy, risk-mitigation, and business disruption (Ziegler et al., 2021). There is a lack of consensus on international standardization of paludiculture innovation in terms of outcome sets, and agreement on sustaining measured variables that must encompass protecting biodiversity (Ziegler et al., 2021). Unlocking the disruptive potential of paludiculture innovation can be met by collaborate use of in-field environmental test-bed facilities (Rowan and Casey, 2021).

Aquaculture is the fastest growing food producing industry in the world that accounts for half of the fish produced globally for human consumption (Nielsen et al., 2016; Liu et al., 2017; O'Neill et al., 2019, O'Neill et al., 2020; O'Neill and Rowan, 2022). Farmed fish is considered to be a more efficient protein utilisation and feed conversion source than other animals destined for protein production (Tschirner and Kloas, 2017). According to the United Nations (UN), aquaculture now provides fish availability to countries and regions that would have previously been limited or non-existent, often at affordable prices; thus, providing improved nutrition and food security (Fish Farming Expert, 2020; Rowan and Casey, 2021). The increasing interest in exploiting low-cost environmentally-friendly 'natural' processes in aquaculture has led to the timely development of integrated multi-trophic aquaculture systems or IMTA, along with accelerating efforts to implement eco-innovation and to improve the monitoring of traditional processes (Granada et al., 2016; Tahar et al., 2018a, 2018b; Naughton et al., 2020). However, advances in aquaculture must also be balanced with the commensurate need to meet commitments as set out by many European directives for environmental protection as well as the Water Framework Directive (WFD), where the latter aims to achieve good water status in all waters across all EU member countries (Voulvoulis et al., 2017; WFD Ireland, 2018).

In addition to these environmental concerns, extreme weather events, such as drought have displayed substantial effects on variances in stocking densities within aquaculture facilities therefore, successful stock assessments will be influenced by our ability to understand, monitor and to predict variances in weather and climate change on aquaculture ecosystem dynamics (Rowan and Pogue, 2021; O'Neill and Rowan, 2022). An increasing number of studies have intimated that climate vulnerability and climate change can have adverse impacts on global food production and food security (Iizumi and Ramankutty, 2015). These authors reported that ongoing climate change, and associated variances in intensity, frequency, and duration of weather/climate extremes, in conjunction with growing populations and dietary requirements, further complicate this drive to improve food sustainability and security. Therefore, stakeholders including policymakers, urgently require better estimates of the likely incidence of extreme weather events, their impact on food production and security, and the commensurate consequential impact in terms of socio-economic losses (Chavez et al., 2015). There is a pressing need to address the uncertainties in climate model predictions not only over years, but also at regional and local scale to inform efficacy of food production systems, and interventions. Mowi Ireland, a coastal aquaculture farmer, recently lost approximately 80,000 salmon due to toxigenic plankton bloom where the rearing water was 13 °C compared to typical 11.5 °C, which was potentially attributed to climate change (Moore, 2021).

This constitutes the first study to report on the potential effects of extreme weather events on the technical performance of a novel peatlands-based IMTA process located in the Republic of Ireland that lead to fish mortality, which coincided with occurrence of COVID-19 pandemic. It describes the worldwide relevance of data generated by using a Quadruple Helix (academia-industry-government-society) approach to advancing paludiculture innovation along with challenges and opportunities. It describes measurable technical and environmental variables for the development of this IMTA system that embraces extreme weather events; it describes smart tools to inform technical, policy and societal readiness level of paludicutlure innovation aligned with U.N.s' sustainable development goals.

2. Materials and methods

2.1. Sampling

Oasis fish farm is an innovative peatland cut-away integrated multi-trophic aquaculture (IMTA) system process set in the middle of Mount Lucas Wind Farm, Co. Offaly (53°17′3″ N – 7°11′45″ W). This IMTA holds European perch (*Perca fluviatilis*), rainbow trout (*Oncorhynchus mykiis*), common duckweed (*Lemna minor*) and gibbous duckweed (*Lemna gibba*) and exploits use of microalgae for waste removal. The aquaculture system consists of four split (pill) ponds connected to an algae and duckweed lagoon with 16 channels serving as a treatment system. Fish are kept at a density that does not exceed the organic farming standard (e.g., <20 kg/m^{-3} for perch), using screens at the D-ends of each split pond. The space between two D-end fish culture areas is also used to treat waste with free living algae in suspension. Flow in each split pond is generated and water is circulated using an airlift. Each D-end fish culture area is equipped with oxygen and temperature probes connected to paddlewheels to provide extra oxygen when necessary. The farm is designed to hold a maximum of 32,000 kg of fish.

Water samples were collected from the Oasis farm in five liter octagonal carboy HDPE bottles (Lennox) and transported in insulated cool boxes directly to the lab, 62 km away, via car. Samples were collected every two weeks from December 2019 to February 2020 and then once a week until October 2020. Samples were taken from each on the culture ponds, the entry and exit points of the duckweed lagoons and the reservoir during this study. Samples were also taken from the overflow tank during times when there may have been a potential for discharge. Refer to Fig. 1 for the locations of all sample points within the farm.

2.2. Physicochemical analysis

Good water quality is critical for the cultivation of fish as well as for the receiving ecosystems attached to aquaculture facilities. Analysing the physicochemical parameters is the most common method of determining the

Fig. 1. Aerial view of Oasis Fish Farm, located in Ballycon, Co. Offaly. The culture ponds, water reservoir, algae & duckweed wastewater treatment channels, overflow tank and bog river are all visible. Blue lines indicate the direction of the flow of water. The green squares indicate all sampling points within the farm to monitor the IMTA process.

current water quality (Shukla et al., 2013). No definite set of physicochemical parameters specific for Irish aquaculture water and wastewater could be found. Therefore, the physicochemical parameters routinely monitored in Irish fish farms to assess water quality were applied. Additionally, a range of previous studies conducted on aquaculture facilities across the world were researched. The range of parameters investigated in these studies were also applied to this research. As no values for the individual physicochemical parameter levels could be found in relation to Irish aquaculture, the standard Irish EPA water quality parameters based on the Freshwater Fish Directive [78/659/EEC], Surface Water Regulations [1989] and surface water regulations [SI 272 of 2009] and amendments [SI 77 of 2019] were used as guidance (EPA, 2001; Irish Statutory Office, 2009; Irish Statutory OfficeOffice, 2019).

Water parameters; temperature, pH, ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), orthophosphate (PO_4^{3-}), dissolved oxygen (DO), biochemical oxygen demand (BOD), suspended solids (SS), dissolved solids (DS), hardness, and alkalinity – were investigated in the laboratory within 24 h of collection to prevent the need for preservation. The Standard Methods for the Analysis of Water and Wastewater were used for all of the parameters employed. See Table 1. Spectroquant® photometric kits were used to assess the NH_4^+, NO_2^-, NO3$^-$ and PO_4^{3-}. Analysis was conducted as per the manufacturer's instructions. Absorbance was analysed using a Shimadzu UV-2250 spectrophotometer. Temperature, pH, dissolved solids and conductivity were analysed using a VWR pHenomenal™ MU 6100 L meter, VWR 111662–1157 pH probe and VWR CO11 conductivity probe. DO and BOD_{5day} were analysed using a Jenway 9500 DO_2 meter and probe. Suspended solids were analysed via filtration using a Buchner flask, Buchner funnel and Whatman 0.45 μm pore membrane filter. Hardness was assessed via titration using pH 10 buffer, Erichrome black and EDTA. Alkalinity was analysed by titration using phenolphthalein indicator, methyl orange indicator and hydrochloric acid.

Table 1
Summary of all physicochemical methods applied to this research. All parameters/variables, their respective methods, standard analysis of water and wastewater method numbers and the detection limits for parameters where photometric test kits were employed have been included.

Parameter/variable	Analytical method	Standard analysis method number	Detection limit (mg L^{-1})
Alkalinity	Titrimetric	2320-B	–
Ammonium (NH_4^+)	Photometric	4500-NH_3-F	0.013–3.86 2.6–193.0
Biochemical oxygen demand (BOD)	Membrane electrode	5210-B	–
Dissolved oxygen (DO)	Membrane electrode	4500-O G	–
Dissolved solids (DS)	Electrode	2540-C	–
Hardness	Titrimetric	2340-C	–
Nitrate (NO_3^-)	Photometric	4500-NO_3	0.4–110.7
Nitrite (NO_2^-)	Photometric	345–1	0.007–3.28
Orthophosphate (PO_4^{3-})	Photometric	4500-P-C	0.007–15.3 1.5–92.0
pH	Membrane electrode	2310-B	–
Suspended solids (SS)	Gravimetric	2540-D	–
Temperature	Thermometer	2550-B	–

2.3. Algae enumeration

Algae cells were both manually and automatically counted. All manual enumeration was conducted using a Superior Marienfeld Neubauer Improved Haemocytometer (0.1 mm, 0.0025 mm^2, Tiefe Depth Profondeur No: 717810) and a Nikon YS100 light microscope. The Miltenyi Biotec MACSQuant® Analyser 10 Flow Cytometer (FCM) was used for the automated enumeration of the algae. Preparation of phytoplankton samples for flow cytometry was adapted from Naughton et al. (2020). A ten millimeter aliquot of each sample preserved with Lugols Iodine were centrifuged at 3500 ×*g* for 20 min. The supernatant was removed and the algae pellet was re-suspended in flow buffer. The flow buffer was prepared by adding 1 mM EDTA, 0.2% Tween and 0.1% NaN_3 to 1 L phosphate saline buffer or PBS (Merck). The buffer was filtered using a 0.20 μm filter (Sigma-Aldrich) to remove impurities which may interfere with the flow cytometer. The re-suspended sample was divided into two aliquots (one three milliliter aliquot and one seven milliliter aliquot). The three milliliter aliquot was used for the unstained negative control samples. The seven milliliter aliquot was used for the stained samples. Two hundred microliters of 10X SYBR Green was added to the seven milliliter aliquot and incubated for 15 min in the dark at room temperature. Using two milliliter Eppendorf's (Merck), 1.5 mL from the unstained aliquot and three 1.5 mL's of the stained aliquot were centrifuged at 3500 ×*g* for 15 min. The supernatant was removed and the pellets were re-suspended in 1.5 mL of fresh flow buffer. Samples were then loaded onto a round-bottomed 96 well plate. Two hundred microliters of each aliquot was loaded onto the plate i.e., four wells containing one unstained and three (triplicate) stained aliquots were loaded for each sample.

The instrument was set to uptake 100 μL of each sample for analysis. The trigger point for the FSC laser was set at 1.0 to eliminate the detection of as much debris as possible in the samples. The FlowJo™ v10.7 software program was used for the analysis of the data generated from the FCM. Gating was used to enumerate the algal and cyanobacterial populations. The gating method was adapted from Haynes et al. (2016), Moorhouse et al.

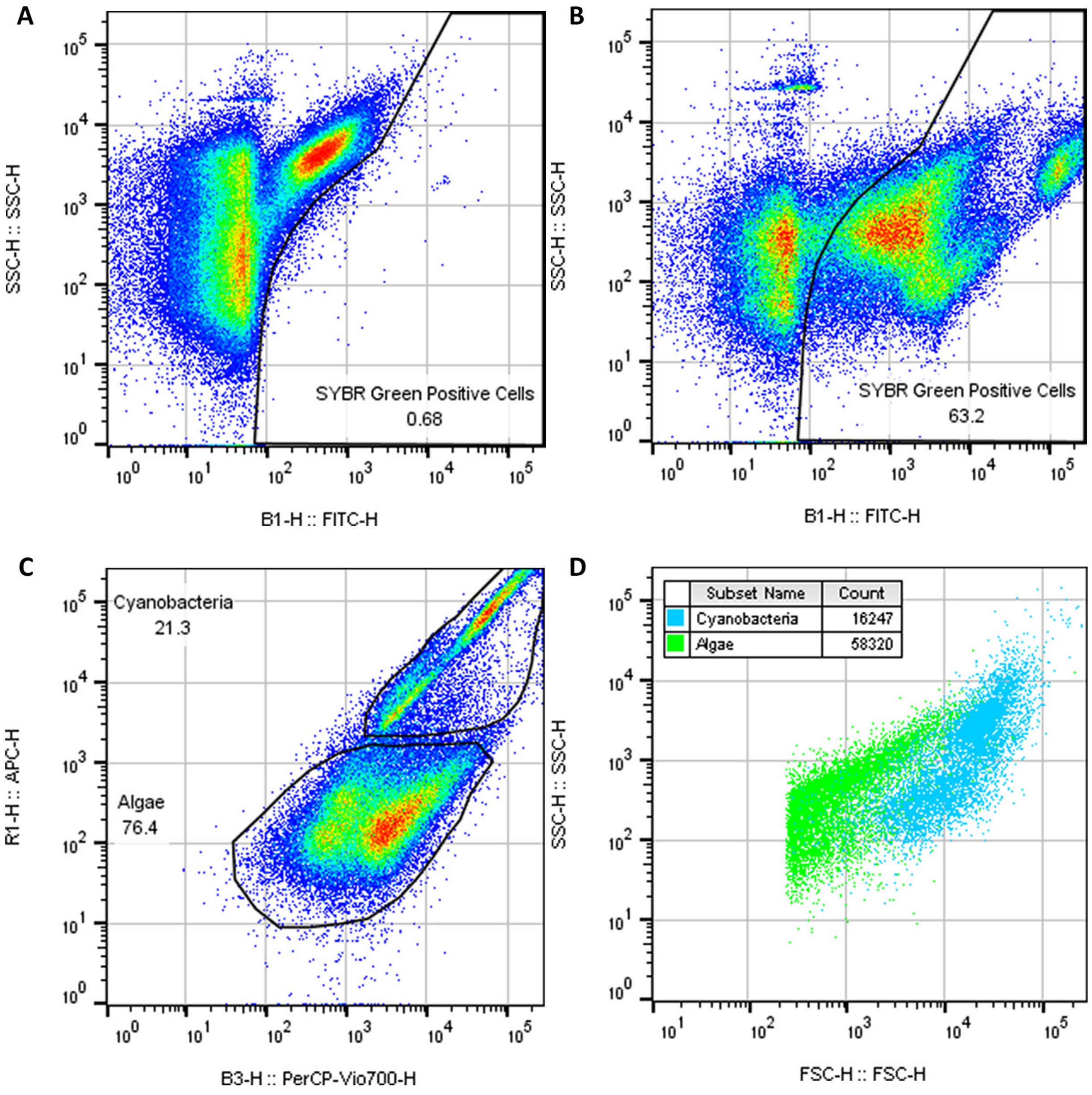


Fig. 2. Flow cytometry dot diagrams for the enumeration of algae and cyanobacteria. A) Unstained samples to eliminate autofluorescence interference, B) cells stained with SYBR Green for the enumerations of algal and cyanobacterial populations, C) chlorophyll and phycocyanin levels used to distinguish between algae and cyanobacteria, D) enumeration of both the algae and the cyanobacteria populations.

(2018), Naughton et al. (2020) and Read et al. (2014). The unstained sample (negative control) was first gated (Fig. 2A) to eliminate as much autofluorescence interference as possible. This gate was then applied to the stained samples (Fig. 2B) in order to identify and enumerate the cells present in each sample. As per Moorhouse et al. (2018) and Naughton et al. (2020), the blue B3 channel, which was used to identify chlorophyll positive cells, was plotted against the red R1 channel, which was used to identify phycocyanin positive cells to distinguish between algae and cyanobacteria. (Fig. 2C). Enumeration of the algal and cyanobacterial populations were then established (Fig. 2D).

2.4. Statistical analysis

All statistical analysis and construction of dose response curves, standard curves, etc. were performed on GRAPHPAD PRISM 7, 8 and 9, and MINITAB 18 and 19. The data generated were grouped and subject to normality tests (Anderson-Darling), to determine if samples were from a normal distribution ($p > 0.05 =$ normal distribution). This in turn would establish whether parametric or non-parametric testing was to be conducted on results. As there was normal distribution, parametric testing was applied. *t*-tests and ANOVA were used to determine if any significant

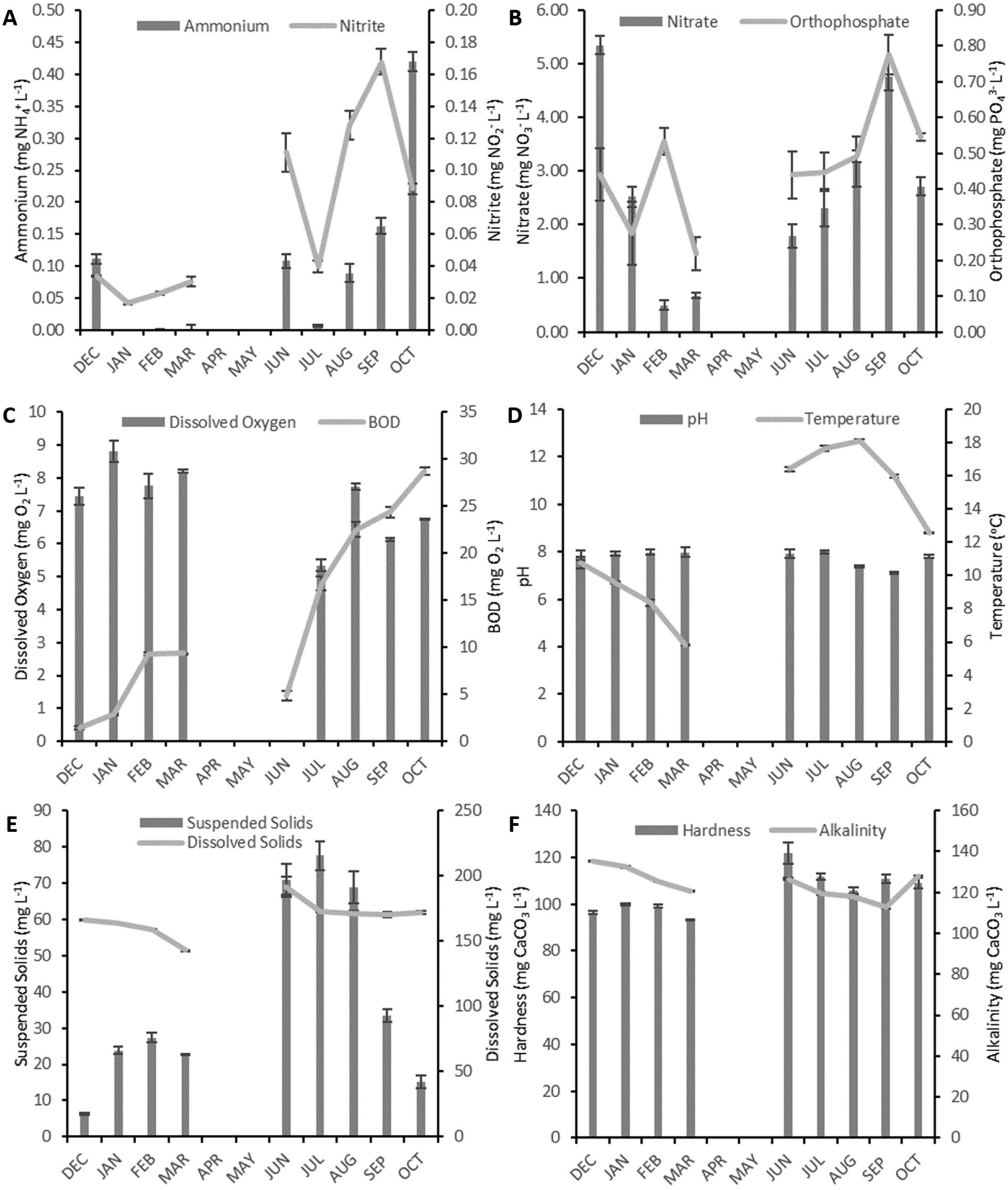


Fig. 3. Breakdown of all physicochemical parameters investigated on the novel trial fish farm between December 2019 and October 2020. Parameters investigated were A) ammonium and nitrite, B) nitrate and orthophosphate, C) dissolved oxygen and biochemical oxygen demand, D) pH and Temperature, E) suspended and dissolved solids, and F) hardness and alkalinity. S.D. indicated, $n = 8$. Samples missing from April and May 2020 due to COVID-19 lockdown and restrictions in the Republic of Ireland.

differences were observed in the variables ($p < 0.05$ = significant difference). Unpaired tests were used as different sets of samples were analysed to assess the quality of the aquaculture water samples. For the correlation studies, the Pearson's correlation coefficient (r) was used to determine whether any relationships existed between any of the parameters investigated.

3. Results & discussion

3.1. Effects of extreme weather variance on the technical performance of a new recirculating IMTA process in the Irish peatland

This timely study describes the effects of extreme weather events experienced in Spring period of 2020 on the performance of a fully-integrated multi-trophic aquaculture process developed in the Irish peatlands. This IMTA process uses a balanced ecosystem of naturally-occurring microalgae, bacteria and duckweed to regulate waste and maintain water quality; in addition, it uses wind turbines as a renewable source of energy to operate aeration systems in the circulatory freshwater aquaculture ponds (O'Neill et al. 2020). This study characterises this IMTA process by way of physicochemical and algae monitoring over a year-long case study. As no statistically significant differences were observed between each of the sampling points results were averaged for ease of reporting (refer to Fig. 3.).

3.1.1. Physicochemical analysis

Prior to the first COVID-19 national lockdown in the Republic of Ireland in March 2020, very little to no NH_4^+ levels were detected within the IMTA farm. This was believed to be due to a combination of issues associated with cyanobacteria levels and increased levels of rainfall experienced in February 2020. NH_4^+ levels increased across all sampling points from the end of July 2020 with spikes of up to 0.90 mg NH_4^+ L^{-1} observed at the beginning of October 2020. However, levels did not rise to greater than the guidance values of 1 mg NH_4^+ L^{-1} (EPA, 2001). Additionally, no NH_4^+ was detected at the discharge point during times of possible overflow and release indicating no potential issues associated with NH_4^+ for the receiving peatlands. Levels of NH_4^+ also decreased between the culture ponds and the duckweed lagoon (treatment lagoon) suggesting that the treatment process was effective at reducing NH_4^+ levels in wastewater.

Before the lockdown period, NO_2^- levels fluctuated between 0 mg NO_2^- L^{-1} and 0.03 mg NO_2^- L^{-1}. However, levels increased greatly after this period, with concentrations spiking to between 0.25 mg NO_2^- L^{-1} and 0.30 mg NO_2^- L^{-1} in mid-July and mid-September, respectively. This was a tenfold increase on previous levels as well as being tenfold greater than the guidance value of 0.03 mg L^{-1} (EPA, 2001). NO_2^- is highly toxic to aquatic life (O'Neill et al., 2019; Pollice et al., 2002) but is extremely unstable and would not remain in this form for long as it would be quickly transformed to NO_3^- (Durborow et al., 1997; O'Neill et al., 2019; O'Neill et al., 2020). As no overflow and release occurred during the times of high levels, the NO_2^- would not cause issues within the bog.

NO_3^- levels dropped considerably the month prior to lockdown (February 2020) going from >8 mg NO_3^- L^{-1} to 0 mg NO_3^- L^{-1}. This coincided with changes in weather conditions and excessive rainfall experienced throughout the month. Once analysis recommenced after the lockdown period, NO_3^- levels slowly increased reaching levels >8 mg NO_3^- L^{-1} in September before dropping back to between 2 mg NO_3^- L^{-1} and 4 mg NO_3^- L^{-1} in October. Levels were well below the guidance value of 50 mg L^{-1} (EPA, 2001). The increased levels in NO_3^- observed in this study may be due to the increased levels of NO_2^- also observed.

PO_4^{3-} levels were observed across all sampling points within the farm. Statistical analysis demonstrated no significant difference between the different sampling points ($p = 0.2160$). PO_4^{3-} levels detected were above the guidance value of <0.035 mg L^{-1} (Irish Statutory OfficeOffice, 2019, 2009) indicating there may be potential issues within the farm and additional treatment process to reduce PO_4^{3-} levels may need to be considered as the algae and duckweed lagoon is not effectively removing it.

Variations in DO levels and BOD levels were observed across the eight sampling points. No statistically significant differences were observed across both parameters (DO $p = 0.1421$, BOD $p = 0.5464$). DO levels fluctuated between 4 mg O_2 L^{-1} and 10 mg O_2 L^{-1}. The recommended DO concentration present in salmonid waters is ≥9 mg O_2 L^{-1} and in cyprinid waters is ≥7 mg O_2 L^{-1} (EPA, 2001). Levels continually increased and decreased above and below these recommended levels. However, they did not drop below the threshold of 4 mg O_2 L^{-1} required for sufficient maintenance of aquatic life (Alam et al., 2007; da Silva et al., 2017; O'Neill et al., 2019; O'Neill et al., 2020).

The SI 272/2009 and SI 77/2019 recommended a mean BOD concentration of 1.30 mg O_2 L^{-1} for high water status and 1.50 mg O_2 L^{-1} for good water status (Irish Statutory Office, 2009; Irish Statutory OfficeOffice, 2019). However, the EPA suggested ≤3 mg O_2 L^{-1} and ≤6 mg O_2 L^{-1} for salmonid and cyprinid waters, respectively (EPA, 2001). Issues were indicated with the BOD levels observed across all sampling points. The BOD is caused by microorganisms using O_2 when consuming organic matter therefore organic matter needs to be reduced in order to decrease BOD levels (EPA, 2001; Gupta et al., 2017; Kasuya et al., 1998; Lee and Nikraz, 2015; Mcintosh and Fitzsimmons, 2003; Sultana et al., 2017). Increasing O_2 levels and the addition of filtration to remove some of the organic matter have been found to decrease BOD levels (Gupta et al., 2017; Lee and Nikraz, 2015). Work is ongoing to reduce BOD levels. However, as no water was released from the farm during times of increased BOD levels, no concerns associated with this issue affecting the surrounding peatland habitat were foreseen.

Fluxes in the levels of suspended solids were observed across all sampling points, while dissolved solid concentrations remained more consistent throughout the study. The levels of suspended solids observed throughout the summer months (June, July, August) were well above the guidance value of 25 mg L^{-1} (EPA, 2001) reaching highs of >120 mg L^{-1}. Given that suspended solids can cause gill irritation, signs of which were observed in some of the fish, this was considered to be a major issue. It was also believed that this issue was linked to the issues with BOD previously mentioned. After filtration methods were applied to different areas of the farm, suspended solid levels dropped back to below the MAC level by September and remained so until the end of the study. Dissolved solid concentrations observed in the study were well below the suggested concentration of <300 mg L^{-1} for excellent water status (WHO, 2003).

Fluctuations were indicated in the temperature range and the pH range observed across all of the sampling points. The elevations in temperature were observed between June and September as would be expected given the season (summer). Although no specific guidance value for temperature could be established as all species of fish have a slightly different optimum temperature, any water released into an aquatic system must be <20 °C (EPA, 2001). Temperatures were >20 °C only once in mid-July. However, as water was not released from the system, this was not deemed to be an issue. Recommended pH levels of between pH 6 and pH 8 were suggested (EPA, 2001; Irish Statutory Office, 2009; Irish Statutory OfficeOffice, 2019). The pH levels remained within this range throughout the study. The pH levels were just below pH 8 however, levels dropped to just above pH 7 from August 2020 to September 2020. Although levels remained within the recommended range, the alteration in pH levels may have had an effect on the BOD issues observed in the farm. Alterations in pH can decrease the rate of organic removal rates thus affecting BOD measurements (Mukherjee et al., 1968).

$CaCO_3$ levels were measured in the eight sampling points in order to determine hardness and alkalinity levels. Statistical analysis was conducted for each parameter and no significant differences were observed (hardness $p = 0.5237$, alkalinity $p = 0.4806$). Hardness levels observed suggested that the water was slight to moderately hard. This correlated with water hardness maps of Ireland which demonstrated water in the midlands around Co. Offaly were also slight to moderately hard. It has been suggested that fish prefer a minimum of 20 mg $CaCO_3$ L^{-1} alkalinity levels. Levels recorded within the farm remained above this optimum threshold throughout the study (Boyd and Tucker, 2015; EPA, 2001). Alkalinity levels observed in this study demonstrated similar results to those reported by Stephens and Farris (2004b).

All physicochemical findings were then compared to previous research. Results were similar to those observed in other studies with the exception of NO_2^-, suspended solids and BOD (Boaventura et al., 1997; Camargo, 1994; Cao et al., 2007; Caramel et al., 2014; Costanzo et al., 2004; da Silva et al., 2017; Fadaeifard et al., 2011; Guilpart et al., 2012; Lalonde et al., 2014; Moreira et al., 2010; Namin et al., 2013; Noroozrajabi et al., 2013; O'Neill et al., 2019; Pulatsü et al., 2004; Stephens and Farris, 2004a, 2004b; Ziemann et al., 1992; Živić et al., 2009). A ten-fold increase was detected in the NO2-levels and suspended solids levels were higher than the majority of the previous studies, as too were BOD levels. Correlations were indicated between BOD levels and a range of parameters including pH, temperature, dissolved oxygen, alkalinity and suspended solids. This demonstrated the importance of maintaining high DO levels as oxygen is vital for the BOD process. Abnormal or irregular pH levels, which were observed for a time in the farm, can decrease the rate of removal of organic compounds which affect BOD levels. By proxy, changes in alkalinity will also have an impact (Chinedu et al., 2015). Small amounts of all suspended solids are considered volatile suspended solids and exert greater pressures on the oxygen demand thus increasing BOD levels (Gerardi and Lytle, 2015). Finally, as temperatures increase so too does BOD removal rates as higher temperatures enhance microbes respiration rates (Lim et al., 2001). The range of correlations with BOD has demonstrated how complex the process is and may be why issues were encountered in controlling the BOD levels within the farm.

3.1.2. Algae & cyanobacteria analysis

Lower levels of algae were observed during the winter months which is to be expected as temperatures are lower and less sunlight is experienced. The spring month displayed a rise in levels which corresponded with the increase in light and temperature. However, a drop in algal numbers were observed just prior to the first COVID-19 national lockdown that occurred in March 2020. This drop was most likely due to excessive levels of rain fall experienced during the month of February. Algae numbers consistently remained between 1×10^5 and 5×10^5 cells mL^{-1} after the lockdown period until the end of the study. This suggested the stabilisation had occurred. Moderately strong correlationships were observed with most of the nitrogen nutrients indicating that NH_4^+, NO_2^- and NO_3^- play a vital role in maintaining optimum algae levels in the novel IMTA process. Results also found that the higher and more stable the levels of NO_3^- present, the more stable the algae numbers. Given that NO_3^- is algae's preferred form of nutrient, and NH_4^+ and NO_2^- are necessary for the natural production of NO_3^- via the nitrification process, this result was expected.

Cyanobacteria levels were also monitored in parallel to the algal numbers, as shown in Fig. 4. Although many species of cyanobacteria can provide beneficial elements (e.g., *Spirulina*) the presence of increased levels cyanobacteria was found to have a negative impact on the novel IMTA system. Increased incidences of mortality were observed as cyanobacterial levels rose. Much like with freshwater bodies, cyanobacteria numbers were always present in the system. They remained below the level of algae being reported highlighting algae's ability to control cyanobacteria levels as both are competing for the nitrogen nutrient source. However, cyanobacteria levels were found to increase just before the lockdown period, demonstrating an inverse relationship with the algae. This suggested that the cyanobacteria were out competing the algae for nutrients. Again, this coincided with extreme weather conditions. Once levels stabilised after the lockdown period, they were once again consistently below the level of algae, remaining between 1×10^4 and 1×10^5 cells mL^{-1}. Reducing in mortality levels also coincided with the stabilisation of cyanobacteria levels.

Correlation studies were conducted between the algae and cyanobacterial levels and all of the physicochemical parameters. In addition to a correlation observed between the algae and the cyanobacteria themselves, correlations were observed between both counts and a range of physicochemical parameters. A correlation was observed with the N parameters (NH_4^+, NO_2^- and NO_3^-) as well as with the P (PO_4^{3-}). As N and P are both necessary for algal growth this was expected. It also highlighted the need to ensure these nutrients were present in the system to ensure the continued presence of algae that was necessary for the novel IMTA process to be effective. The correlation between the pH and algae was also expected as it is well known that although algae can tolerate small fluctuations in pH, increased and more frequent fluctuations can slow down growth rates (Dubinsky and Rotem, 1974).

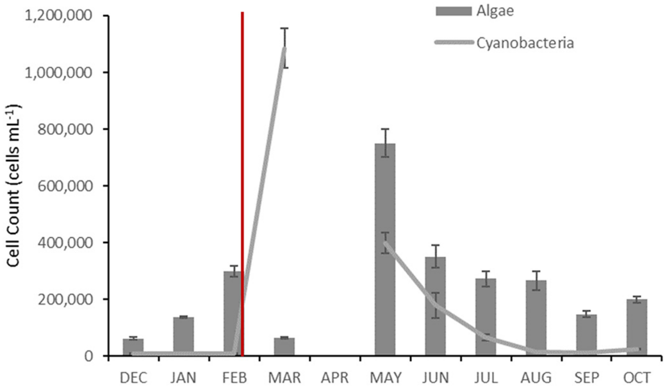


Fig. 4. Cell counts in cells mL^{-1} of algae (bar) and cyanobacteria (line) observed throughout the novel trial fish farm between December 2019 and October 2020. Cell counts conducted via flow cytometry. S.D. indicated, $n = 8$. Samples missing from April 2020 due to COVID-19 lockdown in the Republic of Ireland. Red line indicates when excessive levels of rainfall were observed.

3.1.3. Climate variance

During this research process, algae demonstrated the potential to be used as an early warning indicator for highlighting issues associated with climate change having experiences a range of different weather conditions including flooding conditions in 2020 where record levels of rain fell due to the development of a number of storm systems in close proximity to one another. February 2020 was one of the wettest on record for the Republic of Ireland. This high level of rainfall was as a result of two extratropical cyclone storms hitting Ireland in that month and in close proximity to one another. Storm Ciara (formed 7th February 2020, dissipated 16th February 2020) and Storm Dennis (formed 11th February 2020, dissipated 18th February) affected Ireland less than a week apart. Just after this weather event cyanobacteria levels began to rise within the farm, as shown in Fig. 4, as well as fish mortalities (up to 44%) which had up until that point remained consistently low (□3%). Veterinary post-mortems found signs of hepatotoxicity (liver necrosis) and high instances of gill irritation. Unfortunately, the first lockdown period began in March 2020 and as a result no samples could be analysed after this point until May 2020. Literature searches were conducted remotely to find an appropriate action of reducing or removing the cyanobacterial levels without having additional consequences on the fish health. Both Iredale et al. (2012) and Rajabi et al. (2010) demonstrated successful cyanobacterial control and removal from freshwater bodies with the application of barley straw. This method was suggested and then subsequently applied to the culture ponds at which point the farm reported a reduction in mortalities and cyanobacterial levels. Findings from the overarching Bord Iascaigh Mhara (BIM, 2020) project subsequently revealed that 3402 species of bacteria and microalgae were occurring in the IMTA ecosystem that were identified using next generation sequencing and bioinformatics, of which 1864 are algal. This demonstrated the complexity of the study given the high level of algal diversity within the farm. Of these 1864; 1551 species or sub-species of algae were identified across 210 genera, 60 were identified on family as opposed to genus or species, 42 were classified as uncultured.

In order to determine whether the excessive levels of rainfall indirectly caused issues in February and the lack there of caused issues in May, Met

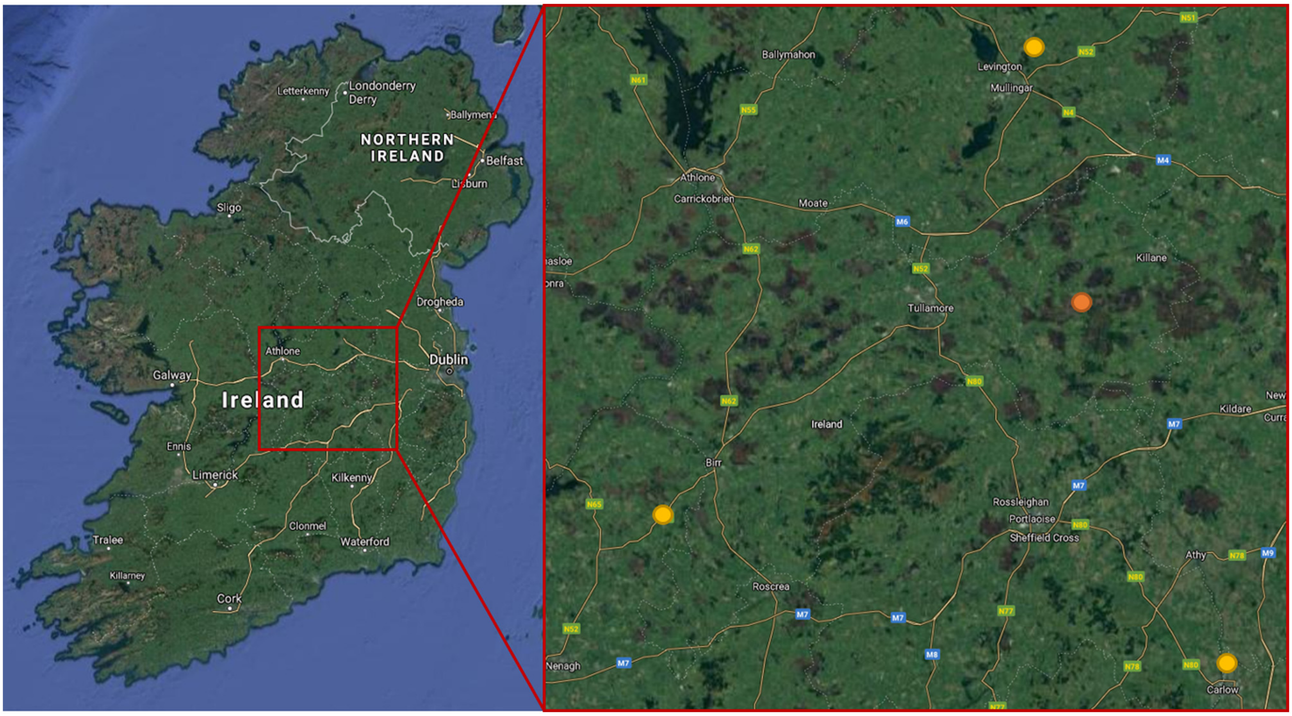


Fig. 5. Map of Ireland indication the approximate location of Oasis fish farm (53°17′03″ N, 07°11′45″ W) indicated with orange, and the three closest Met Eireann weather stations (Gurteen – 53°02′24″ N, 08°00′36″ W; Oak Park – 52°51′36″ N, 06°55′36″ W; Mullingar – 53°33′36″ N, 07°20′24″ W) surrounding the farm, indicated by yellow.

Éireann metadata was once again investigated. The three closest weather stations surround Oasis fish farm at Mount Lucas were used (Mullingar, Co. Westmeath; Oak Park, Co. Carlow; and Gurteen, Co Tipperary), as indicated in Fig. 5. The Irish midlands traditionally get an average of 70.3 mm of rainfall for the month of February. However, according to Met Éireann, 197.7 mm of rainfall fell for that month (Met Éireann, 2021), as shown in Fig. 6. This subsequently would have diluted down all nutrient levels and reduced algal / cyanobacterial numbers within the farm. As nutrients build back up, the ammonium, which is cyanobacteria's preferred source of nutrients, is used by the cyanobacteria before it has a chance to be converted to nitrate via the nitrification process (Herrero et al., 2001) which is the algae's preferred form. This in turn allows the cyanobacteria to grow and out compete the algae. Normally the higher levels of algae and increased levels of nitrate control the levels of cyanobacteria. Leachate or runoff from the bog itself many also be contributing to the issues however no studies on this have been conduct to date. Cyanobacteria levels rose again in May with similar levels or mortality begin observed again. However, there were no instances of rainfall during this instance (Fig. 6.). In fact, May 2020 was considered one of the driest in recent year's (Met Éireann, 2021). No physicochemical analysis could be conducted at this time due to COVID-19 restrictions still being in place. Again, Veterinary postmortems found signs of hepatotoxicity and gill irritation. The Barley straw had been removed from the ponds prior to this event and was therefore though to be the main cause for the problem. It may also be as a seasonal event as cyanobacteria have been known to “bloom” during the spring and early summer months as temperatures increase. However, as this was the first study ever conducted on a peatland IMTA system additional research and analysis would need to be conducted.

Overland flow of water from rainfall events can impact on infrastructure and cause flooding, which is different to riverine flooding. Overland flow

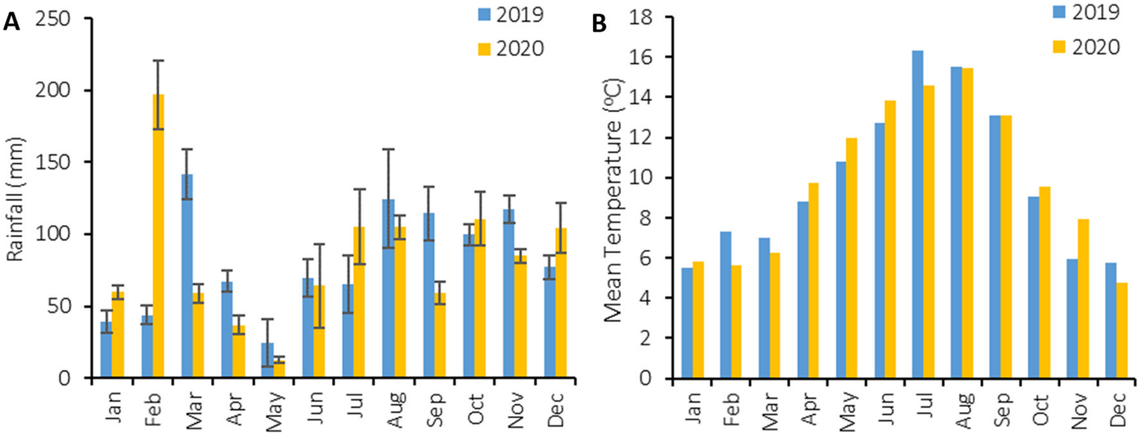


Fig. 6. Average A) rainfall and B) temperature recorded for 2019 (blue) and 2020 (yellow) at three Met Eireann weather stations surrounding the Oasis fish farm during the sampling period of December 2019 to October 2020. Stations were located at 1) Mullingar, Co. Westmeath, 2) Oak Park, Co. Carlow and 3) Gurteen, Co Tipperary. Stations were located north, south-west and south-east of the fish farm, respectively.

Table 2
Relevance of this 'paludiculture-based' IMTA system to enabling the advancement of adjacent and emerging worldwide cross-cutting research and innovation including UN SDGs.

Core topics and enabling innovation, products and services	UN SDG number
Paludiculture 'wet peatland' innovation *Collaborative advancement and standardization of innovation for direct economic viability including horticulture, food production and bio-based industry (Tan et al., 2021; Ziegler et al., 2021) *Ecotoxicology, biodiversity and safety evaluation of emerging innovation and services (Rowan and Galanakis, 2020; Wan Mohtar et al., 2021; Usuldin et al., 2021) *Sustainable Carbon Cycles - supporting the European Commission in reaching climate neutrality through specific focus on quality, credibility and certification of carbon removals in land sector using IMTA system (European Commission, 2021). *Development of novel multimodal sensing technologies, IoT devices, Microsoft Azure Cloud and AI models to inform effective paludiculture innovation and management including carbon reduction (Science Foundation Ireland (SFI), 2021) *Ecosystem Service Management and Pollination, including social enterprises (Goblirsch et al., 2021) *Biorefinery of bio-based products from IMTA-generated microalgae for one-health applications (Wichmaan et al., 2020; Rowan and Pogue, 2021; McKeon-Bennett and Hodkinson, 2021) and bioplastics (Silva, 2021) *Real-time monitoring, testing and development of in-field technologies with sophisticated laboratory equipment, such as flow cytometry with in-field algaTorch™ (Naughton et al., 2020) *Advancement of bioinformatics, next generation sequencing and machine learning (BIM, 2020) *Nexus between water – food – energy for fisheries development including development of LCA, MFA and PCA tools for informing sustainability of products and services (Ruiz-Salmón et al., 2020a,b) *Social marketing, awareness and stakeholder behavioural change towards low-carbon food security including circular bioeconomy (Domegan, 2021) *Effective communication strategies for seafood to promote health and sustainability (Sacchetttini et al., 2021) *Testing of new environmentally-efficient aquafeeds through use of multi-criteria decision-support tools (Cooney et al., 2021). *Sustainable recirculating alternatives to traditional 'end-of-pipe' technologies that negates unwanted pollution to receiving water (Tahar et al., 2017; Rowan, 2019)	1. 2. 3. 6. 7. 8. 9. 11. 13. 14. 15.
Quadruple helix hub concept and approach to sustainable research and innovation *Trans-regional development of Quadruple Helix Hubs (industry-government-academia-society) for advancing low carbon innovation and supporting communities and stakeholders (Rowan and Casey, 2021) *Development of living lab linked to environmental test beds for advancing research, enterprise, entrepreneurship and innovation with nexus to education, training and job creation (Li et al., 2018); Blue Hatch Aquaculture Accelerator Program, 2020: Rowan and Casey, 2021; Rowan and Galanakis, 2020) *Investing and enabling eco-innovation including green finance, design thinking and high potential start up accelerator investment linked to stage gate needs (Rowan and Pogue, 2021) *Early-technical validation (test-the-tech, experimentation/validation in pre-pilot); scaling to real-life setting *Transnational modelling and cluster development including forging European Innovation HUBs such as (Sharebiotech, 2021) and Regional University Network-European Universities (RUN-EU, 2020).	2. 4. 5. 9. 11. 12. 13.
Climate strategy, risk management, awareness and transparency *Publically-backed climate risk insurance for farmers that considers weather indexing for protection against extreme weather events (Doherty et al., 2021). *Risk modelling and assessment of key variables affecting asset and innovation performance and sustainability including use of EPA's SPR model (Tiedeken et al., 2017; Tahar et al., 2017; Tahar et al., 2018) *Supporting sustaining and disruptive innovation and services that also embraces technological, political and societal readiness levels (Geels, 2018; Rowan and Casey, 2021; Schuelke-Leech, 2021) *Current limited short-term focus on risk management, transparency post review of 1168 companies. Also, a lack of understanding of climate risk with few companies having climate strategies (Coppola et al., 2019) *International consensus on best indicators reflecting climate resilience, economy, society and culture (Barry and Hoyne, 2021).	4. 9. 11. 12. 13.
COVID-19 pandemic *Food and supply chain disruption including research provision (Guan et al., 2020; Herreror et al., 2020; Galanakis et al., 2021; Rowan and Galanakis, 2020) *Biorefining alternative sustainable materials for multiple-use PPE (Rowan and Laffey, 2020a,b; Rowan and Moral, 2021) *Food security and safety (Galanakis et al., 2021)	1. 2. 3. 9.
International policy and cohesiveness *Informing EU Green New Deal; UN Sustainable Development Goals; Paris Climate Agreement (Galanakis et al., 2022)	1. 2. 4. 9. 11. 16.
Climate change and action plans *Weather events and disease mitigating simulation and predictive models (Jenkings and Kane, 2019) *Development of in-field biosensors (and digital-sensors) to monitor performance of agri-food security linked to extreme weather events (Naughton et al., 2020; O'Neill and Rowan, 2022). *Informing multi-disciplinary and cross-functional international projects to seek agreement on climate change indicators that addresses ecosystem resilience with nexus to economic and sociocultural indicators (Barry and Hoyne, 2021).	3. 4. 13. 14. 15.
Digital transformation *Development of drones and satellites, IoT devices, AI and cloud-enabled technologies to monitor carbon sequestration of peatlands and other land types to improve understanding on human activity on land use and how it relates to climate change (Science Foundation Ireland (SFI), 2021) *ArcGIS mapping to inform restoration and rehabilitation of peatlands linked to ecology/biodiversity to inform carbon cycles (Rowan and Casey, 2021) *Development of digital twin that includes ARVR (Quality of Experience) for remote specialist virtual training (Braga Rodriguez et al., 2020; Rowan and Galanakis, 2020) *Precision agriculture including blockchain, AI, robotics, along with combining machine learning with bioinformatics to future proof environmental test beds and validate new products and services including ecological/biodiversity forecasting (Rowan and Pogue, 2021; Rowan et al., 2021; George et al., 2021) *Rainfall radar data and rainfall information collected from commercial microwave mobile phone backbone transmission networks (Chwala and Kunstmann, 2019); worldwide there is an interest in changes to sub-daily rainfall regimes for example through the INTENSE project (Blenkinsop et al., 2018) *Agriculture IoT, construction of agriculture IoT infrastructures, data security and data sharing, sustainable energy solutions, economic analysis and operation management in agriculture IoT, and IoT-based agriculture financing and e-business modes. IoT-based precision agriculture (Ruan et al., 2019).	1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 13. 14.

United Nations Sustainable Development Goals (UN SDGs); Augmented Reality Virtual Reality (ARVR); Life Cycle Analysis (LCA); Material Flow Analysis (MFA); Principle Component Analysis (PCA); Artificial Intelligence (AI); Internet of Things (IoT)

occurs when either the ground is already saturated, due to previous rainfall, and the new rain falling can only run off; or when the rainfall intensity exceeds the infiltration rate of the ground and again the rain will run off, these situations are often called a flash flood (Dimitriou, 2011). Detecting trends in long-term rainfall records is difficult due to the highly variable nature of rainfall and scarcity, often, of long records. Information on rainfall intensity, explicitly sub-daily and sub-hourly records, is much more sparse and short term in its record; although, data generated from growing hobby weather station networks can be potentially used to help fill this gap. Other sources could include processed rainfall radar data and rainfall information can be gathered from commercial microwave mobile phone backbone transmission networks (Chwala and Kunstmann, 2019). Worldwide, there is an interest in changes to sub-daily rainfall regimes; for example, through the INTENSE project (Blenkinsop et al., 2018).

Extratropical cyclones, produce more than 70% of the winter rainfall in north-west Europe. The islands of Ireland and Great Britain had their stormiest winter on record during 2012/2013 with more than two intense cyclones per week (Priestley et al., 2017). It is plausible that impacts due to global climate change in the sea surface temperatures in the Western tropical West Pacific along with the reduction in Arctic sea-ice may have allowed this stormy period of weather to occur. Noone et al. (2016) working on a recently homogenised Irish rainfall data set from 1850 to 2010 found there was a positive trend for the winter months and a negative trend for the summer months. In Ireland there are interests in the impact of unusual rainfall events on infrastructure. The impact of rainfall events and the destabilisation of railway embankments in Ireland was studies leading to an intensity and duration curve for significant failures (Martinović et al., 2018). A similar approach may be able to be taken in safeguarding other assets including aquaculture. There is also interest in blanket peat failures on slopes in Ireland, due to excess rainfall (Jennings and Kane, 2019). Flood impacts on aquaculture have been studied in the Czech Republic where during flooding in 2002, 2006, 2009, and 2013 some 54% of fish in pond-based system were lost (Rutkayová et al., 2018). Many of these losses seem to be from flash flood events attributed to riverine and overland flooding. Rutkayová et al., 2018 found the impacts to be different between juvenile and adult fish, and by species. These researchers also noted the importance in term of impacts of what they term the 'train effect', which is a repeated series of large rainfall events over the same area in a short space of time. This is a classic high impact situation where a series of non-record breaking, but high events when combined over a short space of time can have extreme impacts. Commensurate use of tools to inform management and decision-making at the farm level informed by life cycle assessment, material flow analysis and risk modelling will support and enable solutions to these complex challenges (Tahar et al., 2017; Ruiz-Salmón et al., 2020a; Ruiz-Salmón et al., 2020b).

4. Implications and opportunities of IMTA findings for informing emerging paludiculture and adjacent research and innovation

Findings from this fully-recirculating IMTA study have broader implications for informing worldwide collaborative research and innovation in many multidisciplinary and cross-functional domains beyond the initial focus of paludiculture (Table 2), and alignment with United Nations' Sustainable Development Goals (Table 3). Traditionally, there remains reliance on flow-through aquaculture processes that relies upon bespoke understanding of process performance and interventions including end-of-pipe solutions to safeguard receiving waters from polluted effluents (Rowan, 2011; Tahar et al., 2017). The reliable and repeatable operation of this freshwater IMTA process will enable generation of data that can inform the international development and standardization of paludiculture innovation (Tan et al., 2021; Ziegler et al., 2021). This wet-peatland aquculture innovation can be used for informing efficacy of carbon sequestration, GHG emission reductions and carbon cycles (Science Foundation Ireland (SFI), 2021), ecotoxicology and biodiversity (Rowan and Galanakis, 2020), food production, safety and security (Galanakis et al., 2021; Sacchetttini et al., 2021), ecosystem service management and pollination (Goblirsch et al., 2021), real-time monitoring of in-field technologies linked to living labs (Naughton et al., 2020); suitability of new environmental-friendly aquafeeds (Cooney et al., 2021), digital transformation including novel multimodal sensing technologies, IoT devices, AI and cloud-based innovation to inform effective management of carbon reduction (Science Foundation Ireland SFI, 2022); along with use of biorefinery concept to extract high value bio-based materials from microalgae and duckweed for one health applications (Rowan and Pogue, 2021) (Table 2).

Table 3

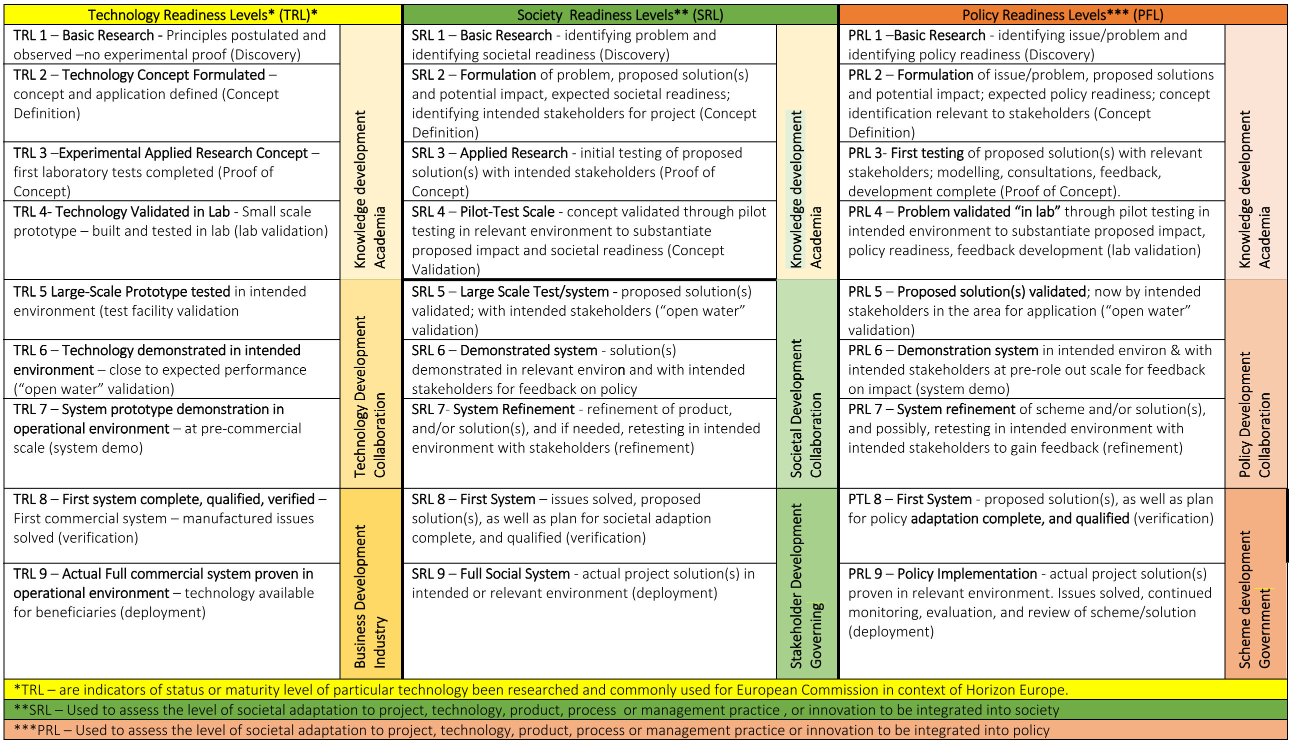
Indicative examples of IMTA activities and tools to support, enable and accelerate potential green innovation disruption under United Nations' Sustainable Development Goals (SDGS*).

UN sustainable development goal*		Sustaining or potentially disruptive activity
1	No poverty	Food production and value chain. Food security and managing climate events to avoid supply chain disruption. Production of high protein sustainable foods via IMTA system. Researcher mobility creating opportunities in education.
2	Zero hunger	Development and future climate-proofing sustainable agri-food processes and crops along with alternative sources for protein that includes training.
3	Good health and wellbeing	Adopting One Health approach to informing eco-green innovation community transition and social enterprise for health including COVID-19 that considers bio-refinery concept (Rowan and Galanakis, 2020; Galanakis et al., 2021)
4	Quality education	Openly sharing knowledge, discoveries and growing collaborations in academia, that cross-cuts STEM with Social Science and humanities, to inform behavioural change. Use of IMTA for specialist training linked to new eco innovation education that encompass green finance, food disruption, climate change.
5	Gender equality	IMTA framework is aligns with gender equality focused with equal representation in research, innovation, entrepreneurship, social enterprise, outreach, education.
6	Clean water and sanitation	Innovative green research and enterprise to promote natural resources for water quality and mitigate waste that moves beyond end-of-pipe solutions
7	Affordable and clean energy	IMTA powered by wind turbines, but also enables development of LCA tools for investing nexus between energy, water and food systems. This also enables commensurate research on sustainable carbon cycles (European Commission, 2021) and green energy using paludiculture platform.
8	Decent work and economic growth	IMTA adopts Quadruple Helix Hub approach that connects industry, government, academic and society – this will lead to informing new job creation and new eco-focused Start Ups along with risk management, transparency for climate action governance in business beyond short-term needs (Rowan and Casey, 2021). This will inform future economic indicators and growth via international collaboration.
9	Industry, innovation, infrastructure	IMTA is trigger new eco or green innovation and research that considers future infrastructure to provide standardization of outcome sets for climate change and sustainability using living labs and environmental demonstrator facilities – this will pump-prime new bio-based research, food production and circularity.
10	Reduced inequalities	Adopting a Quadruple Helix approach will enable broad stakeholder engagement to ensured equalities are met.
11	Sustainable cities and communities	IMTA system is a green innovation aligned with supporting needs of low-carbon communities for regional development and regeneration. This is aligned with European Just Transition and European Green Deal initiatives. This will be informed by social marketing and appropriate communication strategies (Domegan, 2021; Sacchetttini et al., 2021).
12	Responsible consumption and production	IMTA system will support digital transformation of what is a defined sustainable process to support responsible consumption, and production that will inform global needs. Future disruptive innovation likely to emerge from digital domain.
13	Climate action	IMTA system can inform efficacy of future food production processes as it pertains across addressing climate events and inform environmental, ecological, social, political and cultural indicators as state-of-the-art collaborative international demonstrator facility.
14	Life below water	IMTA supports freshwater aquaculture and studies on biodiversity related to natural aquatic ecosystems in peatlands
15	Life on land	IMTA supports biodiversity, pollination and ecosystem service management
14	Peace, justice, strong inst.	IMTA has core tenets that blends academia, industry, authority with communities.
17	Partnerships for the goals	IMTA supports and enable national and international partnerships aligned with UN SDGs that includes mobility and training.

This IMTA process will also support and enable development of low-carbon community and social enterprises promoted through the European Just Transition and Green Deal Initiatives (Rowan and Galanakis, 2020), which can be effectively managed through the use of ‘Quadruple Helix Hubs’ that converge academia, industry, government and society (Rowan and Casey, 2021). This Quadruple Helix Hub framework will also support and enable the commensurate delivery of paludiculture-based and adjacent research, innovation, entrepreneurship linked to education and specialist training of stakeholders and communities, which are essential converging activities underpinning trans-regional European Innovation Hubs. The development and deployment of a validated IMTA process in the peatlands will also support future sustaining and disruptive innovation, where the design, applicability and maturity of the innovation, product or service may be informed by use of various smart evaluation tools including technical, political and societal readiness levels (Fig. 7), life cycle assessment, material flow analysis, principle component analysis, ecotoxicology and so forth. For example, Ruiz-Salmón and co-workers (2020b) used LCA to highlight the important nexus between water, food and energy for development of fisheries including aquaculture across the European Atlantic Area. The open knowledge sharing of IMTA data will also support research into new green business development and transnational modelling of research and innovation (Rowan and Casey, 2021), which will include climate-related awareness, risk management and transparency (Tahar et al., 2019; Coppola et al., 2019) (Table 2). IMTA process and environmental data that can inform future risk mitigation for innovation will be particularly relevant. For example, Coppola et al. (2019) reported that Deloitte asked 1168 Chief Financial Officers (CFOs) what their companies are doing to help address climate change where a thorough understanding of climate risks was rare, few companies had governance mechanisms in place to implement comprehensive climate strategies, and targets for carbon emission reductions were usually not aligned with the Paris Agreement. Coppola et al. (2019) also noted that more than US$30 trillion in funds were held in sustainable or green investments in the five major markets tracked by the Global Sustainable Investment Alliance. The measured effects of extreme weather events, using this technically-defined IMTA process, will also inform development of predictive and simulated disease models influenced by climate change (Interreg Neptunas Project, 2019).

Barry and Hoyne (2021) reported that changes in weather systems, such as increased precipitation, snow and ice events, heatwaves and storms, have led the European Commission to develop new policies and strategies to deal with extreme events. Findings from, and future use of this IMTA system, will help inform a robust set of appropriate indicators to assess the impacts of climate change on adaptive food production and security at local and national levels. Barry and Hoyne (2021) noted that these indicators must encompass a multidisciplinary scope that also embraces ecological, social, cultural and economic changes, with greater awareness within all areas of society (Table 2). Process technical parameters used in this IMTA study will provide a useful environmental case study to help evaluate impact of climate change on paludiculture and other food systems beyond baseline observations of rainfall, temperature, GHG emissions, sea level rise/flooding and soil degradation (Aguiar et al., 2018). There is a pressing need for international agreement of relevant indicators existing outcome set used for scientific audiences that also address public interest and effects of climate change; these should allow public consumption and education through clear and concise communication standards (Williams and Eggleston, 2017). These IMTA findings contribute to climate resilience that relates to the capacity for ecosystems to respond to impacts, events or disturbances that are associated with climate change (Baho et al., 2017).

Moreover, Barry and Hoyne (2021) suggested seeking international agreement on indicators to inform ecological resilience, along with economic (such as number of new SME creation, innovation, investment in training, and specialist upskilling), social enterprise and cultural indicators (such as diversity of youth initiatives to increase civil action, solidarity and engagement). This IMTA system will also support need to inform natural capital and improvements in biodiversity, such as by promoting



Technology Readiness Levels* (TRL)*		Society Readiness Levels** (SRL)		Policy Readiness Levels*** (PFL)	
TRL 1 – **Basic Research -** Principles postulated and observed –no experimental proof (Discovery)	Knowledge development Academia	SRL 1 – **Basic Research** - identifying problem and identifying societal readiness (Discovery)	Knowledge development Academia	PRL 1 –**Basic Research** - identifying issue/problem and identifying policy readiness (Discovery)	Knowledge development Academia
TRL 2 – **Technology Concept Formulated** – concept and application defined (Concept Definition)		SRL 2 – **Formulation** of problem, proposed solution(s) and potential impact, expected societal readiness; identifying intended stakeholders for project (Concept Definition)		PRL 2 – **Formulation** of issue/problem, proposed solutions and potential impact; expected policy readiness; concept identification relevant to stakeholders (Concept Definition)	
TRL 3 –**Experimental Applied Research Concept** – first laboratory tests completed (Proof of Concept)		SRL 3 – **Applied Research** - initial testing of proposed solution(s) with intended stakeholders (Proof of Concept)		PRL 3- **First testing** of proposed solution(s) with relevant stakeholders; modelling, consultations, feedback, development complete (Proof of Concept).	
TRL 4- **Technology Validated in Lab** - Small scale prototype – built and tested in lab (lab validation)		SRL 4 – **Pilot-Test Scale** - concept validated through pilot testing in relevant environment to substantiate proposed impact and societal readiness (Concept Validation)		PRL 4 – **Problem validated “in lab”** through pilot testing in intended environment to substantiate proposed impact, policy readiness, feedback development (lab validation)	
TRL 5 **Large-Scale Prototype tested** in intended environment (test facility validation	Technology Development Collaboration	SRL 5 – **Large Scale Test/system -** proposed solution(s) validated; with intended stakeholders (“open water” validation)	Societal Development Collaboration	PRL 5 – **Proposed solution(s) validated**; now by intended stakeholders in the area for application (“open water” validation)	Policy Development Collaboration
TRL 6 – **Technology demonstrated in intended environment** – close to expected performance (“open water” validation)		SRL 6 – **Demonstrated system** - solution(s) demonstrated in relevant environ and with intended stakeholders for feedback on policy		PRL 6 – **Demonstration system** in intended environ & with intended stakeholders at pre-role out scale for feedback on impact (system demo)	
TRL 7 – **System prototype demonstration in operational environment** – at pre-commercial scale (system demo)		SRL 7- **System Refinement** - refinement of product, and/or solution(s), and if needed, retesting in intended environment with stakeholders (refinement)		PRL 7 – **System refinement** of scheme and/or solution(s), and possibly, retesting in intended environment with intended stakeholders to gain feedback (refinement)	
TRL 8 – **First system complete, qualified, verified** – First commercial system – manufactured issues solved (verification)	Business Development Industry	SRL 8 – **First System** – issues solved, proposed solution(s), as well as plan for societal adaption complete, and qualified (verification)	Stakeholder Development Governing	PTL 8 – **First System** - proposed solution(s), as well as plan for policy **adaptation complete, and qualified** (verification)	Scheme development Government
TRL 9 – **Actual Full commercial system proven in operational environment** – technology available for beneficiaries (deployment)		SRL 9 – **Full Social System** - actual project solution(s) in intended or relevant environment (deployment)		PRL 9 – **Policy Implementation** - actual project solution(s) proven in relevant environment. Issues solved, continued monitoring, evaluation, and review of scheme/solution (deployment)	

*TRL – are indicators of status or maturity level of particular technology been researched and commonly used for European Commission in context of Horizon Europe.

**SRL – Used to assess the level of societal adaptation to project, technology, product, process or management practice , or innovation to be integrated into society

***PRL – Used to assess the level of societal adaptation to project, technology, product, process or management practice or innovation to be integrated into policy

Fig. 7. Applying IMTA ecosystem to develop and track new eco-innovation to align and commensurate with technology, societal and policy readiness levels (adapted from Rowan and Casey, 2021).

agroecological farming, re-establishing organic carbon and microbiota in the soil and land, the potential use of biochar (Galanakis et al., 2022). Funding instruments, such as the European Just Transition Fund with an overall budget of €17.5 billion will help with a fair and equitable transformation to low-carbon communities where challenges will create opportunities through digitalisation that will boost employment and growth (Table 2). George et al. (2021) reported that digital sustainability and entrepreneurship can help tackle climate change and sustainable development (Table 2). Findings of this study will also support research informing sustaining and disruptive innovation (Schuelke-Leech, 2021), where greater awareness will be enabled through social marketing (Domegan, 2021). Bio-based products harvested and refined from microalgae occurring in this IMTA ecosystem can contribute to one-health solutions, including potentially contributing to alleviating COVID-19 (Murphy et al., 2020, 2022; Pogue et al., 2021).

There is a commensurate need to develop tailored communication strategies for promoting greater awareness of health and sustainability in seafood consumption given the diversity of attitudes and perceptions reported among Italian consumers by Sacchetttini et al. (2021) (Table 2). Moreover, Domegan (2021) highlighted the pivotal role of social marketing in critically examining the interface of human and natural systems and their interconnected dynamic forces as a powerful means of influencing behaviours for the accorded transformation and betterment of individuals, communities, society and the planet. In pursuit of Green Deal Innovations, such as embodied in this IMTA process, critical emerging trends in social marketing embrace important systems science, stakeholder engagement and digital technologies.

5. Conclusion

- Peatlands-based IMTA constitutes a potentially important sustainable and resilient system for advancing aquaculture, which will also support and enable development and validation of other sustaining and disruptive innovation, products and services.
  - While this IMTA model successfully produces commercial fish, and typically does not discharge to receiving water, this present study highlighted the challenges of operating a recirculating system with increased, and unexpected rainfall due to storms.
  - This IMTA system can help with improved understanding of environmental, social, cultural and economic indicators for broader appreciation of climate impacts based upon the people who are directly affected by the changes at local and national levels.
  - There is a pressing need to develop real-time approaches to monitor algae species that are potentially toxigenic, and to thoroughly investigate the impact of extreme weather events on balanced algal and microbial population in freshwater aquaculture ecosystem.
  - Given that there are potentially 1864 species of algae occurring in this peatland IMTA system that were identified using next generation sequencing and bioinformatics, there are pressing opportunities to exploit advances in flow-cytometry combined with machine learning to help unlock the challenge of purposeful monitoring.
  - Accessing and using weather data will present using opportunities to inform in field monitoring tools; for example, Ireland has a long-term data set of daily rainfall across 25 stations.
  - COP26 highlighted the pressing importance of enlisting a global response to curb carbon emissions so at to limit temperature rises to 1.5 °C; therefore, there is a commensurate need to investigate and test new sustainable food production systems (such as IMTA) that considers and hurdles extreme weather/climate events.
  - Biorefining products from this IMTA system using circular concept will help advance adjacent innovation, such as developing and testing fish feed improved for immune-stimulation to boost fish immunity to disease may help with priming against unforeseen events.
  - Further development and use of this IMTA process will help communities transition to low-carbon economies; however, there is a commensurate need to improve awareness in sustainable eco-innovation that can be improved by increasing social enterprises and by supporting the creating of new businesses such as through the Quadruple Helix Hub concepts that aligns with collaborative European Innovation Hubs (EIH), European Green deal and European Just Transition progamme initiatives.
  - A future climate-proofed IMTA system will also support and help meet the United Nations Development Goals, particularly alleviating against poverty, hunger along with fostering quality education, economic growth and innovation.
  - There are pressing opportunities to advance paludiculture through digital transformation, which may lead to business model or green-disruption.
  - Use of IMTA-system data to inform IoT-based precision paludiculture and agriculture.

CRediT authorship contribution statement

E. A. O'Neill, **N. J. Rowan**: Conceptualization. **E. A. O'Neill**: Data Curation. **E. A. O'Neill**, **A. P. Morse**, **N. J. Rowan**: Formal Analysis. **N. J. Rowan**: Funding Acquisition. **E. A. O'Neill**: Investigation. **E. A. O'Neill**: Methodology. **E. A. O'Neill**: Project Administration. **E. A. O'Neill**, **N. J. Rowan**: Resources. E. **A. O'Neill**: Software. **N. J. Rowan**: Supervision. **E. A. O'Neill**: Validation. **E. A. O'Neill**: Visualization. E. **A. O'Neill**, **A. P. Morse**, **N. J. Rowan**: Roles/Writing – Original Draft. **E. A. O'Neill**, **A. P. Morse**, **N. J. Rowan**: Writing – Review & Editing.

Declaration of competing interest

The authors declare that there are no competing interests or conflicts of interest with respect to the publication of this article.

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Appendix A. Supplementary data

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