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Review article

The role of digital technologies in supporting and improving fishery and aquaculture across the supply chain – Quo Vadis?

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ABSTRACT

Fish constitute important high protein products to meet the demands of an increasing global population. However, the continued depletion of wild fish stocks is leading to increased strain on the aquaculture sector in terms of sustaining the supply of fish and seafood to global markets. Despite the fact that aquaculture is more diversified than other agriculture sectors, there are significant pressures on the industry to continue innovating in order to enable sustainability including increased fish production, improved appropriate selection of species, disease mitigation, reduced wastage, preventing environmental pollution and generating more employment globally. This viewpoint article addresses how digital transformation can help support and meet expansion needs of the fisheries/aquaculture industries that includes exploiting and harnessing ICT, IoT, Cloud-edge computing, AI, machine learning, immersive technologies and blockchain. Digital technologies are bringing significant operational benefits for global food chain, improving efficiencies and productivity, reducing waste, contamination and food fraud. The focus on digital technologies has recently evolved to Industry 5.0 where AI and robotics are coupled with the human mind in order to advance human-centric solutions. This viewpoint describes the role of Quadruple helix Hub (academic-industry-government and society) in delivering a convergent holistic approach to meeting the diversity of fishery industry needs by connecting and placing fisheries centrally in a defined ecosystem of stakeholders. This includes specialist training, testing technologies, providing access to finance and fostering disruption through aquaculture accelerator initiatives such as that provided by Hatch Blue. Connecting digital Innovation Hubs *trans*-regionally, nationally and internationally will also help mitigate against significant risks for the fisheries and aquaculture industry including climate change, global pandemics and conflicts that can jeopardize fish and seafood production and supply chains. There is also a commensurate need to avail of digital technologies in order to increase awareness of key industry issues across the value chain, such as through social marketing. Thus, addressing key challenges by way of the global digital transformation of fishery and aquaculture industry will meet several sustainable development goals of the United Nations catered around the application of disruptive technology.

1. Introduction

There is increasing depletion of wild fish stocks globally, where fish is an important source of high protein products and omega 3 (FAO, 2020). Aquaculture has been one of the fastest growing food sectors in agriculture globally (Tahar, Kennedy, et al., 2018; 2018b; FAO, 2020). Xia et al. (2022) noted that aquaculture has produced more fish for human consumption than wild-caught fish. The sustaining increase in aquaculture has been positively influenced by new technological developments where there is a pressing need to find appropriate solutions to meet growing world population that will reach approximately 10 billion by 2050 (FAO, 2020). Xia et al. (2022) highlighted potential disruptive solutions in the fishery and aquaculture in number of areas including alternative proteins and oils for fish meal, offshore farming, recirculating aquaculture systems, oral vaccination, genome editing, solar emerging and novel marketing strategies, disease mitigation technologies monitoring tools, artificial intelligence and blockchain for business model development including cybersecurity. Yue and Shen (2022) also reported that aquaculture is more diversified that in other agricultural sector as attested by increased activities underpinning fish

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species, feed, production systems, diseases, products, and new business structures. Sun et al. (2020) noted that it is essential that aquaculture continues to innovate in order to produce more fish products to meet the ever-increasing seafood demands of our growing global population. Sun et al. (2020) remarked that this challenge is particularly daunting given the worsening environmental conditions that reduces our supply of fish meals and oils. O'Neill et al. (2022) reported that extreme weather events can disrupt aquaculture supply chains. For example, these authors reported that extreme climate variance that causes flash flooding can disrupt what is typically an efficient recirculating, integrated, multi-trophic aquaculture system (IMTA/RAS) in the Irish midlands, which can contribute to fish mortalities. These issues present both challenges and opportunities that include developing eco-innovations (Rowan & Pogue, 2021; Galanakis et al., 2021) that can be can enabled and accelerated through digital transformation (Mondejar et al., 2021). Thus, the global agri-food sector faces significant challenges that are influenced by societal demands, increasing competitive pressure and adaptation to climate change, changing diets, demographic change, volatile national and global markets, diverging wages and new technologies (Rowan & Casey, 2021). In order to manage these increasingly complex relationships, the sector is more than ever forced to innovate to improve profitability and sustainability (Ab Rahman et al., 2017) that can be enabled through digitalization. The aim of this viewpoint article is to address key developments, trends, challenges and opportunities surrounding digital transformation of fisheries and aquaculture across the supply chain.

2. Digitalization to achieve sustainable development in fisheries and aquaculture

Globally, we are becoming increasingly more dependent on using digital and computer technologies for our everyday activities. Ceipek, Hautz, Petruzzelli, De Massis, and Matzler (2021) noted digitalization is the integration of digital technologies into everyday life where contemporary technologies can transform socio-economic, environmental, sustainablity and climate research applications. Mondejar et al. (2021) stated that digitalization is a defined process of converting physically collected information (such as sensors) and knowledge into a computer-based language. This enables development of digital technologies that can be integrated into the Internet of Things (IoT) environment. This IoT framework provides robust network of connected physical objects across the internet through embedded sensors, software and other technologies that supports exchange and the gathering of data (Mondejar et al., 2021; Rowan et al., 2022). These authors also noted that the convergence of simultaneously developed digital technologies for real-time analysis, artificial intelligence and machine learning manages enormous amounts of data, also referred to as big data. The generation of such big data is not fully appreciated, nor exploited; but, it does generate novel opportunities that will accelerate the transition to more efficient and sustainable activities across many sectors including across the supply chain for fishery and aquaculture.

Table 1 provides working definitions of common terms used for digital technologies. An example of the various uses of digital technologies in fisheries and aquaculture is shown in Table 2. The digital technologies described in Table 2 align with emerging innovation reported by Connolly (2018). There is increasing interest in end-to-end monitoring for production and supply chain to improve efficiencies that can be met through cloud-edge computing including use of AI to make faster and better decisions (Evensen, 2020). Yue and Shen (2022) highlighted the potential for digital technologies to inform development and potentially disruption of offshore aquaculture systems, including cage aquaculture, submersible cages, vessel aquaculture and fish predominantly moored in deep water. These authors also articulated applications in recirculating aquaculture systems (RAS) such as tanks, vertical aquaponics, multi-story vertical tanks, and tanks in deserts. Yue and Shen (2022) also envisaged breakthroughs in disruptive technology

Table 1
Digital technologies – definitions and applications in fisheries and aquaculture ecosystems.

DIGITAL TECHNOLOGIES*
Information and communications technology (ICT) encompasses the capture, storage, retrieval, processing, display, representation, presentation, organization, management, security, transfer, and interchange of data and information.
Internet of things (IoT) – network of smart, interconnected devices and services capable of sensing or listening to requests and perform actions using actuators. IoT enables network sensors to remote connect, track and manage products and systems.
Cloud computing – use of tools and applications (such as data storage, servers, databases, software) based on a network of severs through the internet. It enables user to rent computer resources on demand to store files and applications in a virtualised servers and access all data via the internet.
Artificial Intelligence (AI) defines machines achieving human-like cognitive functions (ex. learning, reasoning, interacting) that comprises different forms of cognition and meaning understanding (such as speech recognition) and human interaction (signal sensing, smart control, simulators) rooted in algorithms and software.
Machine learning (ML) – a subset of AI, use and development of computer systems that learn and adapt without following explicit instructions, by using algorithms and statistical models to analyse and draw inferences from patterns in data.
Big data – continuous increase in data & technologies that needs to be collected, stored, managed and analysed. Complex and multidimensional that impacts processes, technologies. Characterised by Volume (amount of data sets), Velocity (speed of data processing), Variety (types/sources of data), Veracity (quality of data analysed).
Blockchain is a shared digital, immutable ledger that facilitates the process of recording transitions and tracking assets in a business network using cryptographic algorithms). Blockchain protocols aggregate, validate, and relay transactions within the blockchain network. The blockchain system records the transactions in sequence. A transaction may contain a value transfer or a smart contract invocation.
Augmented reality – a technology that superimposes a computer-generated image on a user's view of the real world; thus, provide a composite view.
Virtual Reality – the computer-generated simulation of a 3D image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as helmet with screen inside or gloves fitted with sensors.
Quality of Experience (QoE) – is the degree of delight or annoyance registered by the use of an application or service.
Logistics – the detailed organization and implementation of a complex operation.
Robotics – a branch of technology that deals with the design, construction, operation and application of robots. In multi-robot or swarm robot systems, the robot collaborate to complete predefined tasks.
Cobot, or collaborative robot, is a robot intended for direct human robot interaction with a shared space, or where humans and robots are in proximity.
Digital twin – a digital win is a virtual model designed to accurately reflect a physical object.
Edge Cloud – Edge computing is developed as complement to cloud computing, encompassing storage and compute assets located at the edge and interconnected by a scalable, application-aware network that can sense and adapt to changing needs, securely & in real time
Cybersecurity or information technology (IT) security – is the practice of protecting critical systems and sensitive information from digital attack. It is how individuals and organisations reduce the risk of a cyber attack where cyber security code function protects the devices (smartphones, laptops, tables).
Cyber-physical systems refer to systems where software and hardware components are seamlessly integrated towards performing well-defined tasks.

*Adopted from Rowan et al. (2022)

breakthroughs in the areas of genome editing, AI, offshore fish production, RAS, alternative proteins and oils to replace fish oils, and oral vaccines. Hrustek (2020) also reported that digital transformation can influence stability for the stable development of the global economy. Schuelke-Leech (2021) reported that the European Green Deal initiative offers opportunities for technology disruption. The reader is directed to the writings of Schuelke-Leech (2018) and Rowan (2019) for a more comprehensive description of intensive sustaining and disruptive innovation, which also embrace food systems and security.

Blockchain can inform fishery by improving safety of business models through combatting fraud, food traceability from farm to fork, food waste and food-related diseases (Altoukhov, 2020). Blockchain will also contribute to addressing crucial supply chain issues as evidenced by COVID-19 pandemic (Rowan & Laffey, 2020; Rowan & Laffey, 2020b).

Table 2
Digital technologies used in fisheries and aquaculture.

Digital Technology	Application	Supporting Reference
Robotics	➢ Address complicated tasks and laborious work, such as cleaning ponds and repair damaged nets ➢ monitoring behaviours, removing diseased fish, feeding ➢ injecting vaccines, ➢ unwater inspections of nets, evaluating fish health and escapes	Lucas et al. (2019) Kruusmaa et al. (2020) Sun et al. (2020) Lee et al. (2013) Paspalakis et al. 2020 Ohrem et al. (2020) Nahavandi, 2019 Ducket et al. (2018)
Drones	➢ Monitor fish farms above and below water ➢ Check holes in damaged cages ➢ Data collection combining AI and cloud computing to improve aquaculture operations	Sousa et al. (2019) Yoo et al. (2020) Weiss et al. (2020)
Sensors/ Remote Sensing	➢ Collecting water parameters in real time ➢ Underwater sensors to monitor hunger levels of fish in ponds and cages ➢ Fish metabolism and heart rates ➢ Reduced wastage and improved feed rates	Antononucci & Costa, 2020 Xing et al. (2019) Zhou et al. (2019) Svendsen et al. (2020) Tsolakis et al. (2019)
AI	➢ Makes better and faster decisions ➢ Less labor intensive, ➢ Improved efficacy of feeders, water quality monitoring and control, harvesting and processing	Razman et al. (2020) Josthiswaran et al., 2020 Yang et al. (2021) Misra et al. (2020) Wang et al. (2021)
Augmented Reality (AR)	➢ Teaching, training and education ➢ Improved production efficiencies, decreased costs ➢ Facilitates under water drones and robots ➢ Monitors fish behaviour, net holes and fish mortality ➢ Risk mitigation ➢ Measure water parameters	Jung (2019) Xi et al. (2019) Rowan et al. (2022)
Virtual Reality (VR)	➢ Real time simulation of environmental situations using digital interface (head sets) ➢ Teaching, training and education ➢ Used for high risk environments (remote) using human computer and multimedia platforms	Ferreira et al., 2012 Prasolova-Førland et al. (2019) Chen and Zhang (2017) Psotka, 1995
3D printing	➢ Printing hydroponic systems ➢ 3D verification devices ➢ 3D printed water sensors for monitoring water parameters ➢ Reduced equipment and production costs	Clark, Moore, Wang, Tan, and McKinley (2012) Banna et al. (2017) Chen and Zhang (2017)
IoT	➢ Connect big data across aquaculture industry ➢ Combined use of social media	Kamaruidzaman and Rahmat (2020) Dupont et al. (2018) Yu et al. (2017) Alonso et al. (2020) Dash et al. (2022)
Blockchain	➢ Cypersecurity, safe data sharing, ➢ Payment processing ➢ Industry protection ➢ Full traceability across value chain ➢ Reduce food wastage, improve food safety	Perez–Pons et al., 2021 Lennox et al. (2020) Bodkhe et al., 2020 Altoukhov, 2020 Feng et al. (2020) Arvanitis & Symenonaki, 2020 Rejeb et al. (2020)

Table 2 highlights that digital technologies offer much potential to address these challenges; but despite this, the uptake of new digital technologies by actors across the agri-food systems has been quite slow. Additionally, much of the potential value of the data that is already collected remains untapped because it exists in silos unavailable to those who might use it. Unlocking the value of this data remains a significant challenge due to technological barriers, lack of trust between the different actors (regarding also data security and safety issues), and economic barriers, such as reluctance of stakeholders to invest because of unclear returns and variable ability of the private sector to serve transparency needs (Rowan & Galanakis, 2020). The potential gains that exist from the automated ICT-based collection and analysis of data and the implementation of precision technologies can only be fully realised when the whole agri-food system and its dynamics and responsiveness is dealt with as a whole (Hrustek, 2020). This enables feedback and learning mechanisms through which consumer and processor preferences can influence the practices of primary producers, which in turn can influence the products developed by feed suppliers. Digitalization also facilitates feed-forward mechanisms where information from aquaculture processes (such as data on production processes, quantity, quality and composition of primary products) can influence the short and medium term plans of processors. Thereby minimising waste, maximising the efficiency of the system, including optimization of the supply chain in terms of energy, waste and overall sustainability, while facilitating the production of higher value end products. Albeit rooted in Agriculture 4.0 that enables real-time efficiencies for new products and services, digital technologies are also becoming intertwined with the human mind for problem solving, such as use of robots under an emerging Industry 5.0 – human centric solution model (Rowan et al., 2022).

Farmery et al. (2022) noted that the supply and consumption of seafood is influenced by a range of 'drivers' including marine regulation and ecosystem changes as well as the growing focus on the role of seafood in meeting nutritional needs. Consequently, there is an opportunity to apply digital tools such as IoT, cloud-based edge and blockchain to evaluate the convergence of these drivers. It is likely that these drivers will be informed by greater appreciation of the needs, potential impacts and solutions in order to facilitate alignment with increasing seafood production and consumption such that they meet many of the sustainable development goals of the United Nations (Mondejar et al., 2021). Farmery et al. (2022) advocate consideration for improved access and utilization to seafood, particularly for those affected by food in security and malnutrition that includes mitigating against waste. The development and application of information and communication technology (ICT) tools has led transforming many sectors by way of creating awareness and improved efficiencies (Mondejar et al., 2021). Dash et al. (2022) conducted a systematic review of published literature in order to highlight potential benefits of socio-economic development and sustainability in the fishing industry. This study reported on evidence-based findings from government, policy developers and researchers to address this topic where these authors noted that the application of ICT in fisheries will enhance profitability and minimize resource wastage, strenthen fishermen's income and improve standard of living.

There has been increased systematic use of novel measurement tools to help understand and address key factors governing sustainability of seafood across the value chain. For example, use of life cycle assessment (LCA), material flow analysis (MFA), principle component analysis (PCA) and transnational modelling where significant regional variances in efficiencies occur in the water-food-energy nexus (Cooney et al., 2021; Laso et al., 2021; Naughton et al., 2020; Ruiz-Salmon et al., 2021; Ruiz-Salmon, Laso, et al., 2021). Interestingly, Cooney et al. (2021) investigated impact categories that can be applied to evaluate aquaculture systems, namely, LCA), global warming potential (GWP), acidification potential (AP), euthrophication potential (EP), freshwater and marine ecotoxicity potential (EAETP and MAEPT), cumulate energy demand (CED), net primary production use (NPPU) and water use.

Additionally, Rowan and Casey (2021) evaluated the maturity of innovation products and services in terms of technology, societal and policy readiness levels. However, there is a commensurate need to monitor and manage such big data in real time to inform standardization, decision-making, strategic policy and management. Given complexity, Rowan and Casey (2021) advocated a more simpler approach to inform the maturity of innovation, products and services that can be applied to fisheries based on technological, societal and economic readiness levels. The underpinning rationale for introducing new sustainable blue economy models and tools is to support efficiency, reduce wastage and risk, improve robustness, increase standardization and future-proof the industry with new innovations and upskilled people. This surge in published materials on sustainability also coincides with the introduction of the European Green New Deal initiative that has provided opportunities for developing cross-cutting eco-solutions (Galanakis et al., 2021; Rowan & Galanakis, 2020). COVID-19 pandemic also provided a pronounced period of reflective thinking for scientists in addition to causing disruption in important supply chains (Rowan & Laffey, 2020; Rowan & Laffey, 2020b; Rowan & Moral, 2021).

3. Novel aquaculture production systems – test beds for monitoring impact of climate change on production

A unique freshwater integrated-multitrophic aquaculture system has been developed in the Irish peatlands that relies upon naturally occurring microalgae, bacteria and duckweed to manage waste stream and water quality through a recirculation process (O'Neill et al., 2019, 2022; O'Neill & Rowan, 2022, p. 802). This two hectare peatland site is powered by wind turbines where this IMTA process is designated as having 'organic' status. This combined research and commercial site produces perch and trout along with harvesting of duckweed as a high protein source where there is no discharge of aquaculture effluent to receiving water, unless under periods of heavy rainfall (O'Neill et al., 2020). This IMTA system is appropriate for end-to-end monitoring using sensors and cloud-edge computing that informs biomass production against feed conversion ratio. The diverse microbiome ecosystem observed in the ponds have been profiled using next-generation sequencing and bioinformatics (O'Neill et al., 2022) where there is also potential to provide real-time decision making when this data is linked to AI and machine learning. This will provide real-time data from a monitoring and production perspective, which is particularly relevant given that fish production was significantly affected by frequent storms attributed to extreme weather events in 2020 leading to fish mortality (O'Neill et al., 2022). O'Neill and Rowan (2022) also highlighted the potential relevance of specific predominant microalgae and cyanobacteria that occur in the ponds as indicative bioindicators of IMTA functionality and performance. Profiling of harmful cyanobacteria in this IMTA system, combined with monitoring physicochemical parameters, can mitigate disruption. Naughton et al. (2020) noted the relevance of linking data generated from using sophisticated flow cytometry with in-farm handheld AlgaTorch™ in order to provide real-time monitoring of fish production. This IMTA-peatland site can also be used to monitor carbon sequestration and energy usage that can be informed by life cycle assessment exercises (Rowan & Pogue, 2021; Laso et al., 2022). This peatland site is also suitable for deploying digital technologies such as drones and robots for addressing a broad range of sophisticated to banal activities, along with using satellites to aid modelling and prediction of extreme weather events that can jeopardize the production (Terrain-AI, 2022). For landbased aquaculture systems, such as paludiculture-based processes, there is potential to consider food value chain feedback loops and to identify actors that are willing to bear part of the cost of the engagement for strengthening ecosystem services (including carbon sequestration, bodiversity protection, protection of water bodies, avoidance of antibiotics, promotion of pollinators) (O'Neill et al., 2022).

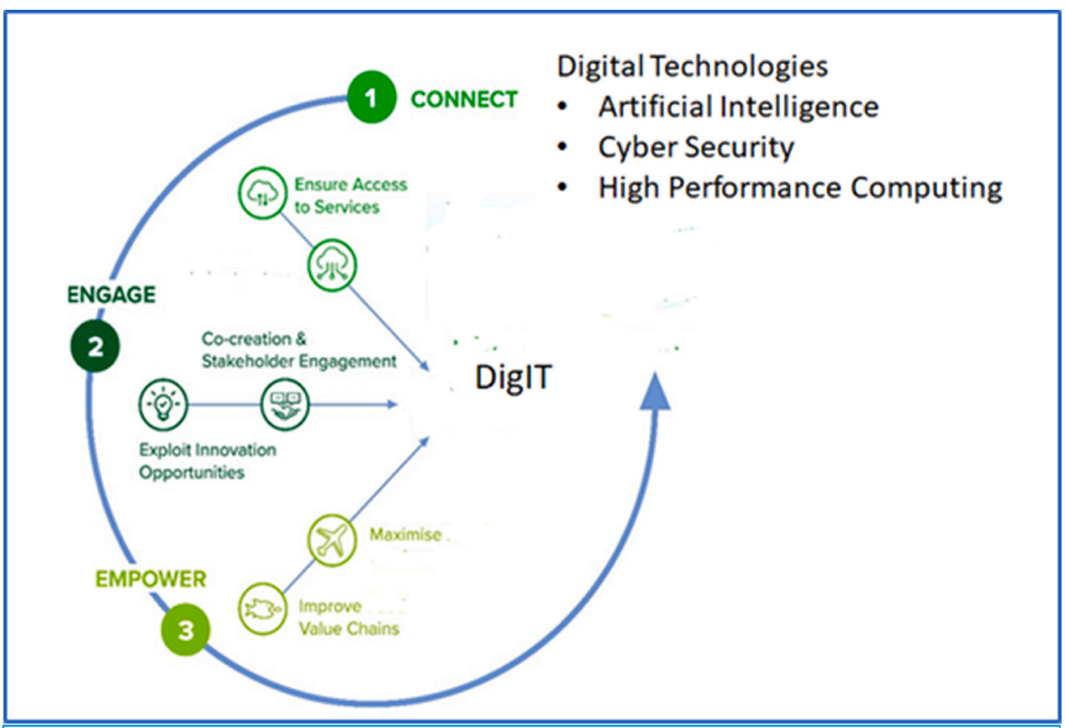
4. Role of Quadruple Helix innovation HUBs in increasing sustaining and disruption innovation

The Quadruple Helix Hub concept refers to a harmonizing and unifying commensurate contributions from academics, industry, government and society to efficiently meet established and emerging needs for the industry sector that also consider impact and added value (Galanakis et al., 2021; Rowan & Casey, 2021). This philosophy of stakeholder convergence for the betterment of society and the economy differs radically from a silo approach to problem solve and to innovate. The Quadruple Helix Hub approach supports and enables access to specialist equipment and subject matter expertise to deliver real-time solutions for the industry that commensurately informs policy and engages society by way of increased awareness and end-user feedback. Given the broad diversity of issues, drivers and stressors affecting fisheries, this holistic stakeholder approach fosters a multi-disciplinary clustering network to address these for to support the industry. This approach enables data to be gathered to inform tools for sustainability such as use of LCA, MFA and PCA to define activities and processes. For example, use of Cloud-Edge computing for end-to-end monitoring of value chain and the use of AI enabled drones and robotics for improved efficiency and to reduce reliance on workforce for menial or hazardous tasks (Yue and Shen, 2022). The Quadruple Helix concept aligns with the Innovation Hub framework; moreover, there are currently 706 digital innovation hubs (DIHs) where the European Commission has catalogued these and is supporting applications to recognise many as European Digital Innovation Hubs (EDIHs) (Rowan et al., 2022). In essence, these EDIHs will be operate to streamline efficiency and to provide real-time solutions to advance industry that also draws upon strengths and lessons learnt from adjacent partnering industry. Innovation Hubs typically enable entrepreneurial needs through five interlinked categories, (1) launching strategic initiatives, (2) re-entering existing programme, (3) updating stakeholder strategic agencies, (4) aligning infrastructure, (5) setting up strategic fora. InvestEU, short term training course are aligned with EDIHs by way of engaging with regional and national policy makers, deploying effective media to highlight resources and opportunities, and by impact assessing activities that includes indicators, and KPIs, developing targets, generating new knowledge including exploiting Open access to achieve benchmarking and policy recommendations.

This clustering of stakeholders in fisheries aligns with Agriculture 4.0 concept that will improve efficiency business models, management decision making and planning and risk mitigation for greater performances and reduction in waste. This convergence of actors will also help address important logistics underpinning sustainable supply chains. Application of the Quadruple Helix model also addresses holistic challenges in order to obtain real-time solutions (Rowan & Casey, 2021); for example, it can be applied to monitor and predict potential consequences of stressors that can jeopardize activities including extremes in climate change. EIDHs can also support and connect SMEs where new technologies can be tested, investment can be sourced, specialist training can be delivered including use of remote immersive technologies and so forth (Rowan and Galanakis, 2020). This approach can improve sustainability for the industry, both horizontally and vertically, and it is not surprising that this converging clustering framework has been adopted to help understanding regional strengths and weaknesses through transnational modelling with view to harmonization, such as through European Interreg initiatives (Laso et al., 2022). Recently, there has been greater focus on personal experiences that has led to the human centric Industry 5.0 concept that will also help with promoting greater awareness of new sustainable innovation, social enterprises and community transition to low carbon innovations. For example, Giron-Nava et al. (2021) noted that effective fisheries management is necessary for the long-term sustainability of fisheries and the economic benefits that they provide, but focusing only on ecological sustainability risks disregarding ultimate goals related to well-being that must be achieved through broader societal policy. These authors reported that if all fisheries in every country was perfectly managed to achieve maximum sustainable yield, average incomes of fishers in up to 49 countries (70% of fishers worldwide), would still not meet minimum living wagers. Thus, the Quadruple Helix Hub approach will support greater efficiencies and it is envisaged that this will not only underpin increasing sustaining innovation, but it will also potentially support disruptive activities creating new eco-innovation, products and services for the new Green Deal era. This is evident in Ireland where Science Foundation Ireland operates a disruptive technology funding initiative where there is increased trend towards exploiting cross-cutting domains of activity such as smart specialisation and digital transformation to inform disruption (Rowan and Galanakis, 2020).

Allied Market Research recently forecast the global aquaculture market will be worth $378 billion by 2027, up from $285 billion in 2019. There is increasing opportunities for enterprise and entrepreneurial accelerator initiatives for this industry. For example, Batch Blue, an Irish aquaculture accelerator has raised over €75 million and has invested in 38 start-ups and companies globally (Taylor, 2021). Among the Irish start-up that received training from Hatch Blue aquaculture accelerator is Plantruption, a company that is developing plant-based seafood where it has also chosen to participate in the prestigious IndieBio accelerator in the US. Eco-innovations developed under the Empower Eco sustainability HUB in the Irish midlands (Rowan & Casey, 2021) will also exploit ditigal technologies aligned with both the EIDH and Quaduple Helix HUB models (Fig. 1).

Use of social marketing to highlight challenges and opportunities in the blue economy that includes promoting behavioural change towards new innovation, consumption of seafood and Marine Citizen Science (Domegan, 2021). Domegan (2021) noted that in this complex world the call to action is large-scale behaviour change. In response, social marketing with its behaviour change prime directive has been expanding in experience, evidence, theories and toolkits. Aligned to the tenets of human centric Industry 5.0 conception, social marketing critically examines the interface of human and natural systems and their interconnected dynamic forces as a powerful means of influencing behaviours for the accorded transformation and betterment of individuals, communities, society and the planet. In pursuit of green deal innovations, critical trends in social marketing as it relates to fisheries will embrace systems science, stakeholder engagement and digital technologies. Marine citizen science is emerging with promising opportunities for science, policy and public but there is still no comprehensive overview of the current state in Europe. Garcia-Soto et al., 2021 reviewed 127 projects identified for the North Sea and observed that untapping the potential of smart mobile apps, do-it-yourself (DIY) technologies, drones, and artificial intelligence (AI) web services will be relevant to for technological advancement. Kelliher et al. (2022) highlighted that the proactive use of green innovation enablers is influenced by openness to engage in green innovation, and their ability to identify, pool and bundle internal and external resources, their capacity to understand and implement green regulations, and their ability to lever



Connect – providing service portal and road mapping approach (Innovation Platform)

Engage – accelerate co-creation and innovation by providing digital experimental spaces and data spaces aligned to using quintuple helix framework and the open innovation community approach

Empower – exploit business opportunities and access to technology and innovation leadership by providing tailored access to the wider European innovation, funding and business ecosystem.

Fig. 1. European Digital Innovation Hub proposition that will support fisheries and aquaculture.

green potential for socio-economic gain that could contributed to sustainable business goals. However, Deloitte (2014) interviewed Chief Financial Officers from 250 companies across 16 countries that included food companies and there is significant under-appreciation to grasp or understand key issues and risks around sustainablity. However, digital tools will support a roadmap that will align sustainablity goals, activities and emetrics with srategic industry goals across enterprise including fisheries. This will have knock-on implications including reducing cost of energy, materials, labor and other inputs including waste, through full value chain and contract management. This trend is also seen in recreational fishers who are increasingly using social and other digital media to share their experiences with followers; but, management of these socio-ecological systems is challenged by monitoring gaps, bias sampling and insufficient resources to conduct social surveys of human populations that include tool availability/accessibility, sampling biases, and making findings relevant and useable to practicionersn (Lennox et al., 2020).

5. Sustainable food processing and safety

Health, nutrition and convenience are significant factors influencing the sustainable direction of the food industry globally (Nagarajarao 2016). Fish products have attracted considerable attention as a important source of protein, vitamins, minerals, and fats. However, as fish are very persihable, appropriate processing and packing is required to maintain their quality. Worldwide, a diversity of preservation methods are been applied and developed ranging from simple chill storage to more complex advances in high pressure and electromagnetic field application (Nagarajarao 2016). Food Standards Agency UK (2021) noted that agri-food industy is experience strong technology push, potentially bringing products and services to the market for the sake of the technology, rather than satisfying a consumer need. This organization considers that modern heavily processed foods and processes may remove the opportunity of immune-priming by making everything unnaturally clean, which is something to be mindful in terms of health for the long term. Digital technologies can transform food processing by enabling end-to-end monitoring that can inform standardization of approaches including incremental innovative steps. Rowan (2019) had reviewed the disruptive potential of pulsed UV with particular emphasis on contact surface disinfection for foods and for packaging where there is a lack of international consensus on defined parameters and disinfection performance for this technology that could be informed by cloud-edge computing, AI and machine learning. Emergence of new studies on the use of novel bioactives in edible and non-edible packaging films such as use of plant antioxidants and antimicorbials for seafood is becoming increasingly popular (Oreopoulou and Tsironi, 2022). The UK Food Safety Authority (2021) intimated that emerging disruptive technologies may arise in active packaging, intelligent and smark packaging, novel nanotechnology packaging films, biodegradable and edible films, and reusable and zero packaging. Masterson et al. (2021) also reported on the use of a mild-temperature extrusion process suitable for combining and treating heat-sensitive bioactives that can have potential applications in fish and seafood packaging. The develop of algorithms and machine learning for the future real-time assessment and modelling of shelf life of processed fish will advanced the field of sustainable food processing (Tsironi et al., 2021).

Relative to other sectors, the food industry has been relatively slow to adopt digital technologies that includes discrete applications at the field, farm and factory level including automation, robotics and performance monitoring where the emphasis has been placed on process optimization (Food Standards Agency UK, 2021). Innovate new internet-embedded food distribution and services have been developed at the consumer level. Digital technologies have been applied at an integrated systems level to connect stakeholders at all stages of the value chain and to secure the gap-less digital traceability of food items for farm to fork, such as use of blockchain (UK Food Standards Agency, 2021).

The UK Food Standards Agency (2021) stated that ditigal technologies that impact on consumers and food safety can be grouped as:

(a) Ditigal technologies that are applied directly to food production processes (such as sensor-based agriculture, traceability, scanning technologies for contaminatn detection, monitoring of producing and delivery, smart packaging), where resulting flow of information is based on input of data collected from the actual food item.
(b) Digital technologies generating information relevant for food from input data not directly collected form that actual food item – such as that used for supporting decision making and influencing consumer choices (such as genomics or bioinformatics data).
(c) The platforms used for aggregating data, transmitting data securely, record keeping, and decision making either autonomously or with human input.

The main digtial technologies relevant to food safety include (a) IoT, cloud computing, bid data, machine to machine communication and remote sensing that enables rapid communication from acros the global value chain (Misra et al., 2020; UK Food Standards Agency, 2021); (b) AI, machine learning, digital twins that offer sophisticated analytics, dignostics and predictive capabilities, self-monitoring capabilities, and smart machines that evaluate and diagnose issues without need for human intervention (Defraeye et al., 2021; UK Food Standards Agency, 2021); and distributed ledge technology (DTL) such as blockchain that facilitates the decentralization of databases across several location to provide secure, verifiable and auditable history of all information stored in the dataset (Rejeb et al., 2020; UK Foods Standards Agency, 2021). Marvin et al. (2017) also noted the relevance of consumer-facing apps that support access to food data and information for decision making that has a nexus to social media, education and early warning systems. Rejeb et al. (2020) reported that their remains challenges with implementation, validation and regulation of digital technologies. Technical integration and interoperability across the worldwide supply chains is complex and be impeded by lack of infrastructure, lack of standardization and harmonization, and data integrity and data security risks (Agency, 2021; Feng et al., 2020; UK Food Standards; Galanakis et al., 2021).

6. Fisheries and aquaculture welfare

Disease mitigation remains an important activity for safe guarding fish welfare (Boutier et al., 2019) where there is a trajectory away from using chemical bioacides and antibiotics. Consequently, there has been increased interest in the development of vaccines in order to address key fish pathogens (Boutier et al., 2019). Facing the lack of efficient treatments for addressing a deadly disease in common carp caused by cyprinid herpesvirus 3 (CyHV-3), safe and efficacious prophylactic method (such as the use of vaccines) represent the most promising approach to controlling this virus. Delrez et al. (2021) reported on the importance of pre-release quarantine for mitigation of glasses eel sanitary. There is potential to include phage therapy also for fish welfare particularly to offset emergence of antimicrobial resistance (Rowan et al., 2022). Fish welfare is a constant challenge given the variety of microbiological, virological, parasitology and cyanobacteria (algal bloom) threats combined with plethora of biological and environmental factors that can influence disease mitigation efficacy (Franseen et al., 2019; O'Neill et al., 2022). Pogue et al. (2021) also highlighted the benefits of prophylacting adminstration of β-glucans in aquaculture including enhanced immune responses, anti-inflammatory effects, resistance to infection, stress resistance, physical growth improvement, as well as extension of lifespan. However, it is important to commensurately evaluate the potential toxicity and safety of bioactives when used in fish feeds, such as bioreactor-grown exopolysaccharides and endopolysaccharides from medicinal fungi mycelium for future aquaculture applications (Usuldin et al., 2021; Wan-Mohtar et al., 2021). Digital technologies such as underwater sensors and drones can be used to monitor fish health (Yue & Shen, 2022; Rowan et al., 2022) with future potential for use of immersive technologies for training.

There is a need to develop robust disease mitigation models to inform monitoring of interventions that can also inform appropriateness of in vitro (lab-based) testing and linked in farm aquaculture technologies (Naughton et al., 2020). It is likely that use of AI and machine learning will be deployed to support and enable automation in disease mitigation processes. There is also increased interest in managing complex algal blooms that can dessimate wild fish stocks (Sakamoto et al., 2021) and IMTA processes (O'Neill et al., 2022). Murray et al. (2017) had reported on the efficacy of pulsed UV light for destroying complex algal toxins under laboratory testing; however, Fitzhenry et al. (2021) highlighted that pulsed UV light was less efficient at energy conversion and less biocidal compared to using conventional low-pressure (fixed wavelength) light. Use of broad spectrum light for disease mitigation would be appealing given that its technically a natural process that leaves no unwanted chemical residues; however, pulsed light needs to be development further and cannot be used directly to treat infected fish. Garvey et al. (2015) reported that PUV was not ecotoxic to receiving water, yet killed Cryptosporidium oocsts. Maclean et al. (2009) reported on the use of fixed wavelength (405 nm) blue light for safely disinfecting a range of pathogens, which highlights the potential of photonics for use in fisheries for disease mitigation. Blue light (400–500 nm) alleviates overexposure risks associated to UV light . However, there appears to be a lack of robust data on relevant intensities, wavelengths and exposure doses for superficial blue light decontamination in food safety context (Lawrence et al., 2022). Understanding molecular and cellular processes that underpin disease migitiaton technologies and approaches are important (Farrell et al., 2010, 2011). Franseen et al. (2019) noted that the literature-based data are diverse and insufficient to model survival of parasite transmission stages as response to different treatment. Moreover, research on foodborne parasites should be improved to standardize experimental approaches for evaluation of inactivation techniques and methods to monitor inactivation. Digital technologies will enable fish welfare by supporting and enabling end-to-end monitoring and interventions that will inform standardization, decision making and policy.

7. Climate change

At the time of writing this viewpoint, the United Nations reported that sea level rise, ocean heat, greenhouse gas concentrations, and ocean acidification have set alarming new records (United Nations, 2022). Human behaviour accounts for approximately 1.0 °C of global warming above pre-industrial levels and calls for wide-scale behaviour change (IPCC, 2022; O'Sullivan, 2022). Researchers have reported that climate change can significantly affect biodiversity, ecosystem services, natural resource management and food security (Weisikopt et al., 2020; Rozenzweig et al., 2020). Galappaththi et al. (2022) recently reviewed case studies between 1990 and 2019 that lay at the cross-section of climate change, adaptation and fisheries where these author observed 3 emerging categories of adaptive responses; namely, (a) coping mechanisms (such as use of traditional knowledge, changing fishing location), (b) adaptive strategics (such as livelihood diversification, incroportation of technology), (c) management responses (such as adaptation planning and adaptive management). These authors identified important areas for future research including studies on the limits and barriers for industry adaptation to climate change that consider multiple stressors including general climate impacts, extreme events, ocean conditions, marine system shifts, climate variability, fishery dynamics, species distribution and atmospheric warming. New challenges in terms of real-time evaluation of big data generated that will inform conceptual and predictive models will be likely met by digital tools such as IoT, cloud-edge computing for end-to-end monitoring, where security and busienss sustainable models will be enabled by blockchain (Mondejar et al., 2021). Barry and Hoyne (2021) addressed social enterprise issues underpinning sustainablity across sectors with a climate change dimension.

In terms of knowledge gaps, key information is required to generate robust climate models that may inform adoption of technological solutions and efficient data sharing within agri-food systems (Yue & Shen, 2022). This can be achieved through use of defined demonstrator sites such as at Mount Lucas for aquaculture (O'Neill et al., 2022; O'Neill & Rowan, 2022, p. 802) that can feed into predictive models including capacity for carbon sink measurements (Terrain-AI, 2022). Specific solutions should be advanced to identify barriers and to leverage innovation in fisheries and seafood by using tailored digital tools and services that can be improved by integrating social science research to help unlock social and cultural practices across the value chain and to develop appropriate business models (Domegan, 2021). There is potential for developing more user-friendly technologies and services, such as ethical nudging tools (example, direct marketing and consumer shopping experience), information tools (e.g., social media, apps), gamification approaches, co-design and so forth (Mondejar et al., 2021). Asche et al. (2018) noted that future emphasis will also be placed on developing integrated, transdisciplinary research to address the three pillaros of sustainability (social, economic and environmental). However, while ditigal technologies can deliver efficiencies in real time, there is a commensurate need to understand beter the costs and benefits of ICT technologies in such agri-food systems spanning employment to nutrition and food security (Rowan et al., 2022). A Quadruple helix framework is appropriate to supporting and enabl fishiers along the supply chain that can influence economic, environmental, social, legislative, geographical, behavioural and busienss management. Data stewardship is also important as it relates to cybersecurity and protection of personal data and rights (Rowan & Pogue, 2021; UK Foods Stanadards Agency, 2021).

8. Conclusion

Wild stock fisheries are depleting rapidly where there is great pressure placed on promoting innovation and sustainablity throught aquaculture. There is increasing pressure on aquaculture to meet the important role of supplying high quality protein to meet the ever increasing growth in our global population. Although aquaculture is more diversified than other areas of agriculture, there are significant challenges ahead for the sector. Digital technologies can help address these concerns and also potentially disrupt fisheries and aquaculture. Digital technologies include cloud-edge computing, AI enabled drones, sensors and robotics, immersive technologies and blockchain. However, increasing converging efforts need to be made to create a greater awareness of the practical applications of digital technologie in order to advance the industy that is slow to adopt new innovation. Use of the Quadruple helix hub concept ('academic-industry-government-society') will provide a reliable and robust interface for supporting and enabling micro, small and large companies across the fisheries and aquaculture ecosystem. This aligns with the tenets of digital innovation hub structure across Europe where the emphasis is on enabling companies to innovate through provision of specialist training, testing new products, and to access to funding linked to innovating incubators/accelerators. Using this clustering hub model, digitalization will facilitate real-time integration, development and testing of various new technologies that will also inform standardization. Given the complexity of this situation, it is highly improbable for a sigle aquaculture company, or farmer, to innovate unless supported by subject-matter experts enabled through a multi-disciplinary structure that reflects the purpose of multi-functional innovation hubs. It is recognised that there will also be particular enterprise/entrepreneurial strenght and weaknesses across each region; thus, there are significant opportunities for applying transnational modelling combined with sustainable tools (such as life cycle assessment, material flow analysis, principle component analysis) to inform appropriate solutions. Priority topics include food-water-energy nexus, circular economy, climate change and biodiversity protection, and fish welfare that includes supply chain for safe nutritious feed and disease mitigation. This approach will also help stakeholders to understand and model the impact of extreme weather events (climate change) and other disruptive events (pandemics, conflicts) that can jeopardize critical supply chains. There are also pressing opportunities to develop blockchain for enhanced security and business models that addresses risk mitigation; but, to also embrace the social sciences and business domains for promoting greater stakeholder awareness and for behaviour change as we embrace the digital era. While it is appreciated that the short to medium term deployment of ditigal technologies will improve efficiencies and speed of production for improved profitability and sustainability, there is also significant potential for use of AI, machine learning and robotics to unlock a weath of innovation when one aligns these ditigal technologies with bioinformatics and next generation sequencing. For example, rapid profiling of microalgae linked to biorefinement of their high-value bioactives for advancing fisheries and adjacent industries. Digital technologies can also inform novel processing of fish and seafood that includes potential for future automation, training and improved standardization. Thus, digitalization will support and enable our ability to make -informed decisions on the use and protection of our natural resources. There is a pressing need to conduct life-cycle assessment aligned with developing e-waste recycling technologies that will be met through better infrastructure, upskilled staff and appropriate policies. Cypersecurity is a pressing topic that informs new business models, risk mitigation and network integrity. There iare increased opportunities to use digital technologies to meet several of the sustainable development goals of the United Nations.

Declaration of competing interest

The author declares not conflict of interest for this viewpoint paper.

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