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Authors	Rowan, Neil J.;Jansen, Marcel A.K.;Klimek, Peter
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Viewpoint

Unlocking the potential of a novel integrated multi-trophic aquaculture (IMTA) approach for producing resilient foods at scale in a post nuclear war world: A perspective exploiting freshwater fish, duckweed and microalgae

Neil J. Rowan[a,b,*], Marcel A.K. Jansen[c], Peter Klimek[d]

[a] Centre for Sustainable Disinfection and Sterilization, Technological University of the Shannon, Midlands Campus, N37HD68, Ireland
[b] Empower Eco Sustainability Research Group, Technological University of the Shannon, Midlands Campus, N37HD68, Ireland
[c] School of Biological, Earth and Environmental Sciences, Environmental Research Institute, University College Cork, Ireland
[d] Supply Chain Intelligence Institute, Medical University of Vienna, Austria

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ABSTRACT

The global agriculture system governing food security is strongly reliant upon environmental conditions including temperature, precipitation and sunlight, all of which could be significantly disrupted by a catastrophe such as a nuclear war. In addition to affecting primary agricultural productivity, a nuclear war would compromise critical supply chains and infrastructure. This perspective paper addresses a potentially new food production approach post catastrophe using integrated multitrophic aquaculture (IMTA) systems operating at scale. Developing a rapidly deployable IMTA system that (a) does not rely on using fertilizers, pesticides, pollination nor seed, (b) does not require arable land, (c) uses wastewater, (c), produces different secondary biomass (food) options rich in protein based on using fish waste produced onsite, (d) uses renewable wind energy, and (e) operates to zero waste principles underscore the rationale for its development and deployment post catastrophe. This regional approach may be rapidly deployed (within 4 to 6 months) to help offset reduced yields achieved from staple agricultural crops affected by abrupt sunlight reduction (ASR) and climatic cooling post catastrophe. By combining IMTA with onsite renewable wind-power, the system could potentially continue to operate, albeit at reduced levels of efficiency based, on previously modelled nuclear winter scenarios. Options for different resilient foods produced and dried at IMTA sites from same fish waste stream are described based on important factors for disaster preparedness and recovery. Despite the efficient demonstration and production of fish, duckweed and microalgae, it would be very challenging to replicate this same approach elsewhere in an appropriate timeframe to offset short term loss of food reserves given current operational challenges ranging from planning permission to meeting supply chain expectations. This paper provides a valuable insight into tangible issues to be addressed for the scaling of IMTA systems to support dietary needs of local and potentially regional populations. Given increasing geopolitical uncertainties globally, this paper highlights the potential need for developing resilient food processes that do not compete with staple foods for water, soil, fertilizer nor seed. However there is a pressing need to strategically invest, share knowledge and prepare IMTA sites ahead of a catastrophe so as to appropriately meet societal needs.

1. Introduction

Global climate disruptions can occur through extraordinary events such as nuclear conflict or super volcanic eruptions that would commensurately affect regional, national and worldwide food security (Xia et al., 2022; Garciá-Martínez et al., 2025). Widespread crop failures, infrastructure collapse, political instability and famine have previously been caused by natural catastrophes, such as after the 1815 Tambora eruption in Indonesia (Sothers, 1984). Crop failures after historic volcanic eruptions are documented by Jägermeyr et al. (2020), which have been used as analogues to model climate and food security effects based on nuclear war scenarios. A major component of these scenarios is due to soot injection into the stratosphere by volcanoes potentially causing abrupt reductions in solar penetration into the

* Corresponding author. Centre for Sustainable Disinfection and Sterilization, Technological University of the Shannon, Midlands Campus, N37HD68, Ireland.
E-mail address: neil.rowan@tus.ie (N.J. Rowan).

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biosphere, in turn, affecting temperature, precipitation (Damany-Pearce et al., 2022), but also photosynthetic performance.

The existence of nuclear weapons implies an existential risk to our planet (Garciá-Martínez et al., 2025). Nuclear weapons have increased in complexity and magnitude of destructive force since the first use of fusion bombs on the cities of Hiroshima (15 kt) and Nagasaki (21 kt) in Japan, triggering an end to WWII (Jägermeyr et al., 2020). Modern day fission hydrogen or thermonuclear bombs have yields from 100 kt to more than 1 megaton Mt, but theoretical maximum yield can exceed 50 Mt, as demonstrated by the Soviet Tsar Bomba test in 1981. The severity of impacts on local, regional or global scales would depend on the interactions between nuclear weapon explosion(s) (type, yield, height and frequency of detonations) and physical and human targets, as well as other phenomena such as atmospheric conditions, geographic location (urban, rural, coastal, ocean environs) and time (hour, day, month, season) (Jägermeyr et al., 2020; NASEM, 2025). Nuclear blasts emit nuclear radiation, thermal radiation, pressure shock waves, and electromagnetic pulses (EMP). These can destroy, amongst others, agricultural (crops), forestry terrestrial and marine and fisheries ecosystems (NASEM, 2025). Immediate effects of nuclear blasts are accompanied by contamination with long-lived radionuclides. For example, the nuclear power plant accident in Fukushima in 2011 emitted ca. 17 PBq of ^{137}Cs. A decade later, ^{137}Cs contamination levels that exceeded Japanese national safety standards were reported for wild plants, mushrooms and animals, and in fish adjacent to ground zero (Komatsu et al., 2021).

In addition to military targets, the potential yet conceivable detonation of nuclear weapons on cities, industries and logistic nodes might also cause catastrophic firestorms injecting enormous amounts of black carbon soot into the stratosphere abruptly affecting solar radiation in the biosphere, and causing a nuclear winter (NASEM, 2025). This effect has clear conceptual parallels with climatic impacts caused by e.g., volcanic eruptions and large-scale wildfires. Scientific reports have modelled the impact of different nuclear war scenarios, such as the conditions that may generate teragram quantities of soot with detrimental consequences to climate, agriculture, infrastructure and supply chains (Xia et al., 2022). It was estimated that the injection of 5 Tg of soot into the atmosphere (regional conflict) would decrease global calorie production by crops by 7% over 1 - 5 year. Soot injections of 47 Tg and 150 Tg (global conflict), respectively, are modelled to result in reductions in global calorie production of 50% and 90%.

It is estimated that food stocks will not extend beyond 4 months with catastrophic implications for maintaining global food security and trade (Garciá-Martínez et al., 2025). Additionally, researchers have predicted massive global ozone loss following regional nuclear conflict (Mills et al., 2008) that can affect food production through increased UV damage to crops. However, this is a highly complex topic where significant knowledge gaps exist on both nuclear war effects and societal and climatic impacts. For example, there is a gap in understanding of how a regional nuclear war can potentially affect mixed food production systems in other distant locations globally (Xia et al., 2022; Wilson et al., 2023). For example, the severity for food yield loss could be exacerbated in the case of impacts on staple crops such as maize, soybean, rice and wheat that are produced at scale for supply chains globally. Other researchers have modelled for benefits of using frost resistant crop production to offset food supply disruption during a nuclear winter catastrophe (Wilson et al., 2023). The National Academy of Sciences, Engineering and Medicine (NASEM, 2025) reported that impacts of nuclear war scenarios are challenging to estimate quantitatively. Given this complexity and importance, the United Nations and World Health Organizations have assembled expert panels to report on the effects of a nuclear war in 2027 and 2029 respectfully. Several authors have reported on the importance of providing appropriate resilient food systems through strategic modelling to meet food demand post catastrophe. However, there is a marked gap in operational research using appropriate demonstration systems for resilient food production including exploiting the bioeconomy.

The aim of this review is to explore ongoing operational research on resilient food systems with a focus on a novel integrated multitrophic aquaculture (IMTA). This is not intended as a quantitative review, but rather as a signpost, indicating the potential, robustness of IMTA systems in a post catastrophe world, and the consequent importance in terms of food production and supply chain management. The paper gives a broad, global perspective on the circular, resource-efficient IMTA model that is relatively independent of supply chains. This perspective paper is presented in 4 inter-related sections (1) methods used to review and discern databases for eligible papers aligning with the overall aim; (2) description of a novel integrated multi-trophic aquaculture (IMTA) circular site supporting resilient food production using the same fish waste stream and uses onsite renewable wind energy; (3) a comparison of different resilient foods produced at an exemplar IMTA site based on tolerance to low lighting and temperature and other considerations ranging from calorific value to, rapid deployment, and (4) supply chain and logistics for preparedness and recovery post catastrophe.

2. Methodology

This perspective paper was guided by using a PRISMA scoping review approach as a as search narrative and is not a quantitative review of the literature for meta-analysis of data purposes. This search approach used Pubmed and Web of Science databases mostly over the period 1946 to February 2026. Key word combinations were “food + nuclear war” (n = 78); “food + nuclear contamination” (n = 2597); “food + nuclear accident” (n = 71); “food resilience + catastrophe” (n = 68); “nuclear war + supply chain” (n = 146); “nuclear + pollination” (n = 9); “RAS + low light + aquaculture” (n = 8); “pollination + nuclear accident” (n = 4); “microalgae + food + cold” (n = 44); “macroalgae + food + freshwater” (n = 86); “duckweed + low light” (n = 36); “mushrooms + low light + low temperature” (n = 7); “duckweed + low temperature” (n = 4); “pollination + low light + food” (n = 46). Emphasis was placed on evidence-based knowledge for understanding food resilience as applied factors influencing the development and operational deployment of any IMTA site post a catastrophe. Eligibility criteria include peer-reviewed published papers supporting and enabling freshwater production of fish, single-cell microalgae, filamentous-macroalgae and mushrooms as well as vertical farming under potentially catastrophe conditions. All journal paper titles were reviewed, papers whose focus aligned with eligibility criteria were downloaded in full for critiquing. Duplications were also removed. This limited the total number of identified papers to n = 363. Excluded papers were those that did not inform production or demonstration of food production approaches under conditions relevant for catastrophe mitigation. Examples of excluded topics from searched databases included non-destructive food testing, nuclear magnetic resonance spectroscopy, cardiovascular disease, bioplastics, cancer treatment, disinfection, biofloc technology, biochar, fertilizers, biomethane, cold plasma, cosmetics, paralytic shellfish, edible packaging, colourants, biostimulants, quality control, soil contamination, biodegradation, radiation protective equipment, acute radiation syndrome, food allergens, training, manpower, food forensics, commercial gamma-irradiated foods. Finally, identified papers were explored for relevant information concerning production and demonstration of resilient foods at IMTA sites. This limited the number of identified included papers to n = 78.

3. Climate change mitigation

Mitigating the severity of a global catastrophe including nuclear war is a multi-factorial challenge where one candidate solution includes developing appropriate resilient crops and foods that are tolerant of reduced light and temperature conditions (Baum et al., 2019; Boyd and Wilson, 2023a; Ord, 2020; Xia et al., 2022; Pinsent and Tan, 2024; Siver, 2022; Garciá-Martinez et al., 2025). Pham et al. (2022) defined these as “interventions capable of producing substantial quantities of calories

and essential nutrients even during a global catastrophe when conventional methods of food production would be inadequate to feed the global population". This perspective paper aimed to align with the definition used by García Martínez et al. (2025) for considering a resilient food method that must: 1) provide sufficient food to reliably feed a significant portion of the global population, 2) be able to maintain high production during the resource-constrained period of a catastrophe, and 3), have the ability to rapidly ramp up production so it can be available before stored food runs out.

Complementary strategies proposed to mitigate the abruptness of such catastrophe on agriculture and crop yield consider redirecting human-edible food used for animal feed that may rapidly increase the amount of available food to avoid famine (Garciá-Martínez et al., 2025). Land dedicated to producing biofuel or fodder crops could be repurposed for growing crops for human consumption. However, government policies would need to tailored to address this necessity including strategic investment for updating disaster preparedness action plans. Strategies that reduce food loss across the supply chain to point of sale along with food waste discarded by end-users are also proposed (National Academies of SciencesEngineering and Medicine, 2025). Coincidently, reducing food waste including use of sustainable conversion systems and valorisation processes at scale are currently being addressed across the bioeconomy sectors (Rowan, 2025). Technologies to unlock scalable innovation as described in this review for enhancing the circular economy may also mitigate food waste post a catastrophe. Despite technological advances, several researchers have argued that current preparedness to feeding regional and global populations post a catastrophe is grossly lacking (Boyd et al., 2024; Boyd and Wilson, 2023b; Wilson et al., 2023; Garciá-Martínez et al., 2025). A substantial decline in crop yields would lead to societal pressures that would cascade to elevating food prices and shortages. Garciá-Martínez et al. (2025) concluded that there remains considerable uncertainty as to what degree of coordination and cooperation may avoid food shortages, and to what extent the development of resilient foods can prevent these instabilities from becoming unmanageable.

4. IMTA demonstration blueprint for resilient foods post catastrophe

Garciá-Martínez et al. (2025) proposed use of an integrated multitrophic aquaculture (IMTA) as a means of resilient food production following a potential catastrophic event that reduces sunlight and temperature. An IMTA system is defined by the enhanced production of aquatic organisms (with or without terrestrial organisms) of two or more functional groups that are tropically connected by demonstrated nutrient flows, and whose biomass is fully or partially removed by harvesting to facilitate ecological balance (Rowan et al., 2024). Emphasis of this perspective paper is focused on use and scaling of an exemplar IMTA site given its ability to achieve full waste management addressing efficient ammonium and phosphorus bioremediation without relying on using fertilizers, pesticides nor seed.

The aim of this review is to explore ongoing operational research on resilient food systems with a focus on a novel integrated multitrophic aquaculture (IMTA). Many currently operational IMTA sites are relatively small scale, and will have limited capacity to meet regional food supply needs; however, key operational activities and limitations for production and its scale up are considered under reduced yield conditions due to abrupt sunlight reduction and climate cooling. The potential to scale-up of IMTA sites is substantial, and this includes both marine IMTAs in coastal zones as well as freshwater IMTAs in naturally wet areas. For example, many farms in the tropic-humid or temperate zones would include relatively wetland that can be easily converted towards IMTA applications. Peatlands comprise another potential zone for IMTA applications, especially degraded peatlands where restoration appears not feasible. This approach is considered appropriate in Ireland where peatlands cover approximately 1.46 million hectares accounting for ca. 20% of the country's total land area (Sabokrouhiyeh et al., 2025). Potential for expansion of IMTA approaches across cutaway bogs in midlands, and potentially into blanket bog in other locations regionally subject to understanding variances in peat soil and types, hydrology, ecology, catchment profiles and so forth. Peatlands occur in every climatic zone (Xu et al., 2018), the total area globally is around 4.23 million km^2, which corresponds 2.83% of the Earth's land surface. According to Xu et al. (2018), the majority of the worlds peatlands are situated in Asia (38.4%) and North America (31.6%, mostly Canada & Alaska). European peatlands make up 12.5%, followed by South America (11.5%), Africa (4.4%), and Australasia and Oceania (1.6%). Estimated peatland area accounts for 5.42% of terrestrial area of North America, followed by Europe (5.2%), Asia (3.6%), South America (2.7%), Australasia and Oceania (0.9%), and Africa (0.6%). Given the degraded state of many peatlands, use of such sites offers potential for rapid upscaling of IMTAs post catastrophe.

4.1. A circular peatlands-based IMTA demonstration site at scale in Irish midlands

As a testable upscaled IMTA model, a new national demonstration site has been constructed for research and demonstration purposes in the Irish midlands adopting bioeconomy principles for full waste mitigation. Specifically, this 12,800 m^2 (ca. 5.4 ha) site is situated at a wind farm in the centre of Ireland (53° 17′3″N - 7° 11′45″ W). An aerial image of this IMTA demonstration site is shown in Fig. 1, and highlights the location of key infrastructure that supports resilient food production and conversion systems. In this IMTA system, freshwater aquaculture species (rainbow trout (*Oncorhynchus mykiis*)) are cultured along with species such as microalgae and duckweed that extract inorganic (i.e. plant nutrients) (O'Neill et al., 2019; O'Neill and Rowan, 2022);, and to some extent organic compounds (Mohedano et al., 2014). Thus, it is possible to maximize resource utilization while minimizing supply chain dependency. This IMTA site does not use chemical biocides nor fertilizers and does not discharge to surrounding environment (Rowan, 2025). This site is less likely to become contaminated from long-lived radionuclide(s)-material from adjacent receiving aquatic environments as it does not require external sources of water such as river water or lakes (O'Neill et al., 2022). Thus, it is argued that a roll-out of IMTAs, pre-, or post-catastrophe, should carefully consider geographic location, including risk of nuclear fallout, water intake and radionucleotide monitoring. This fully circular site consists of four split (pill) ponds for culturing rainbow trout stocked with 30,000 kg of fish (O'Neill et al., 2022a) throughout the year, equating to a production rate of 0.49 ± 0.20 kg fish m^{-2}.$year^{-1}$ (Stejskal et al., 2022). Each D-end fish culture area is equipped with oxygen and temperature probes connected to paddlewheels to provide extra oxygen when necessary. The ponds are connected to a lagoon with sixteen channels serving as a natural treatment system (Fig. 1). The channels are covered by a mixture of two native duckweed species (*Lemna minor* and *Lemna gibba* species) (Paolacci et al., 2022). The duckweed can remediate 0.78 T yr^{-1} of total nitrogen and 0.38 T yr^{-1} of total phosphorous from the fish waste stream yielding ca. 500 T per yr^{-1} duckweed fresh biomass of high protein content ($21.84 \pm 2.45\%$) (Paolacci et al., 2022). The IMTA system currently operates as a circular bioeconomy demonstration site where microalgae and duckweed biomass use nitrogen and phosphorus from fish culture (faeces) waste stream excreted into channels to return clean water to the D-end pill ponds (Fig. 2). The channels are 100 m long, 8 m wide and their depth varies between 90 and 130 cm depending on the morphology of the canal bed. Development of this IMTA site for described foods took ca. 4 years at an investment of ca. €6M from public and private sources (Rowan, 2026). The majority of this time was attributed to granting of fish licence, awarding planning permission, procurement framework, site development and conducting independent ecological reporting that would be considered as grossly underappreciated (Rowan, 2026). Pollination by insects is vitally important for global



Fig. 1. Aerial view of layout for established and proposed (*) resilient food and biofuel production on IMTA peatland site. **A** living lab (funded)); **B** innovation and extended reality suite (funded); **C** Biorefinery (funded); **D** fish pond; E* Biofuel); **F** Duckweed and Microalgae; **G*** Macroalgae; **H*** Mushroom cultivation; **I*** Honey production – ecosystem service management, **J** reception/welfare. ⬭ indicates location for microalgae monitoring and sampling.

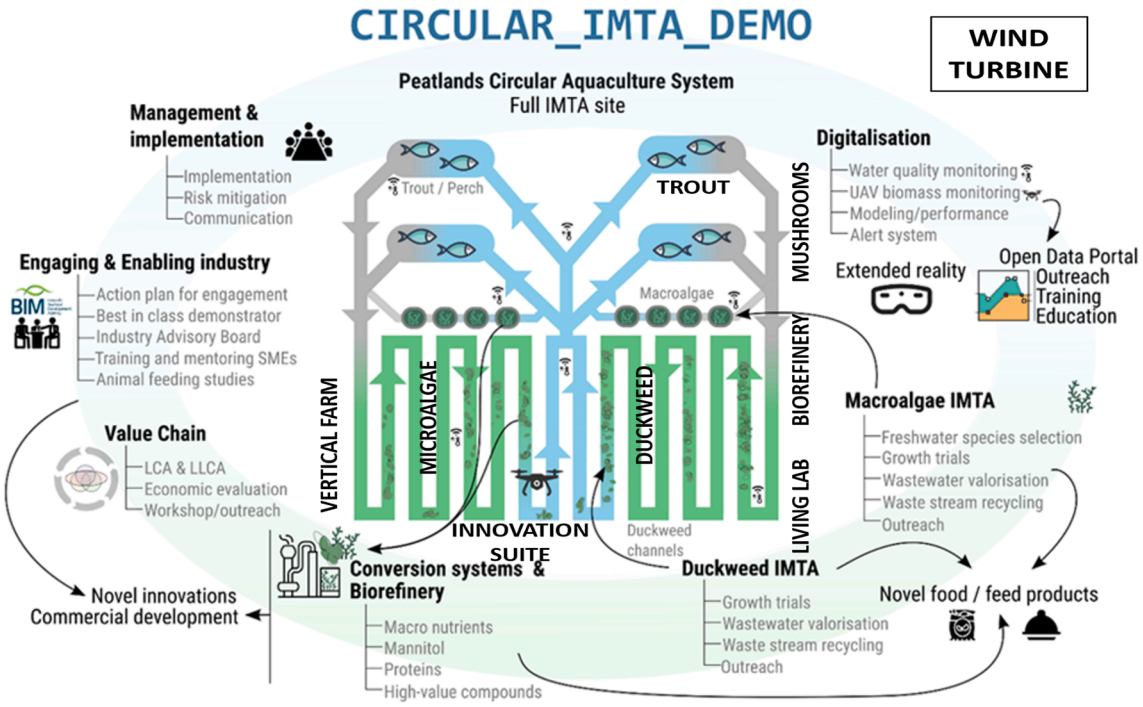


Fig. 2. Schematic of IMTA process for resilient foods in Irish peatlands.

agriculture and sustainable crop production (Dicks et al., 2021). The impact of such extreme events on pollination and ecosystem service management needs to be further investigated (Erenler et al., 2020). However, the particular foods produced at this IMTA site do not require the services of bees or on insect pollinators.

Table 1 highlights key operational, environmental and food production challenges to be addressed in order to develop and deploy IMTA production sites for named foods in this review within a 6 month period. This table shows that a concerted multi-actor process enabled by agile and effective management would be required to meet these considerable challenges where many existing regulatory restrictions for IMTA site development would need to be fast tracked under emergency use authorization. It also underscores the importance of specialist staff, infrastructure, equipment and complex site development works that may not be readily available post a catastrophe without prior preparedness. Additionally, considerable surveying and studies of other peatland locations would be required to understand appropriateness for recreating similar type IMTA system that must address soil type, peatland layers, hydrology, ecology and so forth. Therefore, under crisis conditions, the current IMTA model would struggle to be deployed from a starting undeveloped site to full operation within 6 months to support catastrophe recovery. Therefore, current best-available information would suggest that emphasis would be placed advancing established IMTA site(s) upgraded for cold conditions and reduced sunlight ahead of a catastrophe. Provision and maintaining aquaculture and food production during a catastrophe would entail stocking of materials for water quality management, aeration, fish feeding, biomass harvesting and operation of biorefinery. Core items include water pumps, back up power generators, paddlewheels, automatic feeders, harvesting nets, biocides for biosecurity stations (such as footbaths), protective gear.

Power is supplied by an onsite wind turbine. Each wind turbine at the IMTA site has a capacity of 3MW (there are 28 wind turbines, thus ca. 84 MW in total). It is estimated that the capacity factor is ca. 25 to 30% for each turbine producing ca. 7500 MWh annually. Based on power draw assumptions for all activities on the IMTA site including paddles, living laboratory and biorefinery annually (which amount to ca. 208 MWh), each turbine produces ~35 to 40 times more power than the site uses. (Varne et al., 2024) reported that Northern hemisphere extratropical regions can potentially retain about 65%, and tropical regions around 40%, of baseline wind power under a climate scenario where 150 Tg of black carbon is lofted into stratosphere. Thus, it is plausible that the wind farm couldl theoretically provide sufficient energy to operate the IMTA site post global catastrophe. However, other restricting factors may affect wind power provision to this same site during a nuclear war event ranging from ice accumulation on blades to interference caused by an EMP. However, extent of these potential nuclear war mediated impediments for maintaining sufficient power supply at this IMTA site is unknown. That said, limited amounts of biofuel can be produced onsite from harvested duckweed. Additionally, onsite biofuel production, or peat-based power stations, could be reactivated using locally harvested biofuels to meet regional needs including supporting the IMTA site.

5. Demonstrating resilient foods at scale at peatlands-based IMTA site – Quo Vadis?

Nuclear winter preparation and adaptation are multi-factorial challenges (Baum et al., 2019; Boyd and Wilson, 2023a; Ord, 2020; Xia et al., 2022; Pinsent and Tan, 2024; Siver, 2022; Garciá-Martinez et al., 2025). The degree of disruption caused by a nuclear winter will depend on the magnitude of the climatic change. Thus, nuclear winter preparation and

Table 1
Challenges to be considered to implement key infrastructure and activities at IMTA site for full deployment within 4 to 6 months in order to meet post catastrophe needs.

Site Development Operation Challenges	Resilient Food Systems (Challenges & Unknowns)	Environmental and Climate Challenges
➢ Fast track Fish licence	➢ Daily monitoring of aquatic physico-chemical parameters	➢ Ecological surveys and site LCA, MFA
➢ Expedite Procurement Process (infrastructure and equipment)	➢ Reduce depth of fish ponds for protecting trout to cold shocks.	➢ Peatland soil and layers (analysis)
➢ Standard Operating Procedures	➢ Monitor fish welfare and health.	
➢ Secure investment	➢ Onsite fish hatchery, fish supply and feed	➢ Hydrological profiling
➢ Technical/Finance audits		
➢ *Recruitment and training*	➢ Cultivar selection for duckweed for adapting to cold stress conditions at IMTA site	➢ Climate and weather monitoring – linked or onsite weather station for measuring surface temperature, precipitation, solar radiation and PAR.
➢ *Aquaculture manager	➢ Maintenance of channels for duckweed (competition for against plant invasive species)	
➢ *Site Management & Maintenance, Security.	➢ Optimise for reduced sunlight.	
➢ *Biorefinery manager & operators, Food blends.	➢ Aerial drones for monitoring duckweed coverage.	
➢ *Botanist, Algae Experts, Ecologist, Mycologist.		
➢ Logistics, supply chains		
➢ Consortium agreement & Agile management for decision support process	➢ Agile management for fish waste stream to selected biomass option.	➢ EPA reporting
➢ Co-location to wind farm	➢ Production of positive *Chlorella* in living lab for introducing into IMTA channels	➢ Emissions and energy monitoring
➢ Built material stockpile such as polytunnels		
➢ Procuring/retrofitting-built units for living lab, biorefinery, vertical farms	➢ Select cold-loving microalgae species for production ➢ Appropriate bioprocessing	➢ Influence of nuclear war on wind energy supply onsite.
➢ Civil, mechanical and electrical contract works for infrastructure & cost	➢ Complex production process and sterilization for button mushrooms – disease mitigate	➢ Limited biofuel for mechanization onsite
➢ Health, Safety, Fire Procedures/ Certification	➢ Onsite feed formulation for fish production	➢ Bioindicators for trophic levels (IMTA)
➢ Wifi connectivity for site	➢ Fast growing, cold-loving filamentous macroalgae	➢ Specialist training.
➢ Supply chain (regional)		
➢ Bore hole water facility and pump house	➢ Energy for on site vertical farms, polytunnels.	➢ Monitor water quality effluent (storm water)
➢ Biosecurity & Welfare	➢ Monitoring for radionuclide contamination of site	➢ Inform and tailor strategic policies
➢ Multi-actor Engagement		
➢ Waste water management and recirculation onsite	➢ Digital decision support system for managing circular biomass.	➢ Multi-actor stakeholder engaging.

LCA (Life Cycle Analysis); MFA (Materials Flow Analysis); PAR (Photosynthesis Active Radiation).

adaptation are bespoke processes that are scenario dependent. Nevertheless, a common factor will be the need for a resilient food supply, achieved in the context of lower global temperatures, lower global light intensities and a potential breakdown of global supply chains. Thus, nuclear winter preparation and adaptation would benefit from the development of stand-alone circular agricultural system that is flexible, dynamic and can operate with minimal external inputs. Here it is argued that IMTA systems that maximize resource utilization with full waste mitigation are potentialcandidate model for catastrophe preparation and recovery (schematic, Fig. 2). Production of different food stocks is centred on specific use of waste stream from fish ponds (Fig. 3); thereafter, these are blended and dried at onsite biorefinery to meet energy and nutritional demands for human consumption (Fig. 3).

5.1. Finfish production (Recirculating aquaculture)

Currently, land-based, low-cost, recirculating aquaculture systems (RAS) are growing in popularity as a significant contributor to meet global food and nutrition security (Zhang et al., 2025). Over 50% of aquatic animals produced for human consumption now come from aquaculture (FAO of the United Nations, 2026). Supply of fish from sustainable aquaculture practices has been suggested as a potential solution to offset shock to critical supply chains from catastrophe. Fisheries strengthen resilience by acting as a food safety net during lead times and disasters when crops and livestock productivity is impaired (UNDP, 2025). Depending on the severity of a nuclear winter, and the need to supplementterrestrial crop yields, fisheries are of interest. Yet, only small increases in wild fish capture are possible (Scherrer et al., 2020). Freshwater Rainbow Trout was selected for culture at this Irish IMTA site as it is a cold-living fish species tolerant of environmental stresses (Naughton et al., 2020; O'Neill et al., 2022a,b) (Table 2). With an optimal growth temperature between 12 and 19°C, modest environmental cooling will not impact productivity, depending on the location. Rainbow trout have been shown to tolerate stressful environmental conditions ranging from sub-zero to 26°C at this IMTA site (Rowan, 2026). Thus, resilient aquaculture systems, such as this IMTA model, may play a role in tolerating abrupt sunlight reduction (ASR) and climatic cooling associated with a nuclear winter event. In this model, farmed fish are not just used as a food source, their waste stream that is rich in nitrogen and phosphorous can also facilitate generation of secondary biomass (i.e., microalgae, duckweed and potentially mushrooms that are biorefined and dried onsite). To generate a closed loop, improve resilience and minimise dependency on supply chains, an onsite hatchery can supply fingerlings raised using ca. 5% of total yield of microalgae and plants produced on site as feed. The resilience of IMTA to environmental stressors is demonstrated by a low mortality rate (<3%), which in turn is due to good water quality, low levels of pathogens, and potential consumption of beneficial microalgae and plants (Stejskal et al., 2022), which may trigger immune-modulating properties to the fish. Immune-priming for fish and human health is an emerging area relevant for post catastrophe scenarios (Pogue et al., 2021; Murphy et al., 2022).

5.2. Freshwater IMTA-based microalgae production

Microalgae are microscopic, mostly single celled, organisms that have been exploited for their ability to produce high protein and various bioactive compounds such as pigments, vitamins, polyunsaturated fatty acids, polysaccharides, bioactive peptides, and polyphenols (Ferreira de Oliveira and Arisseto Bragott, 2022; Andrade-Bustamante et al., 2025). Microalgae have also been consumed as a human food source for millennia. In the European Food Safety Authority (EFSA)'s Novel Food Safety Regulation (EU) 2015/2283, species such as *Aphanizomenon flosaquae*, *Arthrospira platensis*, *Chlorella vulgaris*, *Tetraselmis chuii,* and *H. pluvialis* have been approved for human consumption (Andrade--Bustamante et al., 2025) and immune-boosting properties. Use of microalgae as a food source can potentially compensate for the negative impacts of nuclear winter on resource-intensive agriculture (Table 2).

IMTA systems are rich in microalgal biodiversity (O'Neill and Rowan, 2022) where they bioremediate organic waste from fish cultivation. Thus, microalgae cultivation is fully compatible with fish-aquaculture. Although microalgae are autotrophs, most species also display hetero- or mixotrophic growth (Cheirsilp and Torpee, 2012), emphasising their ability to survive the low light and low temperature conditions post nuclear winter (Singh and Singh, 2015). Consistently, photosynthesis typically saturates at low light levels. Adaptation to low temperatures has also been reported, with some species actively metabolising in sea ice at sub-zero temperatures (Lund-Hansen et al., 2024). Thus, microalgae are resilient and can potentially cope with nuclear winter conditions, offering scope for extraction of bioactives and production of food

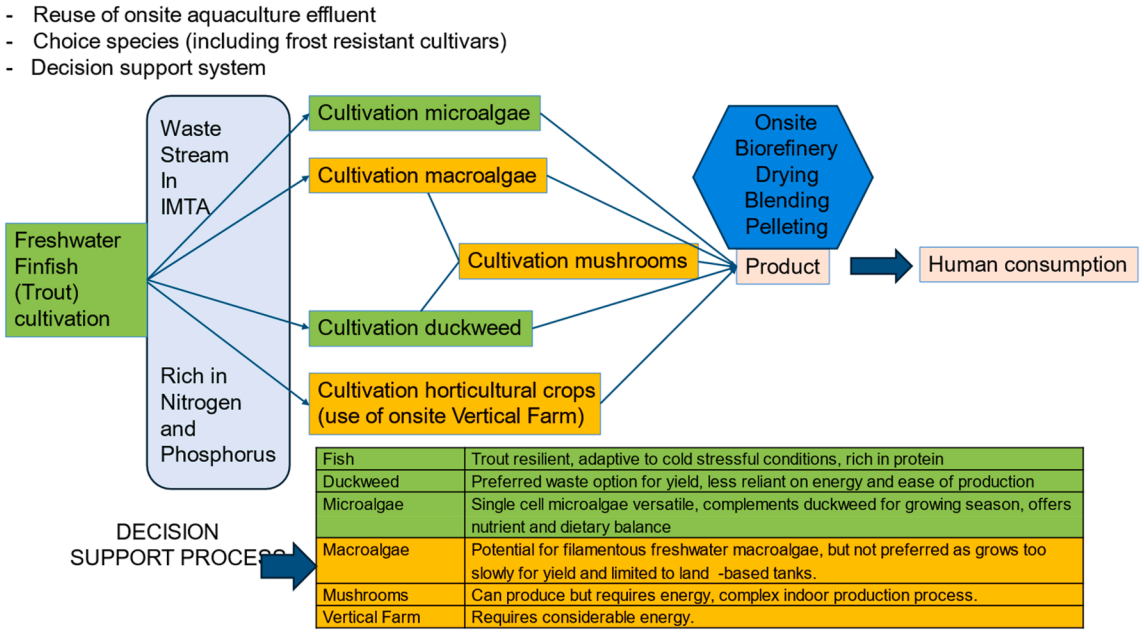


Fig. 3. Flow of fish waste to support different foods onsite in IMTA system.

Table 2
Comparative profile of indicative key considerations for producing different resilient foods in the IMTA site.

Description	IMTA Site [Circular Peatlands Model]				
	Freshwater Fish (trout)	Duckweed	Green Microalgae	Macroalgae (seaweed)	Mushrooms[a]
Calorific value [Dried Kcal/100g]	Range 160 to 300	Range 180 to 440	~294	~296 Red seaweed	Range 290 to 300
Protein	Up to 80% biomass	~30% biomass	up to 70% biomass	30 to 32% biomass	20 to 30% biomass
Micronutrients	Rich in Vit D Vit B12 potassium, phosphorus	3.5 to 26% Potassium Phosphorus, Calcium, Zinc, Selenium B12, Vit E, Beta-carotene, Ash	Essential amino acids, Iron, magnesium, iodine, calcium, Vit A, Vit B12, potassium	Iodine (very high supporting thyroid), calcium, magnesium, Iron	Magnesium Calcium Iron, selenium, Copper, Iodine B vits (Riboflavin, niacin, Panthothenic Acid, Vit D.
Other	Fat, 8 to 10% high in Omega -3s CHO/fiber (0%)	Up to 20% CHO (starch, cellulose pectin) Fats 1 to 14%% high in Omega 3, fibre 7-25%	High lipids and fat 5.8% Fibre 4.6% CHO (38.15%)	Fat 1 to 4% CHO (50 to 52%) Fibre (30%)	CHO up to 40% Fibre up to 30% Fat (low) 1 to 3% Beta-glucans (immune health
Biomass/Yield [IMTA 5.4 ha]	~30 tonnes capacity in 4 D-shaped ponds per day	~500 tonnes per year	Outdoor raceway ponds ~10 to 20 g m-2 d-1 PBR ~ 2 g L-1	Highly variable, ca. 1.3 g m-2 d-1 for specific alga	Commercial ~35 kg/m2
Light tolerance and requirement for survival μmol m^{-2} s^{-1}	Brown trout thrive in low light (active at night)	Absolute min (~4 – 18 μmol m^{-2} s^{-1}). Growth ≥50 μmol m^{-2} s^{-1} (Paterson et al., 2022).	Minimum ~30 to 100 μmol m^{-2} s^{-1} [Some can adapt to 15 μmol m^{-2} s^{-1}]	Typically low (~1 – 10 μmol m^{-2} s^{-1}) [Leukart, 1994]	No sunlight required as not photosynthetic. Small amount of indirect light needed to trigger fruiting.
Temperature (°C)	Active 10°C to 20°C Stress Survival at 0.5°C. Lethal ≥21°C [a]Survived 26°C at IMTA	Min growth *Lemna minor* ca 5°C to 10°C. Active growth ≥6°C	Optimal >20°C; cold adapted strains ≥5°C	Min 0°C to 5°C (marine) *Chordaria* sp. Freshwater *Cladophora* sp [5°C to 10°C]	Indoor process. Oyster/Shiitake *White Button* incubation 13 to 18°C; fruiting 10 to 21°C. Sterilization required for substrate.
Pollination dependent	No	No	No	No	No
Time to full production	Currently: 3 to 4 years Crisis: ~6 months	~3 months Seasonal [growth March to Oct]	~2 to 3 months [less light, temp dependent	~3 to 4 months [freshwater growth is complex]	Oyster/Shiitake ~1 year White Button ~3 months
Infrastructure	Complex Biorefinery Hatchery Living lab	Less complex Biorefinery Living lab	Complex Biorefinery Photo-bioreactors	Less complex Land-based tanks Living lab	Polytunnels must control high humidity, temperature
Manpower[a]	Specialist (aquaculture)	Specialist (cultivars and botany)	Specialist algal biotech	Specialist Freshwater Alga biotech	Specialist for White Button Mushrooms
Complexity	High, fish welfare, onsite hatchery.	Low to moderate– in field monitoring	Moderate: Living lab for prep and monitoring	Moderate including land based tanks	Simple (Oyster) to complex (White Button)
Closed system	Yes	Yes	Yes	Yes	Yes
Waste management	Full reuse to zero waste	Fish waste Bioremediation	Fish waste Bio-remediation	Fish waste stream	Use of plant/microalgae feed
Disease mitigation	No use of end of pipe solutions No antibiotic or pesticides	Reliance on balanced IMTA system No chemicals	Reliance on balanced IMTA system No chemicals	Reliance on balanced system No chemicals	Substrate requires sterilization and high humidity (80 to 90% RH) (White Button)
Potential for tolerance (frost)	Can survive 0.5°C as cold-water fish	Cultivars Genetic Breeding	Cold loving species in IMTA	Uncertain – freshwater is complex	Many mushrooms still thrive in frost
Scalability	Ease of scale	Ease of scale	Indoor complex	Freshwater Complex	Ease of scale
Replication	Likely but must match to peatland system	Adaptive and can adjust to aquatic IMTA systems	Adaptive can adjust to aquatic IMTA system	Replicable as focused on fish waste, alga species	Ease of replication
Unforeseen Challenges [must be considered for rapid deployment and policy]	Fish licence, Planning Procurements Ecological Reporting Site Development	Depth of channels and flow to circulate waste stream Site development	Planning permission if indoor production Site development	Lenghty period to identify alga that can grow on freshwater fish waste	Planning permission would be required if indoor process. Site development

PBR (photobioreactor); PAR stands for photosynthetically active radiation (light wavelengths 400 to 700 nm).
[a] Mushroom details predominately reflect commercial *Agaricus bisporus* (white button type).

under severely disrupted conditions. While optimal growth often occurs at ca. 50 – 400 μmol photons m^{-2} s^{-1} (ca. 5-40% of full sunlight depending on location, season and time of day), microalgae can survive at levels significantly below 50 μmol photons m^{-2} s^{-1} (Table 2). For example, Aleya et al. (2011) reported on cultivation of *Chlorella minatissima* at irradiance of 30 to 350 μmol photons m^{-2} s^{-1} over the temperate range 10 to 35°C.

Dried microalgae biomass produces similar calorific values to that of staple crops farmed conventionally (Table 2). Some algae are adapted to low incident light for extended periods with optimal pH between 7 and 9 that comfortably falls within pH range of IMTA system (O'Neill et al., 2022a,b). Additionally, a combined total of 982 species from 341 genera across nine phyla has been found in this IMTA site by using next-generation sequencing and bioinformatics, (O'Neill et al., 2022a, b). The abundance of these microalgal species detected in the IMTA ecosystem are listed in Table 3, which are being investigated further for cold adaption and for food production purposes given that many similar genera were previously isolated from polar, glacial and alpine

Table 3
Location of where most common algal genera that were identified in the IMTA peatland site using molecular and bioinformatics analysis. Cold loving and tolerant algal genera are in bold.

Algal Genera	IMTA Location			Algal Genera	IMTA Location		
	Pond	Lagoon	Reservoir		Pond	Lagoon	Reservoir
Achnanthidium *[Diatom]*	+			Mallomonas Siver (2022)	+	+	+
Amphora	+	+		*Micratinium*	+	+	+
Ankistrodesmus Singh et al. (2014)	+	+		***Monoraphidium*** Calhoun et al. (2022)	+	+	+
Bracteacoccus	+	+	+	***Nannochloropsis*** Gharib et al. (2024)	+	+	
Cercomonas	+	+		***Nitzschia*** Lundholm et al. (2024)	+	+	+
Chlamydomonas Peng et al. (2021)	+	+	+	*Orchromonas*	+	+	+
Chlorella	+	+	+	*Oocystis*	+	+	+
Chloromonas Schoeters et al. (2022)	+	+		***Paraphysomonas*** (Choi and Peters, 1992)	+		
Chroomonas Peng et al. (2021)	+	+	+	***Peridinium*** Golubkov et al. (2019)	+		+
Chrysochromulina Peng et al. (2021)	+	+		***Prorocentrum*** Golubkov et al. (2019)	+		
Coelastrella Singh et al. (2014)	+	+	+	*Pymnesium*	+		
Coelastrum	+	+	+	*Psudompediastrum*	+	+	+
Coleochaete	+	+		*Pyraminonas*	+	+	
Cryptomonas Bock and Sieber (2026)	+	+		***Rhodomonas***[a] Kholssi et al. (2023)	+	+	
Cyclotella *(Diatom)* Saros and Anderson (2015)	+	+	+	***Scenedesmus*** Lindberg et al. (2022)	+	+	+
Desmodesmus	+	+		*Scrippsiella*	+		
Dinobryon	+			*Stauroneis*	+	+	
Frustulia *(diatom)* Margesin et al. (2007)		+	+	***Stephonodiscus*** (Diatom) Edga et al., 2016	+	+	+
Halamphora		+		*Stigeoclonium*	+		
Hemiselmis	+	+	+	***Synura*** Healey (1983)	+	+	+
Kirchneriella	+	+		*Tetracystis*	+		+
Klebsormidium Singh et al. (2014)	+	+		*Tetradesmus*	+		+
Lagerheimia		+		***Thalassiosira*** Baek et al. (2011)	+	+	+

+ indicates presence of genus at different locations in IMTA system (adapted from O'Neill et al., 2022a,b).
Potentially cold-loving 'psychrophilic' and cold-tolerant 'psychrotrophic' algae reported previously in the literature are highlighted in **bold.**
[a] Example of published studies using algal in aquaculture feed.

freshwater systems. Notably, this table lists 19 different algal species that also were reported previously as cold loving or tolerant by other researchers. For example, *Chlamydomonas* species can thrive in in the cold aquatic environments (4–6°C) (Cvetkovska et al., 2021) at low light levels (Kim et al., 2019). The microalgae species *Rhodomonas* sp. is commonly used in aquaculture for its high nutritional value due to the eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) content (Oostlander et al., 2020). The maximum biomass yield on light was found at light levels between 110 and 220 μmol m^{-2} s^{-1}. The fatty acid profile was only significantly influenced by temperature, with higher EPA and DHA contents at lower temperatures (15°C). *Monoraphidium minutum* 26B-AM, a freshwater green microalga, was identified as a top performer in biomass production in winter season screens (Calhoun et al., 2022). While Lindberg et al. (2022) reported that *Chlorella vulgaris* increased both sucrose and raffinose family oligosaccharides content at 5°C. Moreover, future biodiscovery research will focus on their ability for producing high yields of high protein, polyunsaturated fatty acid and micronutrients under simulated ASR and climate cooling conditions. Thus, several authors have reported on potential of microalgae from cold environments and their possible biotechnological applications (Jo et al., 2020; Montuori et al., 2023). Environmental adaptation using different physiological and molecular strategies allows survival among cold-loving microalgae including membrane fluidity and accumulating polyunsaturated fatty acids, carotenoids, UV-adaptative compounds and phenolics (Montuori et al., 2023). Villanova et al. (2023) reported that microalgae species *Nannochloropis granulata*, *Phaeodactylum tricornutum*, and *Chlorella* sp (Genus present in IMTA site (Table 3)) for their ability to remove nitrogen and phosphate from the Recirculating aquaculture system (RAS) wastewater and can simultaneously produce high-value biomass, i.e., containing amino acids (AA), carotenoids, and poly-unsaturated fatty acids (PUFAs).

Alternatively, by using scalable land-based photobioreactors with artificial lighting, production can be maintained under more controlled conditions (Cheirsilp and Torpee, 2012; Wang et al., 2014). Scalable commercial production of microalgae is achievable for large ponds or photobioreactors (Borowitzka and Vonshak, 2017). Photobioreactors will require a source of electricity, but are otherwise well placed to exploit microalgal diversity under controlled conditions where biomass production rates are stable. Interestingly, the highly adaptive nature of cyanobacteria and microalgae for providing astronauts with oxygen, food, biopolymers and pharmaceuticals is being considered as providing solutions to problems faced by first Martian settlers; however, Mapstone et al. (2022) noted that these can only be realised with appropriate infrastructure and reliable power source. The latter observation is equally applicable for producing microalgae at this IMTA site during a catastrophe.

5.3. Freshwater macroalgae (Seaweed)

Freshwater macroalgae are rich in bioactives that can potentially be used as a resilient food source in a nuclear winter (Table 2). Researchers have reported on the intensive cultivation of freshwater macroalgae for commercial applications (Lawton et al., 2013). Freshwater macroalgae are an under-utilised feedstock with much potential for food and bio-energy application. In contrast, there is substantial knowledge about marine macroalgae. Jehn et al. (2024) recently proposed the use of seaweed as promising resilient food source after a nuclear war as it can grow in a wide range of environmental conditions. These authors simulated growth of macroalgae on a global scale using an empirical model based on *Gracilaria tikvahiae* forced by nuclear winter climate simulations. They simulated scalable growth of macroalgae to an equivalent of 45% of the global human food demand in approximately 9 – 14 months using a small fraction of global ocean area, inferring that macroalgae should be considered as a viable resilient food source for abrupt sunlight reductions scenarios. The main limiting factor envisaged was the speed at which new seaweed farms (infrastructure) could be built. At present, cultivation of freshwater macroalgae is in its infancy at IMTA sites, however, there is scope to cultivate algae such as *Cladophora glomerata* on various wastewaters for generation of biofuels and or food (Ričkienė et al., 2025; Hughes et al., 2025). This species is well known to grow effectively at temperatures above 15°C (Beillis, 1967). However, despite global interest in macroalgae (such as marine seaweed), ongoing laboratory-based investigations for culturing freshwater macroalgae indicate that biomass would be very slow growing to produce scalable yields in land-based tanks post catastrophe. Although there is concerted focus on elucidating appropriate growth parameters and conditions for growing freshwater macroalgae at IMTA sites, it is likely that production of faster growing duckweed and single-celled microalgae in channels an the lagoon would be preferred over filamentous macroalgae using the same fish waste stream post a global nuclear war conflict that would reduce surface temperature and sunlight.

5.4. Duckweed cultivation and harvesting using on site conversion systems

Duckweed is an alternative source for high protein food that is both nutritious and environmentally friendly (Sulaiman et al., 2025). Duckweed is protein-rich and contains all critical essential amino acids (particularly branched-chain amino acids) required by humans (Appenroth et al., 2017). Whole duckweed can be used either in conventional cereal-based foods by partial substitution of soybean or after extraction of proteins and phytochemicals as a functional ingredients (Xu et al., 2021). Alternatively, duckweed can be used as a high protein animal feed, potentially replacing imported soybean [Table 2].

Duckweed species are amongst the fastest growing plants, doubling every 2-3 days. These plants can grow under reduced lighting and temperatures (Pason-Panqueva et al., 2024). For example, growth of *L. minor* saturates at light intensities as low as 400 μmol m^{-2} s^{-1} (Walsh et al., 2021), i.e. roughly one-third of full sunlight. Thus, it is not expected that a decrease in solar radiation during solar winter will negatively impact growth in many cases. Furthermore, this species has a large global distribution, extending to locations just north of the polar cycle in Scandinavia, Russia and Canada (Landolt, 1989), emphasising resilience to low temperatures that will be encountered during a nuclear winter. Pason-Panqueva et al. (2024) reported that duckweed biomass growth rates reach a maximum within specific ranges for temperature (11.4–32.3°C) and daily light integral (DLI) (5–20 mol m^{-2}) (Table 2). However, these light and temperature dependencies are duckweed species specific and there is considerable scope to exploit duckweed biodiversity to improve growth at nuclear winter conditions. Gene editing offers more potential for enhancing indigenous plants' resilience to environmental stress and mitigating effects of climate related challenges including against catastrophe (Xiong et al., 2022).

Duckweed scalability, from multi-tiered indoor cultivation systems (Coughlan et al., 2023) to large lagoons (O'Neill et al., 2020) without requiring arable land that competes for major other resilient crops makes it very attractive (Sulaiman et al., 2025). It is estimated that ca 600 tonnes fresh weight per annum of duckweed can be harvested per hectare in the temperate climate zone (Paolacci et al., 2022) equivalent to circa 10 tonnes pure protein. In turn, this would be sufficient to satisfy the protein demand of 285 average human consumers for one year. The current non-optimal 5.4 ha demonstrator site can meet protein needs for ca. 1500 people.

Conversely, duckweed can be effectively employed as fish feed (Minich and Michael, 2024) creating a circular, resource efficient nutrient flow. Duckweed has been successfully cultivated on the effluents from a fish cultivation system (Paolacci et al., 2022). In this regard there is a likely competition for plant nutrients with microalgae. Greater research is required to understand relationship with microalgae that co-occur in same channels. As part of a bespoke system of nuclear winter adaptation, management of the balance between microalgae and duckweed should be explored. In parallel, to supplement biomass yield, microalgae can also be cultivated on land adjacent to the IMTA channels using photobioreactors and LED technology; however, this will require infrastructure and supply of dedicated power. Additionally, gene editing offers tremendous potential for enhancing indigenous plants' resilience to environmental stress and mitigating effects of climate related challenges including against catastrophe (Xiong et al., 2022). By precisely modifying stress-response genes, breeders can develop plant varieties that perform better under drought, heat, cold or salinity – much faster than through traditional breeding. A key factor is to select appropriate genes as abiotic stress is complicated to address. Thingujam et al. (2024) provided insights into the genomic complexity of *Lemnaceae* species and the flourishing field of transgenic development highlight the opportunities for genetic manipulation and biotechnological innovations. There are also a variety of native plants in the channels that are also fast-growers with potential for protein and nutrient extraction.

5.5. Mushroom onsite cultivation in polytunnels

The production of indoor mushrooms as a resilient food source is an attractive addition to an IMTA given that mushrooms are rich in protein and have various health benefits (Usuldin et al., 2021; Bell et al., 2022), and have been frequently cited as a potential food source post catastrophe (Garciá-Martínez et al., 2025). Notably, wild mushrooms can bioaccumulate hazardous substances including anthropogenic (^{137}C) and naturally occurring ^{238}U, ^{232}Th, and ^{40}K) radionuclides, where Akkaya and Aktas (2025) reported that they can potentially serve as effective bioindicator for residual radioactive contamination post nuclear fallout event. Many mushrooms are of low calorific value and vary in complexity for cultivation and for fruiting (Table 2); however, the IMTA onsite drying process would increase calorific value by way of concentration. These basidiomycetes grow under reduced light conditions that offers considerable strategic benefits to overcome conditions triggered by a nuclear winter. Although many mushrooms fruit best under slightly elevated temperatures, this might not be a problem under the indoor conditions typically employed for cultivation. An understanding of varying light and temperature levels of basidomycetous mushroom productions are lacking particularly at the molecular mechanistic levels (Nakazawa et al., 2008); this is relevant given ASR and cooling associated with nuclear war.

Typically, composted cellulose, hemicellulose and lignin are used as substrates in mushroom cultivation depending on the target mushroom (Suwannarach et al., 2022). For example, cultivation of oyster or shiitake mushrooms is a relatively simple process; however, this requires lengthy mycelial colonization from spawn (~6 to 12 months to fruit) using typically straw, sawdust and hardwood logs. Actual mushrooms have typically low calorific values and yields (Table 2) which is not desirable given the main priority of meeting scale requirements for feeding a population and to prevent starvation. However, blends of

foods must also be considered for nutrition as mushrooms are a rich source of Vitamin D and researchers have demonstrated health promoting benefits from a range of isolated bioactives from mushrooms including gut and immune-modulating properties (Masterson et al., 2020; Murphy et al., 2020; Park et al., 2023) that may help survival post nuclear war.

Production of mushroom spawn (the seed) is highly sensitive and requires strict cleanliness and sterilization to prevent contamination that may present additional challenges post catastrophe. For example, button mushrooms (*Agaricus bisporus*) are very prone to contaminants and do not grow on straw or woodchips alone, but require specific substrate preparation (typically adding manure that may not be available), fermented compost that must be pasteurized to remove contaminants), humidity needs to stay consistently high (85-90% RH), and the right balance of fresh air is required (keeping $CO_2 < 1500$ ppm). Thereafter, a special layer of casing (peat mixed with lime) must be applied to the compost that acts as water reservoir and provides the right pH for mycelium to turn into mushrooms. As part of a resilient, sustainable IMTA farm, some dried duckweed substrate could be used as an alternative cultivation medium (Jain et al., 1988), creating a further nutritional beneficial resilient food source. Furthermore, onsite harvested algae can similarly be used as a medium for the growth of mushrooms (Lavega González et al., 2025). However, the low calorific yield and complex sterilization processes for mushrooms would infer preference for producing more duckweed andmicroalgae from fish waste stream at this IMTA site. This underlines the importance of understanding role of potentially producing mushrooms for blending, such as with duckweed on site in the biorefinery, for meeting all nutritional and dietary intake post catastrophe.Moreover, considerable advance planning will be required to prepare mushrooms in advance of an catastrophe event including appropriate species that deliver fast end-to-end process such as commercial white button mushrooms (*A. bisporus*) that takes 3 to 6 weeks, aeration and energy.

5.6. Vertical farming, greenhouses and climate-controlled polytunnels

Vertical farming (hydroponics) for growing and scaling fresh vegetables have been extensive reported (Van Delden et al., 2021). Two major inputs for these indoor systems are artificial lighting and nutrients. The incorporation of wind turbines in an IMTA system creates resilience and facilitates the supply of electricity for LEDs in vertical farming, independent of any disturbance of the electricity network, but also independent from the effects of nuclear winter. Vertical farming systems can obtain plant nutrients by using wastewater from fish cultivation (Khandaker and Kotzen, 2018). Thus, creating another sustainable nutrient cycle. Alternatively, greenhouses can be deployed to cultivate additional crops under temperature modulated conditions to produce temperature sensitive crops in an era of nuclear winter. Greenhouses trap heat from sunlight producing warmer conditions for crop cultivation ranging from simple low-tech open-source structures to large scale industrial production (Alvarado et al., 2020). However, future design innovations should be considered that would enable both rapid and mass production and implementation of greenhouses IMTA sites appropriate for nuclear winter conditions (Alvarado et al., 2020). Greenhouses typically require substantial energy input for temperature control, and therefore fully enclosed, climate controlled polytunnels are a more realistic scenario (Maiwald et al., 2023). Additionally, the general availability of building materials, such as for polytunnels, may present an operational challenge due to supply chain disruption caused by a nuclear war. Strategic stockpiling of such materials should be considered for preparedness.

5.7. Decision support process for selecting food biomass type for use of fish waste stream

Prioritized selection of biomass type reflects need for continuous ability to culture open raceway channels and lagoon over the entire year as there can be significant variance in light, temperature and precipitation levels. Selection will be context dependent, and thus global roll out of IMTA systems will need to involve bespoke solutions reflecting local climate, water conditions and supply chains. It is expected that in many freshwater systems duckweed biomass is seen as priority given its near-global distribution, ability to double biomass every 2 days, high protein content, and relative ease of harvesting from open raceways that uses natural sunlight and paddlewheels for circulation. However, duckweed growth will be seasonal in most climate zones, except the tropics. Microalgae generally are more versatile and contain more calories than duckweed on dry-weight basis (i.e., denser in fats and proteins) (Table 2); but, algae are likely less efficient producing biomass in open raceways especially as duckweed surface coverage would limit sunlight penetration into channels. Microalgae cultivation can be supplemented by a hybrid land-based closed bioreactor approach, but this requires additional infrastructure, equipment, energy and specialist staff. Unlike duckweed and microalgae that rely on photosynthesis to produce proteins, lipids and other nutrients. Mushrooms are non-photosynthetic fungi, this means that mushrooms depend on breaking down organic matter (such as harvested duckweed and microalgal biomass). Thus, limited mushroom production can be addressed onsite from these harvested sources (Fig. 3), but this will require scoping studies to understand best candidate basidiomycetes using IMTA generated biomass. For example, traditional *Agaricus biosporus* (button mushroom) production are secondary decomposers and would require a defined pre-compost mixture of duckweed and microalgae, if possible. Other mushroom types are less fastidious such as using raw wood that can be sourced from nearby woodlands. Despite published papers citing potential use of mushrooms as reliant foods for a catastrophe, given so many operational unknowns emphasis should mainly focus on duckweed and microalgae production using waste stream (Fig. 3).

Fish cultivation is central in an IMTA system, with wastewater effluents fully used for cultivation of microalgae, macroalgae, duckweed, mushrooms and vegetables. In turn, to ensure fish feed security innovative feeds can be made locally using plant biomass (duckweed), microalgae (such as *Spirulina platensis* and *Schizochytrium* sp and macroalgae (Fantatto et al., 2024). However, this demonstrates the importance of a decision support tool that informs, 1) what species are grown on fish cultivation effluents and 2) whether any plant or algal biomass is used as fish feed or human food. Any such choice will depend on the severity of the nuclear winter, including shortages of food for human nutrition, suitability for the cultivation of a particular taxon under the nuclear winter-climate, creating an “a la carte” menu of options for any IMTA farm. Additionally, bioactives from mushrooms and microalgae used in powered supplements have been reported to enhance immune function (Masterson et al., 2020; Park et al., 2023). Future field studies that focus on using frost resistant plants (cultivars) and cold loving microalgae isolated on site to meet optimal yield for fish feed and human consumption are merited. The closed loop IMTA site operates to zero waste principles and does not require arable land, seed, fertilizers, nor pesticides that limit traditional crops; however, additional studies that model impact of climate variance to reflect ASR and cooling conditions at this IMTA site would be informative. Current established crop models do not include these IMTA food types. Staffing would be considered more specialist at this circular IMTA site given focus on aquaculture, microalgae and duckweed cultivation, and potentially vertical farming (Table 2).

5.8. The resilience of IMTA systems post nuclear winter scenarios

This review is a perspective, and first step, that highlights potential robustness of IMTA systems post catastrophe. Further studies will need to explore quantitative links between catastrophe scenarios, production constraints, circular resource flows, and deployment/logistics constraints. Under normal (no catastrophe) conditions, the production,

conversion and drying of microalgae and duckweed biomass at IMTA sites would provide similar calorific values to that of staple crops that rely on supply of seed and fertilizer (e.g. Table 2).

Forecasted reductions in mean air temperature would be in the increasing continuum of ca. 1°C to 2°C (5 Tg soot), ca. 3°C to 4°C (16 Tg soot), ca, 4.5°C to 6°C (27 Tg soot) and ca. 6°C to 8°C (46 Tg soot) at IMTA site over 1 to 5 years post catastrophe based on interpretation of data modelled by Xia et al. (2022) from nuclear war scenarios described by Toon et al. (2019). In comparison, during the last Ice Age 20,000 years ago, global average surface temperatures were about 5°C cooler than present (cited Xia et al., 2022). A regional conflict scenario injecting 5 Tg soot into stratosphere, and a reduction of temperatures by ca. 2°C, would limit growing months for duckweed in Ireland to March to October (Table 4). A global nuclear conflict resulting in the generation of 150 Tg soot from firestorms would potentially reduce air temperature by up to 16°C in year 2 that would devastate outdoor production abilities for fish, duckweed and algae at many IMTA sites (Table 4). However, there are currently significant limitations in accurately simulating and modelling appropriate climate conditions at this IMTA site for nuclear war preparedness; for example, additional climate parameters could be monitored such as solar energy available for photosynthesis, known as photosynthetically active radiation (PAR), is one of the important factors controlling the growth of plants and phytoplankton. It regulates the composition and evolution of marine and land-based ecosystems such as at this IMTA site. Additionally, a weather monitoring station could be located at the main food production sites.

6. Supply chain and logistics considerations for resilient food production

Translating production capacity into accessible nutrition for affected populations requires careful consideration of the supply chain and logistics, which are often overlooked in discussions about resilient food production. While the IMTA approach offers inherent advantages through closed-loop nutrient cycling and reduced dependence on external inputs (i.e. supply chain dependency), realising its full potential for food security requires attention to geographic distribution, transportation networks, scaling pathways and the economic mechanisms that govern food access and allocation. This section addresses these critical logistical considerations, recognising that even the fast tracking of this technologically advanced food production system will fail if its outputs cannot reach targetted populations.

Current global food supply chains have been optimised primarily for cost efficiency rather than resilience, creating systemic vulnerabilities that would be ruthlessly exposed by catastrophe scenarios (Garciá Martínez et al., 2021). The COVID-19 pandemic period showed how minor disruptions to transport networks, labour availability or international trade can lead to major challenges in accessing food, even in wealthy economies (Laborde et al., 2020). A nuclear winter scenario would compromise multiple supply chain nodes simultaneously (e.g. infrastructure destruction, fuel scarcity, workforce disruption and communication failure), rendering conventional distribution networks largely inoperable precisely when food needs are most acute. This IMTA approach deliberately departs from these vulnerable globalised systems. However, realising its resilience benefits requires explicit attention to the supply chain dimensions that connect production sites to end consumers.

6.1. Network perspectives on food supply chain vulnerability

To understand IMTA supply chain considerations, we must move beyond single-product or single-country analyses and adopt network-based frameworks that capture the interconnected nature of global food systems. Recent research using multilayer network models has revealed that dependencies in the international food production network can transmit localised shocks across multiple products and regions, resulting in cascading effects that far exceed the initial disruptions (Laber et al., 2023). This network perspective shows that food supply shocks spread not only through direct trade relationships, but also through indirect conversion pathways where inputs are transformed into downstream products.

The structure of supply networks significantly influences vulnerability and resilience outcomes at multiple scales. Research on food supply networks at the establishment level demonstrates that concentrated market structures, in which a small number of large companies dominate processing and retail, create heightened systemic risk, even when individual firms appear robust (Diem et al., 2025). An analysis of the Austrian pork supply network, which comprises around 23,000 nodes including farms, slaughterhouses, processors and retailers, revealed that highly centralised supermarket chains act as critical hubs, the disruption of which cascades through the entire network. Adopting a multilayer network perspective sheds light on key insights relevant to IMTA logistics planning. Firstly, the aggregate impact of indirect cascade effects often exceeds that of direct trade disruptions, meaning that even IMTA systems with limited direct exposure to regions affected by catastrophes may experience significant supply chain disruption through downstream conversion networks. Secondly, the impact of networks varies greatly across countries and products — some regions experience severe shortages, while others remain largely unaffected, depending on their network position and diversification. Thirdly, previous studies that treat products in isolation substantially underestimate vulnerability by failing to account for production conversion relationships that transmit shocks across seemingly unrelated commodity categories (Sartori and Schiavo, 2015).

Table 4
Mean meteorological data from Mullingar station Met Eireann (Ireland) in 2025 that is closest proximity to IMTA site at Mount Lucas. Reductions in climate data also shown for 5 Tg soot injection and for total degree days below 15.5°C representative of worst case 150 Tg perturbation.

Month[a] (2025)	Mean Rainfall	Mean Air Temperature (°C)		Mean 10 cm Soil Temp (°C)	Solar Radiation	Degree Days below 15.5°C
	(mm)	Measured	5 Tg Adjusted	Measured	(J/cm^2)	[Min days at ≤0°C [150 Tg soot]
January	59.8	4.1	2.1	4.3	8744	352
February	70.6	5.9	3.9	5.0	12008	270
March	24	7.5	5.5	6.8	27588	250
April	86.1	10	8	9.8	45145	175
May	64.5	11.9	9.9	13.8	65225	132
June	92	14.5	12.5	15.9	50667	69
July	77.1	16.3	14.3	17	50429	34
August	50.4	16.1	14.1	13	44529	37
September	90.5	12.2	10.2	13	33308	110
October	118.1	10.7	8.7	11.1	13098	150
November	155.1	7.4	5.4	7.8	9314	245
December	85.3	6.2	4.2	5.5	5378	288

[a] Climate data recorded by Met Eireann in 2025 (https://www.met.ie/ga/climate/available-data/monthly-data/public-works/mullingar (accessed 7th April, 2026)).

These findings have direct implications for IMTA distribution design: models that are distributed and cooperative and that avoid hub-and-spoke dependencies may be more resilient than systems that concentrate distribution through single points of failure. For circular IMTA systems, these findings suggest that supply chain resilience depends not only on the sourcing of direct inputs, but also on understanding and managing one's position within broader production networks. Network centrality measures provide a practical means of assessing the vulnerability of IMTA sites and designing optimal distribution networks. Countries and production systems that are highly connected to vulnerable regions of the network face an increased risk of cascading effects, whereas decentralised networks with redundant pathways demonstrate greater resilience to localised disruption (Kummu et al., 2020). This has important consequences for operation and product distribution of IMTA systems whose aim is to supply food in a post catastrophic world. Current IMTA supply models will need to be amended as part of post catastrophe mitigation, refocussing product distribution to local, decentralised distribution systems. This will require considerable forethought as part of catastrophe mitigation.

Morever, the production network insights reviewed above suggest three categories of concrete design parameters that should guide IMTA distribution network planning under catastrophe conditions. First, a maximum distribution radius for fresh products is likely bounded by fuel availability constraints during a nuclear winter scenario, where petroleum refining and distribution infrastructure would be partially compromised by both physical destruction and electromagnetic pulse effects (Garciá-Martínez et al., 2025). Under severe fuel rationing, return-trip distances for refrigerated transport of fresh fish and wet microalgae biomass (requiring continuous cold chain and high bulk-to-calorie ratios) are unlikely to exceed ranges of, say, approximately 50–80 km in a single daylight transit window. For preserved outputs (dried duckweed protein concentrate), this radius might extend to a few hundred kilometers given substantially relaxed time constraints, though the binding limitation remains fuel availability rather than product stability. These estimates are crude; dedicated logistics modelling under simulated nuclear winter fuel and infrastructure scenarios is needed to refine them.

Secondly, drawing on the finding that centralised hub actors create single points of failure in food supply networks (Diem et al., 2025), each IMTA deployment region should plan for a minimum of three independent distribution hubs. This redundancy ensures that road obstruction, fuel depot loss, or communication failure affecting any single node does not cascade into total distribution collapse for the region. The network analysis literature provides no validated minimum for catastrophe-specific food networks, but the principle of $n + 2$ redundancy derived from critical infrastructure resilience research offers a defensible starting heuristic.

Thirdly, priority pre-investment targets emerge directly from the transportation and infrastructure vulnerabilities: (i) all-weather road connections from each IMTA site to its primary and secondary distribution hubs, as unpaved or single-lane rural roads are disproportionately vulnerable to flood, frost heave, and debris during the cascading infrastructure failures that follow catastrophe; (ii) on-site dry and cold storage capacity sized for at least two weeks of continuous production, providing buffer against intermittent transport schedules; and (iii) redundant communication links (satellite back-up or high-frequency radio for each hub) to maintain coordination when cellular and internet infrastructure fails due to EMP or grid collapse. These investments address failure modes that cascade from nuclear winter-specific infrastructure degradation, which conventional food distribution planning does not consider.

Perhaps the most fundamental logistics challenge for this decentralised approach to food security is the geographic location of IMTA sites in terms of proximity to population centres. Peatland ecosystems are predominantly found in remote, rural or peripheral regions where land availability is high and population density is low. The Mount Lucas demonstration site in Ireland's Midlands exemplifies this pattern: it is located at a wind farm in a rural area with limited access to the local population. However, post-catastrophe scenarios could concentrate surviving populations in urban centres where infrastructure, services and organisational capacity remain functional or can be more readily established. The resulting spatial disconnect between food production and demand creates logistical challenges that must be addressed through strategic planning (Bode and Wagner, 2015). Highly complex supply networks with an extensive geographic reach are more susceptible to geographically localised disruptions, whereas simpler, more concentrated networks may be more resilient in the event of certain shocks (Bode et al., 2022). For IMTA systems, this suggests that limiting geographic scope to regional markets rather than national or international ones may reduce vulnerability, even if it means reduced market access under normal conditions.

6.2. *Transportation and distribution challenges*

The biophysical characteristics of IMTA outputs present specific transportation challenges, setting this approach apart from the distribution of conventional commodity crops. Fresh fish and other fresh aquatic produce such as duckweed biomass require continuous cold chain maintenance to prevent spoilage, and have a shelf life measured in days rather than weeks or months. Therefore, emphasis at IMTA sites should be placed on biorefinery activities for providing dried, resilient food products and blends thereof for nutrition. This averts away from transportation of wet biomass, particularly under warm conditions that may prevail during post-catastrophe periods when the availability of energy for refrigeration is uncertain. This also addresses issues such as the bulk and mass of these products, relative to their caloric density, which would further complicate transportation economics. Additionally, this one-the-ground operational strategy moves away from supply of low-value, high-mass commodities over long distances that becomes increasingly impractical when fuel availability is highly constrained.

Essentially, on-site primary processing is the most effective strategy for overcoming the challenges of transporting wet biomass. Smoking, salting and/or fermentation of fresh fish products, which are traditional in many cultures, provide preservation pathways that require minimal energy inputs. Drying duckweed reduces its moisture content, dramatically extending its shelf life while concentrating its nutrients and reducing its mass for transport (Xu et al., 2021a,b). Protein extraction and concentration of fresh duckweed and algal biomass transforms perishable produce into stable, compact products that are suitable for long-term storage and efficient distribution (Habeeb, F. et al., 2025). The biorefinery and conversion systems under development at the Mount Lucas site not only facilitate value-added production, but also perform critical pre-processing functions that enable efficient downstream distribution. Investment in these processing capabilities is essential for supply chain resilience, rather than being an optional means of economic optimisation.

Research into network resilience demonstrates that disruption to transportation infrastructure propagates through supply chains with effects similar to those of production shock (Gaupp, 2020; Dolgui et al., 2018; Burgos and Ivanov, 2021). IMTA systems must therefore plan for transportation network degradation affecting multiple routes and modes simultaneously, rather than isolated corridor failures. Adopting a network perspective supports the idea of distributed processing and preservation capacity at multiple sites rather than concentration at centralised facilities. This ensures that transportation network failures affecting one route do not eliminate the entire distribution capability. The potential contribution made by interventions at any IMTA site are highlighted in Table 5 that focuses on effects and impact of disasters on the agriculture sector as set out in UNDP 2025 guidelines. Additionally, the role of IMTA activities and innovation in meeting DRR and BBB rehabilitation, reconstruction and recovery needs is outlined in Tables 5 and 6.

Table 5
Indicative activities undertaken at IMTA site compliant with disaster risk reduction (DRR) and building back better (BBB) norms for rehabilitation and reconstruction post disaster affecting agri-food sector.

Affected Asset(s)	Affected Subsector	Example(s) of Type of Hazard	Rehabilitation/reconstruction recommendations for DRR and BBB		
			Short terms: Emergency (Early Recovery)	Medium term: reconstruction	Long term: policy framework/ structural change
INFRASTRUCTURE					
Fish ponds, farm buildings, modular units for training/ testing, land-based tanks (macroalgae), greenhouses, poly-tunnels, onsite biorefinery and anaerobic digestor	all	Floods, storms, cyclones	➢ Build secure temporary shelters – units at IMTA site are modular so readily replaced and replicated ➢ Execute agile action plan with stakeholders for DRR/BBB approved via site management committee as part of operational activities and risk mitigation.	➢ Rebuild infrastructure such as safer location (peatlands) ➢ Promote use of resilient materials that can withstand shock (reinforce walls) ➢ Provide stakeholder training on asset protection ➢ Enhance alternative energy sources such as biofuel production for energy security, particularly if wind turbines affected. ➢ Engage climate, crop and fisheries models to help monitor and predict changes in extreme weather events and with Met Eireann (early alerts)	➢ Review laws, policies and regulations to integrated resilient infrastructure, watershed management ➢ Improve capacity of subject-matter experts in resilient construction techniques ➢ Develop techniques for mitigation of soil erosion and water supply/ conservation (peatlands affords natural vegetative composition) ➢ Support development of environmental impact assessments, risk assessments and hazard mapping using peatland model.
Irrigation channels and water points	all	Floods, storms, cyclones, drought, ASR and climate cooling	➢ Overflow of IMTA system to receiving environment (flooding), or intake of water from peatlands (drought)	➢ Excavation/deepen ponds and channels that consider design aspects for improved flow and recirculation ➢ Monitor for emergence of invasive species of plants in IMTA system	➢ Replicate system in other peatland locations based on evidence-based effects and adaptive solutions for ensuring circularity through IMTA system
Roads and power structures	all	Floods, storms, and cyclone	Location of IMTA rural to urban nexus where site uses wind turbine	➢ Adopt innovation systems that will increase resilience to shocks (e.g., draining systems	Promote diversification of power source at IMTA site, in addition to existing wind use solar). Work with crisis response (government).
Agricultural assets (tractors, fishing gear, quad bike)	all	Floods, storms, and cyclones	Increase biofuel use for mechanization (tractors, excavators, quad bike)	Review and promote dissemination of key information on safer location to store assets and provide training to protect assets	Support sustainable mechanization strategies (FAO, 2016) and facilities for securing aquaculture equipment and gear
Amphibious boats (channel maintenance and harvesting duckweed)	Aquaculture	Storms, cyclones,	➢ Monitor performance using drones/sensors with physicochemical parameter testing ➢ Climate modelling ➢ Add nets to protect ponds/fish ➢ House boat in shed.	➢ Enhance training on resilient repair techniques ➢ Introduce additional submerged cameras for ponds to monitor fish and channels ➢ Use of aerial drones to monitor and assess damage/recovery processes for using boat	➢ Improve design standards for IMTA including remote sensing and use of AI for efficiencies (risk planning) ➢ Introduce new innovation or interventions to offset shortcomings for biomass in channels and fish yield, harvesting & waste reduction
Forests and natural resources supporting primary agriculture	All	Drought, floods, storms, cyclone, ASR, climate cooling, radioactive nuclide contamination	➢ Provide alternative bioenergy sources ➢ Mitigat waste	➢ Support reforestation at margins of IMTA site and introduce new resilient foods ➢ Mycelium inoculation of roots for mushroom harvesting	➢ Promote and demonstrate shift from traditional bioenergy to more sustainable efficient technologies ➢ Site operation to climate friendly principles including zero waste

For more related information, see UNDP (2025); FAO, Fisheries and Aquaculture and Climate Change, https://www.fao.org/fishery/climatechange/en (accessed 5th November, 2025); FAO Seed Systems, https://www.fao.org/agriculture/crops/thematic-sitemap/theme/seeds-gpr/seed-sys/en/(accessed 5th November, 2025); FAO (2017), 'C5 – 2.1. Mapping multiple risk and vulnerabilities' in Climate smart agriculture sourcebook, https://www.fao.org/climate-smart-agriculture-sourcebook/enabling-frameworks/module-c5-climate-resilience.chapter-c5-2/en/(5th November, 2025).

6.3. Replication speed and scaling constraints

To achieve meaningful contributions to food security from IMTA systems, there needs to be rapid scaling up from demonstration to deployment at thousands of sites around the world. However, this is a challenge that the timelines for construction, commissioning and operational ramp-up may significantly constrain (Table 1). This requires careful future mapping of resources, infrastructure relative to regional needs that are often specialised, but food insecure. The purpose of this review is to highlight operational challenges for delivering on the scaling of production of candidate foods adapted to grow under reduced lighting, temperatures, pesticide, fertilizer and energy requirements with a regional supply focus (Table 2). Training and individual capacity development are critical dependencies that cannot be arbitrarily

Table 6
Indicative activities undertaken at IMTA site compliant with disaster risk reduction (DRR) and building back better (BBR) norms for inclusive recovery interventions post disaster affecting agri-food sector.

Affected Asset (s)	Affected Subsector	Example(s) of Type of Hazard	Recovery recommendations aligned with DRR and BBB guidelines		
			Short terms: Emergency (Early Recovery)	Medium term: rehabilitation	Long term: policy framework/structural change
DISRUPTION OF SERVICE DELIVERY AND AVAILABILITY/ACCESS TO GOODS AND SERVICES					
Losses in production (crops, fisheries)	All	Floods, storms, drought, extreme temperatures, abrupt reduction in lighting supporting photosynthesis for crops	➢ Improve access to early maturing frost-resistant cultivars/varieties in pre-paredness so as to accelerate recovery ➢ Consider resilient plant breeding informed by genomics/informatics ➢ Active early-warning system repair, re-activation, for food security and moni-toring (including radioactive nuclide contamination in partnership with EPA, FAO, IAE, stakeholders ➢ Strengthen communications channels	➢ Promote multi-stress tolerant crops, fish vari-eties or species ➢ Implement conservation agriculture (waste mitigation) and climate-smart systems ➢ Support diversification including trees for windbreaks and variety of resilient crops ➢ Demonstrate resilient crops throughout entire year ➢ Enhance water management ➢ Onsite fingerlings production for food security (Hatchery) ➢ Converge primary production of resilient crops and use of biorefineries	➢ Make appropriate evidence-based changes in laws, policies, regulations, management practices for more sus-tainable resilient crops, fish produc-tion (IMTA) with local government ➢ Us of IMTA site to inform national and local preparedness planning, contingency plans for food ➢ Update existing policies. ➢ Support establishment of Early-Warning Action plan ➢ Conduct risk mapping, monitoring and training. ➢ Deploy diversification of resilient crops avoiding reliance on limited solutions
		Storms, cyclones	➢ Restore safety, welfare of fish stocks ➢ Restore vertical farm activities and use of poly-tunnels ➢ Introduce beneficial resilient microalgae in fish ponds	➢ End-to-end monitoring of fisheries ➢ Alternative fish feed produced onsite using algae/duckweed. ➢ Promote resilient stress-hardened plants on site ➢ Consider other resilient crops growing in channels such as native bivalve cultivation	➢ Increased production of IMTA crops (duckweed, microalgae)
Agriculture services, social support, networks	All	all	➢ Open data portal for sharing recovery interventions ➢ Support social network analysis to strengthen their resilience and cohesion during disasters	➢ Enhanced digital solutions ➢ Augment appropriate supply chains for food distribution	➢ Develop manuals and guidance materials on DRR with government and local authorities ➢ Promote policies of waste reduction and conservation ➢ Co-create and implement biodiversity and ecosystem service

For more related information, see UNDP (2025); FAO, Fisheries and Aquaculture and Climate Change, https://www.fao.org/fishery/climatechange/en (accessed 5th November, 2025); FAO Seed Systems, https://www.fao.org/agriculture/crops/thematic-sitemap/theme/seeds-gpr/seed-sys/en/(accessed 5th November, 2025); FAO (2017), 'C5 – 2.1. Mapping multiple risk and vulnerabilities' in Climate smart agriculture sourcebook, https://www.fao.org/climate-smart-agriculture-sourcebook/enabling-frameworks/module-c5-climate-resilience.chapter-c5-2/en/(5th November, 2025).

compressed. IMTA system operation requires multidisciplinary competence in aquatic ecology, fish husbandry, plant cultivation, water quality management, mechanical systems maintenance and food processing. Development programmes can accelerate the acquisition of these capabilities, but cannot eliminate the need for them (Table 1).

Strategically pre-positioning equipment, materials and personnel offers the potential for further acceleration. Stockpiling critical components, such as pumps, pipes, sensors and processing equipment, for rapid installation at new sites eliminates delays in procuring materials during a crisis response (Table 1). Furthermore, establishing cooperative agreements with local contractors who are familiar with site development reduces mobilisation times. Identifying and pre-qualifying potential sites through GIS analysis enables operations to commence immediately when scaling decisions are made. However, these pre-positioning investments require an ongoing commitment of resources with no immediate return, which can present challenges for organizations operating under constrained budgets. Nevertheless, they may be essential for realising IMTA's potential for rapid response.

6.4. Economic and market mechanisms for resilience

The sustainable operation of IMTA systems requires viable economic mechanisms to govern production decisions, distribution allocation and access to consumption, rather than merely technical production capacity. Normal market mechanisms may malfunction during catastrophic conditions, with conventional price signals potentially failing to equitably or efficiently allocate scarce food resources. Emergency procurement frameworks, rationing systems and cooperative ownership models offer alternative approaches that should be explicitly considered during system design, rather than being improvised during crisis response.

Government emergency procurement preferential contracts are one way of ensuring that IMTA production has guaranteed markets and is operational during preparedness phases. The European Commission's contingency plan for ensuring food supply and security in times of crisis provides a policy framework that must incorporate agile circular IMTA systems as part of broader resilience strategies (European Commission, 2021a,b). Such contracts would provide a predictable revenue stream to support ongoing operations and continuous improvement, while also

building relationships with emergency management agencies. In addition to an awareness, pre-positioned procurement commitments, which are triggered automatically when catastrophe conditions are declared, could help to maintain production continuity through the initial emergency period, eliminating the need for real-time market transactions. While these arrangements would require advance negotiation and formalisation, they would offer mutual benefits for IMTA operators and emergency management systems, along with stimulating innovation.

Cooperative ownership models align economic incentives with resilience objectives, ensuring food access is governed by membership and contribution rather than market capacity alone. The Penta-helix hub approach, which is outlined in this manuscript, provides a governance framework for cooperative development that exploits sustainable advances in effective food waste management for feeding populations (Rowan and Casey, 2021), which is of critical importance post catastrophe. Stakeholders from government, academia, industry, civil society and primary producers work together to shape the operation of the system (Rowan et al., 2022; Rowan, 2025). Research shows that transformative service research, which focuses on service and well-being outcomes, provides conceptual frameworks that are relevant to cooperative food systems which prioritise social welfare over profit maximisation (Anderson and Ostrom, 2015). Cooperative membership could confer distribution rights and food access priorities, ensuring that IMTA production serves community food security rather than maximising profit for external investors aligned with corporate social responsibility and humanitarian principles (Rowan et al., 2024.

6.5. Multiactor coordination, emergence procurement contracts and cooperative ownership for appropriate crisis responses

Current economic models of competitiveness for food production provide limited insight into crisis responses to a catastrophe. The Mount Lucas site is located approximately 15 km from nearest town (Tuallamore), 25 km from nearest military barracks (Athlone) and 60km from nearest city (Dublin) and is connected to supply chain mainly by road networks. To potentially recreate deployment of the IMTA site in other locations for a catastrophe-preparedness strategy, pre-procurement commitments, rationing systems, and cooperative structures need to be revisited to upgrade existing national and EU-level contingency plans. Ireland has a National Plan for Nuclear and Radiological Emergency Exposures (Government of Ireland, 2019) that is linked through two-early warning systems managed by the International Atomic Energy Agency and the European Commission. These systems quickly notify the Irish Government of any threat. Ireland also has an agreement with the UK the Irish Department of Climate, Energy and the Environment and the EPA would be informed directly in the event of a radiation emergency in Ireland. As part of this National Plan, the EPA operates a 24-h radiation monitoring networks that would automatically trigger an alarm if an emergency exposure situation is detected (EPA, 2019). In the event of a nuclear emergency that would require National Emergency Coordination Group (NECG) encompassing the Department of Agriculture, the Food and the Marine (DAFM) and Food Safety Authority of Ireland (FSAI), Met Eireann would provide current and forecasts for wind speed and direction and likelihood of rainfall in any part of Ireland that may be receiving radionuclide contaminated fallout including the midlands where this IMTA site is located. Stakeholder bodies may be responsible for gathering samples Irish Water (drinking water), DAFM/FSAI (milk, meat, grains etc), Met Eireann (air and rain samples from weather stations including radionuclide dose rate monitoring). Regular national training plans are carried out to test this plan (Department Energy, 2025); however, this plan would require new updates for recovery process that includes resilient food production systems (such as at Mount Lucas) and prioritisation of scare resources (e.g., fuel, materials, skilled staff) in the event of a global catastrophe, particularly to consider servicing other critical sectors. Section 7.1 of National Plan (EPA, 2019) refers to hazard analysis studies indicating that the "most significant and long-term consequences for Ireland of a nuclear emergency exposure situation would be most likely socio-economic in nature, rather than related to public health. There would be particular consequences for agriculture and wider food production sector". This National Plan would appear to require updating for a potential nuclear winter event. Akin to other countries globally, Ireland needs to consider its food security (Hanrahan, 2022; Hegarty, 2022; Irish Examiner, 2025).

7. Future considerations towards food resilience post catastrophe

- There is an urgent need for resilient food systems as developing these immediately post a catastrophe would be extremely difficult to achieve given numerous operational and deployment challenges.
- There is a need to identify relevant resilient crops for performance under simulated abrupt reductions in light intensity and temperature informed by using pilot facilities to validate simulation models including that can operate to zero waste.
- This paper highlights IMTA systems as a potential, promising and robust food supply system that warrants more attention from a catastrophe management perspective.
- Considerable mapping and optimizing of key parameters affecting production of different biomass at scale from fish waste stream is required to inform plausible yields under reduced growing conditions at IMTA sites including additional meteorological monitoring.
- Future life cycle assessment (LCA) material flow analysis (MTA) is required to understand best candidate food biomass type using fish waste stream for catastrophe where IMTA processes do not compete with staple crops for arable land, fresh water, fertilizers, pesticides nor seed.
- Strategic local, regional and national planning has to include mixed crop cultivation to sufficiently meet food security and nutrition in the event of a global catastrophe.
- There is a need for training and investment for farmers to cultivate variety of crops for self-sufficiency beyond their normal specialization(s) prior to catastrophe along with ascertaining capabilities of farmers to rapidly pivot to grow mixed crops on their land that they are unfamiliar with post catastrophe.
- Appropriate planning permission would need to be granted rapidly by local government in order to approve the demonstration of different resilient food solutions at scale.
- Solution(s) for effective use of mechanization (equipment) such as for crop production, harvesting and distribution, such as limited onsite biofuel.
- Sources of effective electricity supply for operation of IMTA system under catastrophe.
- Supply chains from circular site so as to meet urban needs given challenges with supply chain, infrastructure, communications, and security post nuclear war.
- Multi-actor Penta helix hub approach to help tailor appropriate disaster preparedness and recovery plans that includes infrastructure and supply chain vulnerabilities. This should augment coordinates with CTB, FAO, IAE for transregional radioactive fallout measurements including soil, water, food and ecosystem for recovery.

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CRediT authorship contribution statement

Neil J. Rowan: Conceptualization, Formal analysis, Funding acquisition, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. **Marcel A.K. Jansen:** Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Peter Klimek:** Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing.

Declaration of generative AI in scientific writing

The authors did not use generative AI in scientific writing.

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Data availability

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