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Digital twinning & sensoring

Current market trends

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ENGINEERING SOUL. FROM SOURCE TO SEA

13-4 SEAWEED

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Introduction

This report is part of the I3-4-SEAWEED Knowledge Hub initiative, which is designed as a central platform to support innovation and knowledge exchange in algae-based food systems across Europe. It brings together recent scientific findings, emerging market developments, and key industry needs, while promoting dialogue with stakeholders from academia, industry, and the public sector. Its mission is to accelerate the transition towards a resilient, competitive, and sustainable blue bioeconomy, with a strong emphasis on seaweed and algae-based solutions.

The present report focuses on **the evolving market landscape and a focus on digital technologies in aquaculture**. As seaweed cultivation scales up, market expectations are shifting towards greater efficiency, precision and sustainability - trends that are driving **the adoption of smart monitoring systems, automation, and decision-support tools across the sector**. The Digital Twin (DT) solution responds to these demands by creating a real-time virtual model of seaweed farms, allowing producers to monitor environmental parameters, forecast biomass growth and optimise operations.

Beyond this example, the report contributes to the broader objectives of the Knowledge Hub: to promote innovations that are scalable and market-responsive; support strategic cooperation across the Seaweed value chain; and strengthen Europe's leadership in emerging blue bioeconomy markets.

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1. Global context

As the global population continues to grow, the demand for natural resources increases. It became essential to use and produce these resources sustainably, without exceeding ecosystem boundaries and respecting sustainable resource exploitation. Over time, aquaculture has become one of the fastest growing sectors worldwide and is seen as a promising approach to meet these objectives (Brito et al., 2023).

In Europe, seaweed cultivation is still not very mature, even though first small-scale farms were established in early 1985 (Barbier et al. 2020). However, seaweeds are expected to be used in a range of fields such as food production (Nayar and Bott, 2014), feed and feedstock for the bio based economy (Stévant et al., 2017; Helmes et al., 2018; MacMonagail et al., 2018), pharmaceutical applications (Kang et al., 2016), cosmetics (Couteau and Coiffard, 2016) and bioremediation (i.e., removing pollutants from the aquatic environment; Elizondo-González et al., 2018). Additionally, due to their rapid growth, seaweeds can absorb carbon, nitrogen and phosphorous from seawater, offering a good and natural solution for CO_2 sequestration (Alevizos and Barille, 2023; Wu et al., 2023).

Nowadays, most seaweed production takes place in Asia, where this activity is deeply embedded in the local culture (Araújo et al., 2021). It was in Asia where seaweed was first used not only as fertilizers but also in medicine and even as food (Porterfield, 1922). In recent years, the consumption of macroalgae has reached the West, largely due to the popularity of Asian cuisine and its nutritional value and health benefits.

Taking these factors into account, the European Commission has been encouraging the development of seaweed farming across its maritime territories (European Commission, 2021, Communication No. 52021DC0236). Nevertheless, there is still a significant gap in fundamental knowledge regarding the potential of this activity in European waters. In November 2022, through the EU Algae Initiative (European Commission, 2022, Communication No. 52022DC0592), the European Commission identified several obstacles and outlined recommendations to support the transformation of the seaweed sector into a resilient, sustainable, and regenerative industry that can respond to rising demand within the EU.

1.1. Market size

Aquaculture is one of the key providers of food for human consumption. In the context of a growing global population, fish farming in particular is playing a crucial role as a source of protein. This trend is also seen in global numbers for aquaculture finfish production, which increased from 38 to almost 60 million tonnes between 2010 and 2020 (FAO, 2022).

According to Duarte et al. (2021), seaweed aquaculture accounts for 51.3% of global mariculture production and it is increasing at a rate of 6.2% per annum. To date however, seaweed production only represents a small fraction (0.3%) of the total global food production. For the first time in history in 2022, aquaculture surpassed captured fisheries regarding the production of aquatic animals. Global aquaculture production reached 130.9 million tonnes, of which 94.4 million tonnes were aquatic animals, which is in turn 51% of the total aquatic animal production (FAO, 2024b). However, **currently 99% of seaweed production in the EU depends on wild-stock harvesting while at global scale there is an opposite trend, with 99% of the production coming from cultivation** (Vazquez-Calderon et al., 2022).

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There are approximately **163 macroalgae producing companies** operating across Europe, with France, Ireland, and Spain standing out as the leading countries, each hosting more than 20 registered enterprises (Figure 1). Most of this production is concentrated in the North Atlantic, while only a limited number of operations exists in the Mediterranean region.

Aquaculture represents only 32% of the production methods used by European macroalgae companies. When cultivated, macroalgae are predominantly grown at sea (76%), and the potential for expanding offshore cultivation is considered significantly higher compared to land-based systems (Araújo et al., 2021).

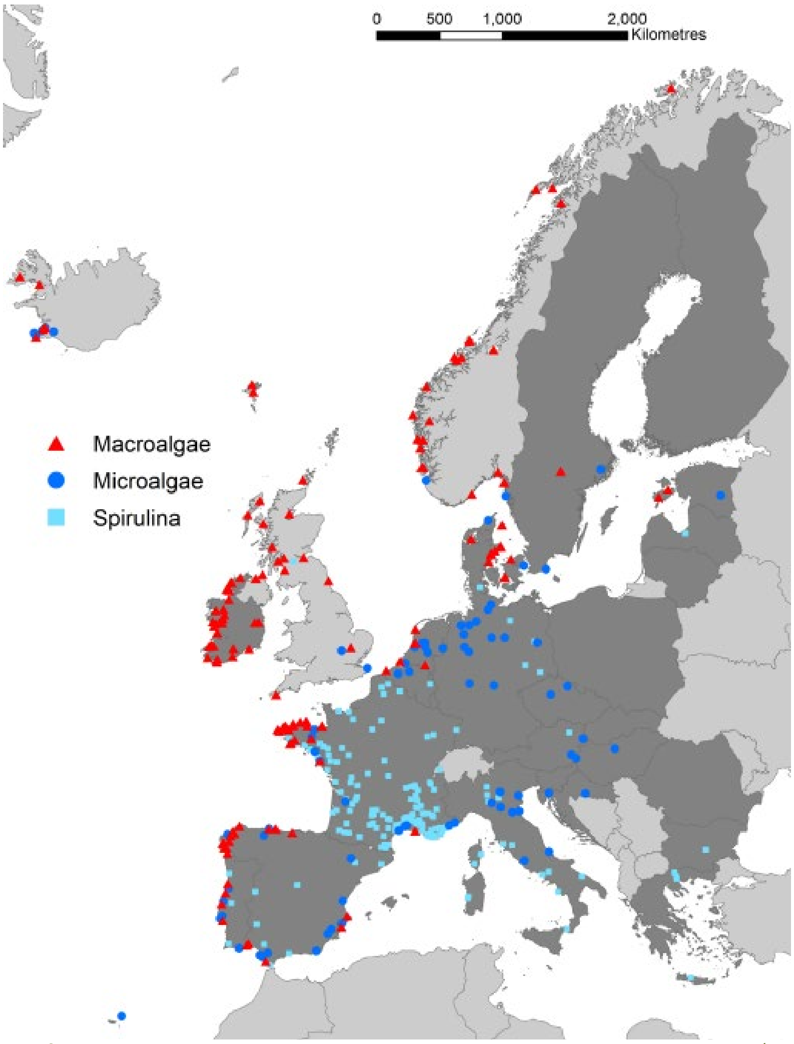

Figure 1. Distribution of macroalgae-, microalgae- and Spirulina production plants in Europe (Policy Department for Structural and Cohesion Policies, 2023).

This section provided a market characterization of the aquaculture sector. This analysis is directly relevant to the digitalization market in which the Digital Twin product under development is positioned. It highlights the scale and growth potential of aquaculture, as well as the operational challenges and inefficiencies that digital tools can address. By examining production trends, geographic distribution, and cultivation practices, priority areas can be identified where digital twin technologies may improve monitoring, optimize resource use, enhance traceability, and support data-driven decision-making. Ultimately, these improvements can contribute to increased productivity and sustainability within the sector.

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1.2. Opportunities & challenges

The aquaculture sector represents a rapidly growing and dynamic market with significant potential for innovation and digital transformation. This evolving landscape presents **numerous opportunities for digitalization, particularly through the integration of advanced tools such as digital twins**. Digital twins can provide near real-time monitoring, predictive analytics, and risk management capabilities, addressing critical operational challenges such as environmental variability, resource efficiency, and regulatory compliance. The ability to assimilate diverse data streams - from satellite observations to sensor networks - into a unified platform enables stakeholders to make informed, timely decisions that enhance productivity while reducing environmental impacts. Furthermore, digitalization can improve transparency and traceability across the supply chain, which is increasingly demanded by consumers and regulators alike.

However, realizing these opportunities requires to overcome several challenges. The sector's fragmented nature - with a mix of wild harvesting and cultivation methods, varying regional practices, and differing scales of operation - complicates the standardization and adoption of digital solutions. In Europe, only a minority of macroalgae producers currently use aquaculture, and many still rely on traditional methods, which may limit immediate uptake**. Data availability, quality, and interoperability remain significant barriers, particularly when integrating heterogeneous sources such as environmental models, sensor networks, and operational data**. Additionally, ensuring that **digital tools are accessible** and usable by diverse stakeholders - from small-scale farmers to large enterprises and regulatory agencies - is essential for widespread adoption.
The DT platform under development, leveraging high-performance computing and real-time data assimilation, aims to directly address these challenges by providing a flexible, scalable solution tailored to the needs of the aquaculture sector.

2. European Political trends in aquaculture digitalization

2.1. Opportunities and EU investments

Emerging trends in the digitalization of the environment are transforming the ways in which aquaculture systems are tracked, operated and evolved in coherence with shifting global dynamics. One of the most innovative developments in this sphere is the creation of Digital Twins of the Ocean (DTOs). These are virtual copies of sea and coastal regions which utilize real-time information, artificial intelligence (AI), and sophisticated modelling approaches to create models of the physical world with high precision. This idea of a "Digital Twin" has recently begun to acquire traction in the area of seaweed cultivation for biomass production due to its growing demand in applications such as water treatment, biodiesel production, and pharmaceutical industries (Ali et al., 2022). **Digital Twins have significant potential to change how seaweed physical systems are maintained and might enhance seaweed biomass production, even with changing environmental conditions** (Moretta et al., 2022; Ubina et al., 2023).

Moreover, the knowledge gained from the deployment of smart systems in seaweed cultivation for biomass production is now contributing to the growing development Digital Twins applied to seaweed aquaculture. These digital tools allow us to simulate a range of scenarios, assessing how different social and environmental conditions might affect the implementation of mitigation strategies. Technological progress in the field of seaweed Digital Twins is expected to **transform the way seaweed cultivation for biomass production systems is understood**. This can offer new opportunities to anticipate and manage adverse events, that are likely to affect crops, more effectively in the future. Digital networks and data-driven innovations that have grown increasingly are now integrated with water quality parameters, particularly influencing seaweed biomass

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growth (Sheik et al., 2024). Despite the current upsurge in the usage of these technologies and research owing to its broad use, there is **still a scarcity of information on this topic.**

To address this issue, the EU is currently making significant investment in the sector in order to improve sustainability and innovation in the activities associated to aquatic ecosystems. The market in digital technologies is a recent field to be increasingly explored in the future. In this regard, the European Maritime, Fisheries and Aquaculture Fund (EMFAF) is a program that runs from 2021 to 2027 and supports the EU common fisheries policy (CFP), the EU maritime policy and the EU agenda for international ocean governance. This program has a shared management of 5 311 billion euros that is provided through national programmes co-financed by the EU budget and EU countries, and a direct management of 797 million euros provided directly by the European Commission services or delegated to CINEA, with the relative calls being published in this portal. This funding program aims to support innovative projects that contribute to the sustainable exploitation and management of aquatic and maritime resources, including, among others:

- the development of a sustainable and competitive aquaculture contributing to food security
- the improvement of skills and working conditions in the fishing and aquaculture sectors
- innovation in the sustainable blue economy
- international cooperation towards healthy, safe and sustainably managed oceans

These are crucial points that can be addressed using digital technologies in aquaculture activities. Furthermore, the **European Digital Twin Ocean** (DTO) was announced by President von der Leyen at the One Ocean Summit in Brest in February 2022. Its ambition is to make ocean knowledge readily available to citizens, entrepreneurs, scientists and policymakers by providing them with an innovative set of user-driven, interactive and visualization tools. This knowledge is expected to help in designing the most effective ways to restore marine and coastal habitats, support a sustainable blue economy and mitigate and adapt to climate change. The European DTO will provide multi-dimensional descriptions of the ocean, including its physical, chemical, biological, socio-ecological and economical dimensions, with forecasting periods ranging from seasons to multi-decades.

The European Commission has invested about €15 million annually since 2021 through the Mission Restore our Ocean and Waters work program to develop the European Digital Twin Ocean. This complements the 19 million euros Iliad project, funded under the Green Deal Call for research proposals to pilot the DTO concept, as well as a number of research projects developing background science (European Commission, 2025).

In the last decade, the European Union has developed core data infrastructures and ocean services such as:

- Copernicus Marine Service (CMEMS)
- Copernicus Data and Information access services (DIAS)
- European Marine Observation and Data Network (EMODnet)

They offer global and pan-European quality-controlled ocean observation data, forecasts, analysis and projections.

The DTO is a main element of the Digital Ocean Knowledge System under the EU Mission Restore our Ocean and Waters. It is also a priority in many different initiatives such as the International Ocean Governance, the UN Decade of Ocean Science for Sustainable Development, the All-Atlantic Ocean Research Alliance and the G7 working group Future of the Seas and Oceans Initiative which the EU contributes to (European Commission, 2025).

Since the announcement by its President, the European Commission has been launching many funding programs to improve the digital solution for our water bodies, including aquaculture.
Under this scenario, the EU is currently interested in investing in projects aimed at improving the monitoring of water bodies and activities in the ocean. However, most of the technology, especially for seaweed aquaculture, is still under development and at the study stage, which also represents a significant market opportunity.

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2.2. Market Trends in Digital Solutions for Aquaculture

There are many authors that recognize the importance of integrating digital solutions in the management of aquatic activities (Rowan, 2023a). These authors also noted that the convergence of simultaneously developed digital technologies for real-time analysis, AI and machine learning (ML) techniques can manage 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 the supply chain for fishery and aquaculture. Table 1 provides definitions of common terms within the field of digital technologies, also used in fisheries and aquaculture.

Table 1. Digital technologies – definitions and applications in fisheries and aquaculture (Rowan, 2022).

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 – the use of tools and applications (such as data storage, servers, databases, software) based on a network of servers through the internet. It enables users to rent computer resources on demand to store files and applications in virtualized 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. It is complex and multidimensional which 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 – 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, which may contain a value transfer or a smart contract invocation, in sequence.
Augmented reality – a technology that superimposes a computer-generated image on a user's view of the real world; thus, provides 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.

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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 – a robot intended for direct human-robot interaction with a shared space, or where humans and robots are in proximity.

Digital twin – 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 – 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 – systems where software and hardware components are seamlessly integrated towards performing well-defined tasks.

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 (Rowan, 2023a). Digital Twins of the Ocean are of great importance in aquaculture, especially regarding predictive environmental monitoring, spatial planning, and risk mitigation. These systems receive information from **satellite monitoring systems (e.g., Copernicus), in-situ sensors, and even the public, and use advanced ML algorithms to forecast the impacts of changing environmental conditions on the aquaculture farm**. Specifically, in aquaculture, this translates into the ability to predict and model critical environmental factors, like ocean currents, salinity, temperature, levels of oxygen and nutrients, and even harmful algal blooms. Besides that, it enables a more informed site selection and more effective disease control (Horizon Magazine, 2024). Additionally, DTOs support the modelling of "what-if scenarios". These models enable aquaculture managers to simulate the effect of changes in the farm's spatial arrangement, a mix of species cultivated in a cost-free environment and, therefore, test these mitigation approaches prior to real-world application. DTOs can also support nature-based solutions by evaluating the environmental consequences of such interventions (Macias et al., 2022).

Across Europe, the development of Digital Twin technologies is being supported at the highest policy levels. The EU is actively investing in a Digital Twin of the Ocean, through platforms such as the Copernicus Marine Environmental Monitoring Service and the Joint Research Centre's Blue2 Modelling Framework (Blue2MF). These tools offer high-resolution environmental simulations for the five EU marine regions and can support assessments of seaweed growth potential under different scenarios (Macias et al., 2022).

In the private and research sectors, a diverse range of Digital Twin applications are emerging for aquaculture. While most existing solutions focus on fish farming, the enabling technologies - such as sensor networks, ML, hydrodynamic models, and image-based disease diagnostics - are rapidly maturing and becoming more affordable. This creates favorable market conditions for broader adoption.

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Recent studies highlight various digital tools already in use or under development:

- Zhabitskii et al. (2021) demonstrated a Digital Twin for aquaponics, incorporating real-time data on fish and plant health, water quality and system performance, showing the potential for integrated multispecies systems.
- Ahmed et al. (2022) used ML and image processing to detect fish diseases with high accuracy, reflecting a market trend toward automated diagnostics.
- Davis et al**.** (2023) developed a drone-based IoT framework (HAUCS) for water quality monitoring in ponds, showcasing how robotics can address labor shortages and optimize resource use.
- Alver et al. (2022) and An et al. (2023) contributed fluid dynamics and oxygen distribution models, informing tank and cage design to improve animal welfare and farm performance.
- Mathisen et al. (2021) presented a decision support system based on case-based reasoning, providing operators with predictive and explanatory tools to guide site selection and operational planning.
- Yu et al. (2021) introduced a hybrid soft computing model for real-time estimation of ammonia nitrogen levels, addressing a critical gap in water quality monitoring technology.

These examples illustrate that Digital Twin solutions are increasingly integrated with IoT sensors, AI algorithms, hydrodynamic models, and robotic systems, forming comprehensive, modular platforms for aquaculture management.

The market is clearly moving towards flexible, scalable and data-centric systems capable of supporting decision-making in dynamic marine and freshwater environments. Despite this progress, one of the most striking findings from recent literature is the lack of Digital Twin applications in seaweed aquaculture. As noted by Le, Woo, Lee, and Huh (2024**)** in their global review of Digital Twin use in aquaculture from 2017–2024, no published studies focused specifically on macroalgae cultivation. This represents a significant gap in both the scientific literature and the innovation pipeline, and consequently, a potential opportunity for market development.

In summary, the digital solutions market for aquaculture is evolving rapidly, with growing demand for integrated monitoring, automation and predictive capabilities. While finfish farming currently dominates this space, the enabling technologies are transferable to other forms of aquaculture, including seaweed. Addressing this gap could strengthen the competitiveness of the seaweed sector. However, it is assumed that the growth of seaweed aquaculture will also drive increased efforts in the development of Digital Twin solutions specifically tailored to seaweed farming.

In the past five years, there has been a proliferation of not only start-ups, but also mainstream aquaculture service companies, developing their own digital offerings in the sector (FAO, 2022). Currently, there are several technologies to be used to digitalize the fisheries and aquaculture sector as reported by (Connolly, 2018; Rowan, 2023a) and described in the following table (Table 2).

Table 2. Digital technologies used in fisheries and aquaculture. Source: Rowan (2023a).

Digital Technology	Application
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
Drones	• Monitor fish farms above and below water • Check holes in damaged cages • Data collection combining AI and cloud computing to improve aquaculture operations

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Digital Technology	Application
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
AI	• Makes better and faster decisions • Less labor intensive, • Improved efficacy of feeders, water quality monitoring and control, harvesting and processing
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
Virtual Reality (VR)	• Real time simulation of environmental situations using digital interface (headsets) • Teaching, training and education • Used for high risk environments (remote) using human computer and multimedia platforms
3D printing	• Printing hydroponic systems • 3D verification devices • 3D printed water sensors for monitoring water parameters • Reduced equipment and production costs
IoT	• Connect big data across aquaculture industry • Combined use of social media
Blockchain	• Cypersecurity, safe data sharing, • Payment processing • Industry protection • Full traceability across value chain • ➢Reduce food wastage, improve food safety

Even though digital technologies hold significant potential to address current challenges, their adoption remains slow. Much of the value of existing data is still untapped, as it is often stored in isolated silos inaccessible to potential users. Unlocking this value is hindered by technological limitations, limited trust among stakeholders - particularly regarding data security and safety - and economic factors, including uncertainty about returns and uneven capacity in the private sector to meet transparency requirements (Rowan & Galanakis, 2020; Rowan, 2023a). By providing valuable insights, predictive abilities, and remote management tools, these technologies aim to increase yields, reduce resource consumption, and ensure the well-being of aquatic species. Ultimately, the goal is to transform traditional aquaculture practices (Rowan et al., 2022; Rowan, 2023a, Rowan, 2023b). For example, ensuring the production of healthier aquaculture products at scale necessitates continuous monitoring of water-related factors, including dissolved oxygen, temperature, salinity, ammonia, pH, nitrogen dioxide, bromine, feed input, and disease prevention. Accurate monitoring is vital to prevent disasters like unexpected fish mortality and stunted growth rates (Oddsson, 2020; Lopes et al., 2021). Digital platforms are the most common digital solution in aquaculture, enabling data collection from databases, sensors, cameras, and manual inputs. As they are now capable of high-definition real-time streaming, they have become essential for monitoring salmon feeding, fish health, and net inspections. Advances in AI-powered video analytics allow automated fish sizing, parasite detection, and feeding optimization. Emerging technologies aim to diagnose individual fish health and welfare through camera systems (FAO,

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2022). Norwegian salmon farms have long used feed control centers, which are now adopted in Australia, Canada, Chile, and Scotland. Costing up to USD 14.6 million, these facilities connect to hundreds of underwater cameras and sensors, enabling a single operator to feed up to 15 million salmon. AI and acoustic systems help prioritize cages needing attention, track biomass and growth rates, and forecast harvest dates. While such large-scale solutions suit only major companies, more affordable digital tools are increasingly available to small-scale producers, improving efficiency, precision, animal welfare, and environmental performance, while opening access to certified markets. However, automation may reduce low-skill jobs, even as it creates more roles for digital system operators (Måløy, 2020; Facts and Factors, 2021; Aqua Spark, 2020; Statista, 2021).

Despite all the research done, increasing converging efforts between academia, industry, government and society need to be made to create a greater awareness of the practical applications of digital technology in order to advance the industry that is slow to adopt innovation (Rowan, 2023a).

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Conclusion

Seaweed production is increasingly recognized as a strategic sector with significant potential to address multiple global challenges, including food security, climate change mitigation and the sustainable development of coastal regions. Throughout this project, it became evident that seaweed aquaculture represents a promising solution to diversify food sources, replace high-impact raw materials, and enable the creation of high-value product.

However, despite its acknowledged potential, the sector remains at an early stage of development. Both production and consumption of seaweed represent only a small fraction of the global and European markets. Nevertheless, notable changes are emerging, and there are promising prospects for future growth. When it comes to the use of Digital Twins and digitalization tools in this sector, there is still a long way to go, particularly in seaweed aquaculture, where available data and digital integration remain limited.

In conclusion, while the digitalization of aquaculture systems, especially seaweed farming, is still in its infancy, there is growing recognition of seaweed's strategic value. Combined with advances in digital technologies there is a significant opportunity to accelerate sustainable growth, improve operational efficiency, and unlock new market potentials in this evolving sector.

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