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Digital twinning & sensoring

Most recent and impactful research

2026

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13-4 SEAWEED

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Introduction

This report is part of the I3-4-SEAWEED Knowledge Hub initiative, which objective is to serve as a central platform to promote innovation in algae-based food systems across Europe. It aims to consolidate the most recent research insights, emerging market trends, and pressing industry needs, while actively encouraging engagement with stakeholders from academia, the private sector, and the broader public. Knowledge Hub's mission is to contribute to the acceleration of the development of a resilient, competitive, and sustainable blue bioeconomy, with a particular focus on seaweed aquaculture and algae-based products.

The report highlights the most impactful research in Digital Twin technologies, with a specific focus on their application in aquaculture, particularly algae aquaculture. The latest best practices for Digital Twin systems enable the creation of a real-time virtual model of seaweed farms, allowing producers to continuously monitor environmental conditions, forecast biomass growth, and optimize operational decisions. In this context, it is also important to understand the challenges associated with the innovation and implementation of this technology. Integration of digital technologies into the aquaculture value chain promotes a shift towards smarter and low-impact practices—crucial for enabling sustainable growth and reinforcing Europe's leadership in the global algae sector.

Beyond this specific case, the report contributes to the wider goals of the Knowledge Hub: to promote replicable and scalable innovations, foster collaboration across Europe and beyond, and lay the foundation for a long-term strategy. It seeks to facilitate ongoing partnerships, stimulate knowledge exchange, and position the Hub as a central node in the European algae innovation ecosystem.

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1. Innovation in the Aquaculture Sector

Aquaculture is one of the fastest-growing sectors in recent years. Its development requires innovative approaches and improvements to enhance operations, reduce environmental impacts, and increase the overall efficiency of aquaculture. There are also some challenges related with the economic pressure (Chen et al., 2025). To achieve good fishing management and an appropriate growth of the animal under culture, water quality parameters such as temperature, oxygen, pH, ammonia, nitrite and nitrate levels, are very important and need to be controlled (Dupont et al., 2018).

To respond to this need, **Industry 4.0—also known as the Fourth Industrial Revolution—**represents the most recent stage of industrialization, not only in aquaculture but across industry as a whole. It relies on smart devices to create a physical–digital connection between the components of the production flow, enabling a fully optimized and integrated process. Examples of technologies in this phase that can act as key tools to produce more sustainable food are the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), computer vision (CV), and optimized sensors (Vaidya et al., 2018).

Nevertheless, there remains a notable absence of comprehensive EU-wide assessments regarding the potential of seaweed cultivation. The EU has prioritized investments in monitoring technologies and research aimed at enhancing our understanding of environmental conditions across its marine regions. Yet, current data remains insufficient to offer a complete overview of the aquaculture sector, encompassing both spatial and temporal variability of marine environmental variables. Alongside these monitoring endeavours, strides have been made within the EU towards developing numerical models capable of delivering expansive insights into environmental variables within EU waters (Macias Moy et al., 2024).

2. Digitalization of the Aquaculture sector

2.1. Introduction to Digital Twins

A Digital Twin is commonly understood as a digital representation of one or more critical and interrelated equipment systems (e.g. automatic feeding system, oxygen and temperature sensors, water circulation pumps, etc) (Aheleroff et al., 2021; Zhabitskii et al., 2021). At its core, a Digital Twin is a dynamic virtual model of physical systems or processes which is continuously updated using real-time data, enabling constant monitoring, predictive simulations, system optimization, and data-driven decision-making (Figure 1) (Gonzalez Jimenez et al., 2023; Park et al., 2023). It leverages physical models, sensor data, operational records, and other inputs to integrate simulations across multiple disciplines, physical domains, scales, and probabilistic parameters, effectively mirroring the real-world system within a virtual environment (Thelen et al., 2022; Pylianidis et al., 2021).

Over the past twenty years, the Digital Twin concept has evolved significantly - from its early use in manufacturing and engineering to a versatile technology now being applied across a wide range of industries, including aquaculture (Hamzah et al., 2024).

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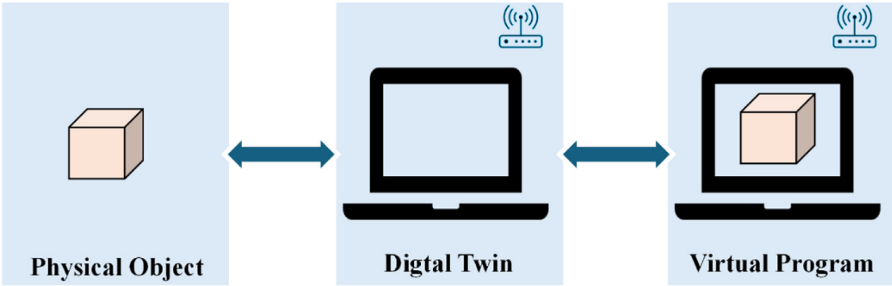

Figure 1. Common sensors used in aquaculture (Chen et al., 2025).

A Digital Twin is constructed with several key components, such as sensors, data analysis and processing platforms, virtual models and control systems (Chen et al., 2025). The sensors are used to collect real-time data from the environment (physical object). These sensors feed the collected data (various environmental and biological parameters critical to the health and productivity of the aquaculture system) into a central processing unit, often connected through a cloud-based IoT platform, which sends the data to the Digital Twin model for further analysis and simulation (Chen et al., 2025; Ghandar et al., 2021)

The data analysis and processing is the point in the process where the application of big data analytics, machine learning, and artificial intelligence becomes essential. All the data collected by the sensors are analysed through algorithms to detect patterns or anomalies, and it is possible to predict future events with machine learning based on historical data (Lee et al., 2024; Chen et al., 2020; Yang et al., 2024). The virtual models are at the centre of Digital Twins and are the virtual representation of the physical system. These models are continuously updated enabling operators to simulate different scenarios and analyse the effects of potential changes before implementing them in the real world, allowing operators to make informed decisions that are likely to yield the best results (Zhang et al., 2023; Mohammadi Moghadam et al., 2024).

The control systems are the last key component of a Digital Twin system. The system identifies problems or proposes optimisation suggestions, and it will either act on the physical environment automatically or send an alert for the aquaculturist to take action. (López-Barajas et al., 2023). In some cases, these systems can be autonomous according to preset rules or the results of predictive analysis. For example, if the Digital Twin system indicates that dissolved oxygen is falling beneath optimal levels, it can automatically initiate aeration to correct the imbalance (Gorgan-Mohammadi et al., 2022).

In a Digital Twin system, the decision support component goes beyond simply transmitting data. It should provide an interactive interface that helps users grasp how the Artificial Intelligence (AI) model reaches to its conclusions. By using these tools, operators can explore how different choices might affect operations and how to intervene to adjust system responses when needed (Chen et al., 2025).

2.2. Digital Twins in Aquaculture

The integration of a Digital Twin technology into aquaculture marks a rapidly evolving shift that has the potential to redefine how aquaculture systems are monitored, managed, and optimized. Digital twinning technology has emerged as a powerful tool for transforming aquaculture, making it more intelligent, sustainable and efficient (Aheleroff et al., 2021).
The development of faster and more reliable wireless communication technologies has transformed the way data is gathered from remote or hazardous environments. Based on these advancements, sensors can now be deployed in the field to collect environmental data and transmit it wirelessly to centralized platforms, where the information can be stored, managed, and analyzed - overcoming many of the traditional challenges associated with on-site data collection (Ubina & Cheng, 2021).

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Such a tool offers a **digital representation of a real-world system**, and it is used to enable the **description and prediction of a system dynamics**. Using Digital Twins, it is possible to monitor and estimate aquaculture system states that are difficult to observe directly, by linking the physical and digital worlds (VanDerHorn and Mahadevan, 2021). In aquaculture, Digital Twin technology can be applied to the entire aquaculture system, including tanks, water circulation systems, feeding systems, health monitoring systems, and waste management processes, covering both inland and open water systems (Lambertini et al., 2022; Lv et al., 2023; Purcell et al., 2023). One of the most important advantages is the possibility to optimize resource utilization (He et al., 2020). This technology also helps to reduce waste, improve feed efficiency and reduce water and energy consumption, and in consequence, maximize yields and minimizing environmental impacts (Liu et al., 2021; Reyes et al., 2022; Mohammed et al., 2024; Tzachor et al., 2023).

Although the development and application of Digital Twins has been advancing rapidly in other sectors, there have been few attempts to apply this technology in aquaculture (Føre et al., 2024). One of the possible reasons for this is that intensive aquaculture, especially algae aquaculture, is a relatively young industry, and usually expensive. However, much of the R&D efforts have already succeeded in addressing several challenges related to the exploration of living organisms underwater. The current challenges in aquaculture now lie in the development of management tools to improve farming practices, as well as the monitoring and control of the production in the systems.

Developing improved farming practices in aquaculture demands a solid understanding of the underlying biological and physical processes, along with the ability to monitor them continuously. However, this remains a significant challenge, as most of these dynamics take place underwater. Digital Twin technology offers a promising way to overcome this barrier. Given the current trajectory of aquaculture expansion and its anticipated role in future global food security, it is essential to assess the potential of applying Digital Twins in this context and to define a clear roadmap for their development and implementation.

Comprehensive assessments of seaweed cultivation potential across the EU are still lacking. While the EU has made significant investments in research and monitoring to better understand the environmental conditions and their variability in its marine areas, existing data remains too limited to offer a complete overview - particularly in terms of spatial and temporal dynamics. Alongside these monitoring initiatives, progress has also been made in advancing numerical modelling tools capable of delivering large-scale descriptions of environmental parameters in EU waters (Macias et al., 2025).

In this context, the application of Digital Twin technology in intelligent aquaculture is expanding, yet its use remains quite limited - particularly in seaweed farming. Most existing examples are still designed primarily for finfish aquaculture. However, many of the functionalities and operational frameworks can be adapted to seaweed systems. The Figure 2 illustrates the main areas where Digital Twin technology is currently applied in fish aquaculture.

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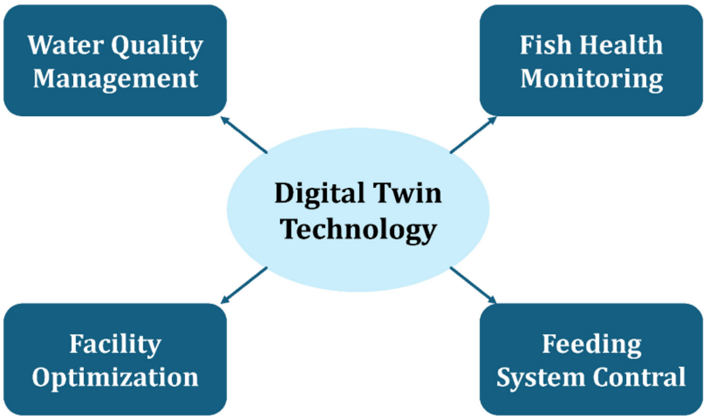

Figure 2. Applications of DT in intelligent fish aquaculture (Chen et al., 2025).

Water quality management has been one of the primary challenges in aquaculture, ensuring the optimal conditions for the health and growth of the organisms. This can be both applied to fish and seaweed aquaculture. Digital Twins allow for continuous and real-time monitoring of key water parameters (e.g. temperature, salinity, pH, dissolved oxygen, nutrients…). By combining real-time sensor data with predictive models, the systems simulate how these environmental factors interact with each other (Burke et al., 2021; Alver et al., 2016; Alver et al., 2022). The ability to simulate future environmental conditions, based on a combination of historical and real-time data is one of the major advantages. The system can simulate how these changes in the environment might impact farms health, allowing aquaculture operators to adjust their strategies in advance, which reduces potential risks (Lima et al., 2022).

Regarding the health monitoring in fish aquaculture, Digital Twins provide a proactive approach to fish health management by integrating sensor data on water quality, fish behaviour, and growth patterns and combining such data with machine learning algorithms (Chen et al., 2025). The facilities optimization is another critical application of Digital Twins. Through this technology, it is possible to simulate different designs to determine the most efficient setup (Ren et al., 2024; Chen et al., 2025).

The **precision feeding systems** are also a critical application of Digital Twins, mainly for fish aquaculture. This process involves the control of fish behaviour, growth and water conditions. Through these data, the Digital Twin system can optimize feeding schedules, ensure that the right amount of feed is delivered, and minimize feed waste. This contributes to improving feed conversion ratios (FCR), reducing environmental impact, and improving aquaculture system (Chen et al., 2020).

2.3. Digital Twins – Challenges

Digital twinning technology has the potential to transform the aquaculture industry. However, there are several challenges, especially ones related to technical barriers, data management issues, economic factor and complexity of the implementation of the systems in real-world environments. Data management is a major challenge for implementing Digital Twin systems in aquaculture, due to the high volume of sensor-generated data and the complexity of storing, processing, and analysing it efficiently (Vasilijevic et al., 2024). These systems rely on continuous real-time data streams - such as water quality and fish behaviour - which require advanced computing, cloud infrastructure, and robust algorithms (Mileti et al., 2022). Additionally, ensuring data quality, security, and privacy is essential, particularly as sensitive information is transmitted across various platforms, making encryption and access control critical for system reliability and trust (Vasilijevic et al., 2024; Mileti et al., 2022).

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To introduce a Digital Twin system, there is a **high initial investment** that remains a significant barrier, particularly of small and medium scale operation. Costs related to sensor installation, computing infrastructure, software development, and staff training can be substantial. Furthermore, beyond the upfront expenses, there are ongoing costs for system maintenance, updates, and the integration of new components as technology evolves (Le et al., 2024; Tzachor et al., 2023).

The **interoperability** is another challenge that can be found when applying Digital Twins in aquaculture. This issue can be found especially in older facilities that are not designed for smart technologies. Traditional farms that manage water quality, feeding, and waste manually may encounter technical barriers, such as data mismatches or system errors when adopting Digital Twins. Moreover, the complexity of these systems can hinder adoption among operators lacking technical expertise, making user training essential to ensure proper data interpretation and effective decision-making (Chen et al., 2025).

3. State of the art - Sensoring and Digital Twins

3.1. European Union's efforts

Seaweed cultivation depends on environmental factors that regulate the growth rates of the different species. To quantify the potential for cultivation at open sea, a detailed investigation of the environmental characteristics of EU marine regions is necessary. To date, studies on seaweed cultivation potential in EU waters are limited. For example, Thomas et al. (2019) assessed the potential for seaweed farming on the western coast of Sweden, in an area within Skagerrak, expanding 150 km of coast. Kotta et al. (2022) further explored the potential for seaweed cultivation in the Baltic Sea using modelled environmental data to calculate potential growth rates and nutrient removal capabilities. A similar model-based approach was previously used by van der Molen et al. (2018) to identify potential environmental impacts of existing seaweed facilities in Dutch and UK waters (Macias et al., 2025).

The European Union is actively advancing efforts to develop its Digital Twin of the Ocean over the coming years. Notable examples include numerical outputs from the Copernicus Marine Environmental Data service (https://marine.copernicus.eu/) and the Blue2 modelling framework (Blue2MF), created by the Joint Research Centre (JRC) of the European Commission. However, Copernicus has limited application in aquaculture, as its spatial resolution is relatively low. The Blue2MF is specifically designed to assess how different policy scenarios might affect the environmental status across all EU marine areas (Macias et al., 2022). It is capable of delivering essential environmental indicators relevant to assessing seaweed growth potential in marine environments (Macias et al., 2025). This integrated modelling system delivers high-resolution numerical simulations of key environmental variables across the five EU marine regions (Baltic Sea, North Western European Shelf (NWES), South Western European Shelf (SWES), Mediterranean Sea, and Black Sea). This framework incorporates various components, including atmospheric inputs derived from reanalysis data or Global Circulation Models, land-use models, freshwater flow and quality simulations via hydrological models, region-specific coupled hydrodynamic-biogeochemical models, as well as high trophic level marine models and Lagrangian particle tracking tools. This tool has been specifically designed to assess the status of EU marine ecosystems under various management scenarios (Macias et al., 2025; Miladinova et al., 2017).

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3.2. Recent research withing digitalization in aquaculture

In recent years, multiple researchers have explored the integration of Digital Twin technology and broader digitalization strategies in aquaculture, with the aim of optimizing production processes, increasing operational efficiency, and supporting data-driven decision-making. Selected examples, based on most recent studies, from the literature are outlined below.

Zhabitskii et al. (2021) discussed the integration of Digital Twins technology in aquaponics. Their work demonstrates how Digital Twin technology can optimize food production within the aquaponics system, involving real-time monitoring, control, and analysis of data related to fish health, plant growth, and system performance. Data sensors include temperature, light intensity, water flow, dissolved salts (TDS/EC sensor), and pH. The primary components of the simulation encompass fish feed, total dissolved solids (TDS), fish weight gain, pH levels, nitrates, and plant development.

Yasruddin et al. (2025) developed a stacked ensemble learning framework for fish health management which utilizes deep learning-based detection models to identify fish diseases and evaluates the impact of pH level and temperature on disease probability through logistic regression. By bridging the gap between image-based diagnosis and water quality analysis, this study provides a comprehensive and real-time diagnostic system, enhancing disease management in aquaculture. Ahmed et al., (2022) proposed an image-based machine learning framework using a support vector machine (SVM) with preprocessing techniques (e.g., k-means segmentation, adaptive histogram equalization) to detect diseases in salmon fish, achieving 94.12% accuracy on an augmented novel dataset.

Davis et al. developed the Hybrid Aerial Underwater Robotic System (HAUCS) as an IoT framework designed to streamline simulations for water quality monitoring in aquaculture farms. It uses a network of unmanned aerial vehicles (UAVs), or drones integrated with underwater measurement devices to collect pond data. The system aims to develop an efficient path-planning algorithm to sample all ponds with minimal resources. Initial results show that drones can be used to monitor water quality levels, reducing farmed fish costs and addressing labour shortages in the North American aquaculture industry. Simulations show that Google Linear Optimization Package and Graph Attention Model path planning methods are more efficient for smaller farms, while HAUCS Path Planning Algorithm is more efficient for larger farms.

The study carried out by Resnick et al. (2023) used the Gao Merrick model to simulate pond water temperature in Bangladesh's southwest and northeast regions. The model accurately predicts daily temperatures, but accuracy decreases with heavy rainfall events. The research contributes to early warning systems in aquaculture, improving practices and modelling techniques. It also lays the groundwork for globally accessible and open-source climate service products, especially in regions with limited meteorological data.

Teramoto et al. (2024) found that the artificial neural network and support vector machine methods, based on artificial intelligence and water quality parameters, can be used to develop a model to predict total suspended solids content. These are based on AI and water quality parameters, using nitrite and turbidity as predictive variables. The results show higher accuracy when using machine learning techniques with SVM. It is recommended as an alternative to use SVM with nitrite and turbidity as predictive variables for estimating TSS, but has a tendency towards overestimation and an error range of around 19 %. Even though the recommended Total Suspended Solids (TSS) concentrations found in literature have a wide range and there is an inherent error in the gravimetric methodology, the results suggest acceptable outcomes in TSS prediction and control, with potential application in biofloc technology aquaculture systems.

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The study carried out by Katrasov et al. (2021) explored the usage of hydrodynamic simulations to determine the most suitable area for marine aquaculture farms. The Delft3D Flow model was used for the hydrodynamic regime of Voevoda Bay, Russia, and compared with published recommendations for off bottom and bottom culture of Pacific oysters and yesso scallops. The study identified zones and boundaries for bottom culture, with 1-m isobaths for that culture and 5-m for off-bottom culture. The work aims to help aquaculture practitioners make informed decisions to ensure the success and sustainability of their operations while minimizing negative environmental impacts.

Kim et al. (2023) proposed a preprocessing and probabilistic fish growth model for smart aquaculture systems. The authors explored the use of probabilistic modelling to support Digital Twin systems in smart aquaculture, focusing on predicting fish growth based on environmental data collected by IoT sensors. Their approach integrated real-time water quality data with historical datasets to estimate biomass development over time. The model was modular and data-driven, allowing for flexibility across aquaculture environments and supporting operational decisions, such as feeding optimization and harvest timing. This study is relevant by addressing a central challenge: accurately forecasting fish growth in dynamic farming conditions. The study exemplifies how Digital Twins can enhance productivity and efficiency in precision aquaculture systems.

Ahmed et al. (2022) conducted research on the salmon fish disease classification with a machine vision-based technique. Image processing techniques were used to extort the features from the images, then a support vector machine was employed for the successful classification of infectious disease. Many others did related work: Malik et al. (2017) proposed an image-based detection technique which firstly applied image segmentation as an edge detection with Canny, Prewitt, and Sobel. However, they did not specify the exact technique that engrossed for feature extraction. In feature extraction, they combined Histogram of Gradient (HOG) and Features from Accelerated Segment Test (FAST) for classification. They tried to discover a better classification with a combination instead of applying a specific method with less exactness. Another technique, proposed by Lyubchenko et al. (2016), is called clustering of objects and is based on grouping similar objects within an image and applying multiple image segmentation steps at different scales to accurately separate these objects. Here, they chose markers for individual objects and objects encountered with a specific marker. Finally, they calculated the proportion of an object in the image and the proportion of infected area to the fish body to identify fish disease. However, individual marking of an object is time-consuming and not effective.

Regarding the optimization of the water flow in aquaculture systems, An et al. (2023) used fluent software to perform computational fluid dynamics simulations. A circular water tank, considering the rotational flow generated by tangential water injection and the non-rotational flow generated by the low waterfall inlet, provides a reference for drainage structure design.

As dissolved oxygen is as an important factor affecting fish welfare, Alver et al. (2022) developed a mathematical model for 3D estimates of this parameter based on the advection-diffusion equation. The model made it possible on one hand to understand the influence of cage size, shape and design on dissolved oxygen concentration, and on the other hand the interaction between fish biomass and environmental conditions. The model required input of farm geometry, ambient oxygen levels, current speed and direction, feeding rates, fish distribution and biomass statistics. The model provided realistic outputs, but it can be improved with detailed information about fish behaviour and current conditions within the cage. It can be used to predict the risk of hypoxic conditions in cages, and to evaluate the risks of hypoxic conditions in new types of open, semi-closed or closed production systems.

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Mathisen et al. (2021) developed a decision support system to help decision makers manage the aquaculture better, and to increase the level of automation and planning. This system will allow the operator to predict the success of an aquaculture at a specific site. The system is trained to learn a similarity function between recorded operational situations/cases and use the most similar case to provide explanation-by-example information for its predictions. This system not only differentiates feasible from unfeasible operations but also provides explanation by example.

In what concerns the ammonia nitrogen concentration, Yu et al. (2021) developed a method to control and monitor the water quality conditions in an aquaculture system. This is of special importance since there is no accurate equipment to measure the content of these parameters in the ecosystem, while fulfilling the requirements for aquaculture. This soft computing method included empirical mode decomposition (EMD), improved particle swarm optimization (IPSO) and extreme learning machine (ELM), in order to predict the ammonia nitrogen content in aquaculture water in real time. The authors also used statistical indicators, including root mean square error (RMSE), mean absolute error (MAE) and the mean absolute percentage error (MAPE), to compare three artificial soft computing methods. The results showed that the EMD-IPSO-ELM model provides moderately and roughly accurately real time prediction value of ammonia nitrogen in aquaculture water.

From the examples previously listed, it is possible to understand that Digital Twins enable the continuous monitoring of key parameters in aquaculture systems, such as water quality, temperature, salinity, and others and apply different modelling techniques for analyses and interpretation. However, as it was previously stated, most studies are applied to fish aquaculture, showing a significant lack of research on specific applications of Digital Twins in seaweed aquaculture. A study by Le, Woo, Lee, and Huh (2024), which presents a comprehensive review of the use of Digital Twin technology in aquaculture across global studies from 2017 to 2024, did not identify a single study focused on seaweed farming. This highlights a clear gap in the literature regarding the application of these technologies specifically in algae aquaculture systems.

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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. The current project aims to highlight the potential of seaweed aquaculture and how it represents a promising solution to diversify food sources, replace high-impact raw materials, and enable the creation of high-value product.

At the same time, scientific and technological innovation must be at the core of this sector's evolution. The implementation of digital solutions - such as Digital Twins and intelligent monitoring systems - can increase efficiency, sustainability, and public confidence in seaweed production. Research should also focus on assessing the ecological impacts of large-scale cultivation, to ensure that environmental benefits are not offset by unforeseen negative effects on marine ecosystems.

In conclusion, the future of seaweed production in Europe will depend on coordinated, cross-sectoral, and forward-looking actions. Through stronger policy alignment, robust scientific support, and enabling investment in environment, the EU can position itself as a global leader in this emerging sector. It will be essential to ensure that the growth of seaweed production is sustainable, inclusive, and environmentally responsible to maximize its contribution to the blue economy and the broader European objectives in climate and food policy.

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