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REVIEW

Mediterranean Aquaculture in a New Era of Challenges: Digital Transformation and Precision Fish Farming

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Mediterranean aquaculture is a strategic component of regional food production and the blue economy, supplying high-value marine species with a comparatively lower environmental footprint to many other animal protein systems. Yet the sector is entering a period of intensified pressure. Climate change, resource constraints, rising production costs, market competition, fragmented production structures, and increasingly complex regulatory demands are reshaping the conditions under which Mediterranean fish farming operates. At the same time, conventional husbandry practices remain heavily dependent on labor-intensive routines and limited observation of biological and environmental processes in open marine systems.

This paper examines how digital transformation and precision fish farming can support a more resilient, efficient, and sustainable Mediterranean aquaculture sector. After outlining the current characteristics of marine fish farming in the region, the paper discusses the main structural, environmental, and economic challenges affecting production. It then presents precision fish farming as a management paradigm based on continuous observation, reliable data collection, quantitative analysis, and timely decision-making. Key enabling technologies are reviewed, including sensor networks, cameras, Internet of Things systems, remote sensing, drones, remotely operated and autonomous underwater vehicles, automated feeding systems, artificial intelligence, decision support systems, and digital twins.

The paper also highlights current application areas such as environmental monitoring, forecasting and modeling, non-invasive monitoring of fish behavior and morphology, feeding optimization, site suitability analysis, and cage inspection. Particular attention is given to barriers to adoption, including investment cost, data quality, interoperability, capacity building, cybersecurity, data ownership, and the responsible use of artificial intelligence. The central argument is that digital transformation is no longer optional for Mediterranean aquaculture: it is becoming a prerequisite for adapting production systems to environmental uncertainty, improving operational performance, and strengthening long-term sustainability. However, successful implementation will depend not only on technology availability, but also on skills development, organizational readiness, and cross-disciplinary collaboration.

Introduction

Aquaculture has become one of the most important food-producing sectors globally, contributing substantially to food security, employment, and the supply of aquatic protein (FAO 2024). Within this broad field, marine aquaculture occupies a particularly significant position because it supports the production of high-value species while often showing a lower environmental footprint than several alternative animal protein systems (FEAP 2024). In the Mediterranean region, marine fish farming has evolved into a major productive activity, with European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*) forming the backbone of regional output (FAO 2024; FEAP 2026).

Despite its importance, Mediterranean aquaculture is facing a new generation of pressures. Some of these challenges are longstanding, including biological complexity, fragmented farm structures, strong price competition, and differing regulatory and administrative contexts across producing countries (EUMOFA 2024). Others are intensifying rapidly, especially climate-related stress, rising costs of feed and energy, resource scarcity, and growing demands for environmental accountability (European Commission 2021; EUMOFA 2024). These pressures are unfolding at a time when many farming practices still rely on labor-intensive observation, routine-based decisions, and partial visibility of what is occurring within cages and the surrounding marine environment (Føre et al. 2018).

The growing complexity of aquaculture production has made it increasingly difficult to manage farms effectively using conventional practices alone. Modern marine cages are large systems holding high fish densities in dynamic and often exposed conditions (Long et al. 2024). Monitoring fish growth, welfare, feeding behavior, environmental quality, and infrastructure integrity in real time is therefore both more necessary and more challenging than in the past (Bjelland et al. 2025). In this context, digital transformation is emerging as a strategic pathway for the sector.

Precision fish farming (Føre et al. 2018) provides a useful framework for understanding this transition. By combining continuous monitoring, data integration, quantitative analysis, predictive tools, and automated or semi-automated responses, precision fish farming aims to improve decision-making at farm and system level. It does not simply introduce new devices into existing production routines; rather, it redefines aquaculture management as an evidence-based, adaptive, and increasingly predictive process.

This review discusses why precision aquaculture has become particularly relevant for Mediterranean marine fish farming. It first outlines the structural characteristics and main challenges of the sector. It then examines the main technologies and applications currently shaping digital transformation and concludes with the principal barriers to adoption and future perspectives.

Mediterranean Marine Aquaculture: Current Status and Structural Characteristics

Mediterranean marine aquaculture is centered primarily on the production of European seabass and gilthead seabream, two species that dominate the regional industry in both volume and value (FEAP 2026). A defining characteristic of the sector is the predominance of open-sea floating cage farming. This production model has proven effective and scalable, supporting the expansion of industrial marine fish farming across multiple countries (Mozes et al. 2011). Typical cage systems in the Mediterranean are large, often with substantial circumference (120-160 m), and depth (30 to 50 m), and can contain very high numbers of fish (150,000 to 250,000 individuals) (AVRAMAR S.A. 2025, *Personal communication*). Such scale reflects the maturity and industrial success of the sector, but it also creates serious operational demands. As cage volume increases and farms move into more exposed conditions, direct observation of fish and infrastructure becomes more difficult, while the consequences of management errors become more significant.

Another important feature is the diversity of production contexts. Although seabass and seabream dominate, Mediterranean aquaculture is not fully homogeneous. Different farmed species (e.g. meagre *Argyrosomus regius* or red seabream *Pagrus major*, etc.) may have distinct feeding requirements, behavioral patterns, thermal tolerances, and disease susceptibilities. At the same time, the industry is distributed across countries with different administrative systems, legal frameworks, spatial planning traditions, labor conditions, and market structures (Papageorgiou et al. 2021; FAO 2023; Nielsen et al. 2025). This diversity complicates the development of universal management solutions and often limits the applicability of one-size-fits-all technologies.

The production structure of Mediterranean fish farming is also highly fragmented. In many areas the sector includes small- and medium-sized enterprises operating under variable investment capacities (EUMOFA 2024; Nielsen et al. 2025). This affects the pace at which innovation can be adopted.

In practice, Mediterranean aquaculture still relies heavily on operator experience, visual inspection, and discontinuous measurements. This reflects the inherent difficulty of farming live animals in flexible structures exposed to currents, waves, thermal variability, and seasonal changes (Evjemo et al. 2026). However, as environmental and economic pressures intensify, the limitations of this management model are becoming more apparent (EUMOFA 2024; FAO 2023).

Key Challenges Facing the Sector

The pressures currently affecting Mediterranean aquaculture are interconnected and cumulative (EUMOFA 2024). At the environmental level, climate change is increasingly central (European Commission 2021; FAO 2021). Climate change also interacts with site suitability, disease dynamics, and the spatial distribution of production capacity (Cascarano et al. 2021; Stavrakidis-Zachou, Lika, et al. 2021)

Economic pressures are equally significant. Feed remains the largest operating cost in marine fish farming (Petereit et al. 2022), while energy and logistics costs are rising. At the same time, producers operate in competitive and price-sensitive markets and often face difficulties in expanding production through new sites or farm enlargement. Administrative complexity, licensing delays, and conflicts with other coastal users add further constraints.

At farm level, the sector must manage tightly coupled interactions among environment, fish physiology, feeding, welfare, and infrastructure. Oxygen influences feeding behaviour, temperature affects metabolism and growth, and infrastructure condition affects both welfare and escape risk. Conventional observation methods often capture these interactions only partially. As a result, increasing production is not simply a matter of adding capacity; it requires better tools for observation, prediction, and decision-making.

Digital Transformation and the Concept of Precision Fish Farming

Digital transformation in aquaculture refers to the adoption of technologies, methods, and analytical tools that enable more automated, data-rich, and adaptive forms of production management. Precision fish farming is one of the most important expressions of this transformation (Føre et al. 2018). The concept is based on the idea that aquaculture operations should be managed through continuous observation, accurate measurement, quantitative interpretation, and informed intervention. Producers use data to detect variation, identify patterns, forecast outcomes, and refine decisions. This management logic parallels developments in precision agriculture and precision livestock farming, where sensors, cameras, geospatial tools, and machine learning have already reshaped operational practice.

The significance of precision fish farming lies not only in the quantity of data produced, but in the quality and usability of those data. Reliable measurements are essential because management interventions in aquaculture have immediate biological and economic consequences. Overfeeding increases waste and environmental impact; underfeeding reduces growth; delayed detection of disease or low oxygen can trigger severe losses; and poor infrastructure monitoring can elevate safety and escape risks. Precision systems seek to reduce such uncertainty by improving situational awareness and enabling more timely responses.

Precision fish farming can therefore be understood as a cycle of observation, interpretation, decision, and action. Sensors, cameras, remote systems, and other tools collect information; analytics, models, and artificial intelligence (AI) help interpret it; and managers or automated systems use these outputs to guide feeding, husbandry, maintenance, and risk mitigation. In open marine systems such as those of the Mediterranean, this transition is especially relevant because direct, continuous human observation is difficult to achieve.

Enabling Technologies and Current Applications in Mediterranean Aquaculture

The value of digital transformation lies in the way technologies are translated into practical monitoring and decision-support functions. In Mediterranean aquaculture, several applications are already demonstrating this shift.

A first and foundational area is **environmental monitoring**, where sensor networks and Internet of Things architectures are increasingly used to provide continuous information on water quality variables such as dissolved oxygen, temperature, salinity, pH, and turbidity (Chatziantoniou et al. 2022). In cage farming, where conditions can change rapidly, real-time monitoring improves visibility and supports faster responses. There are several farms in the region that currently use commercially available systems but still it is not considered as common practice. These systems are also relevant to pathology and biosecurity, because they can identify environmental conditions associated with elevated stress and disease risk, support earlier warning, and inform decisions on husbandry adjustments, surveillance intensity, and handling practices. In this way, digital monitoring begins to transform the farm from a site of episodic measurements into a data-rich operational environment.

The importance of this transition becomes even clearer when environmental monitoring is linked with **forecasting and modeling** (Chatziantoniou et al. 2023). Rather than relying only on present-time observations, precision aquaculture increasingly incorporates satellite data, remote sensing products, in situ measurements, and simulation tools to anticipate environmental stressors. Such systems can support short-term prediction of low oxygen conditions, heatwaves, algal bloom risks, and other climate-related drivers that affect production. This predictive capacity is central to adaptation, since it allows husbandry practices to be adjusted before stress intensifies. In the Mediterranean context, where climate change is emerging as one of the sector's defining pressures, these tools can support both farm-level management and broader planning at aquaculture-zone scale (Porporato et al. 2020; Stavrakidis-Zachou, et al. 2021). Such tools are rarely used at farm level where only experimental applications exist. They may also support more preventive biosecurity decisions by identifying periods of increased environmental risk in which fish are more vulnerable to stress, opportunistic infections, or disease outbreaks (see for example Cawthron Institute 2026).

Camera systems and computer vision methods enable non-invasive monitoring of fish inside cages (Voskakis et al. 2021; Georgopoulou et al. 2021), extending management beyond what can be achieved through occasional human inspection. During feeding, underwater video systems can capture changes in schooling structure, swimming intensity, vertical distribution, and feed response (Chen et al. 2023). By converting visual observations into quantifiable indicators or classification outputs, digital systems can help identify whether fish are feeding normally, approaching satiation, or being overfed. The significance of **automated and data-driven feeding systems** follows directly from this (Georgopoulou et al. 2024). Feed is typically the largest operating cost in marine fish farming, and errors in feed allocation result in both economic loss and ecological impact. Precision approaches aim to reduce this uncertainty by combining sensor inputs, behavioral monitoring, and algorithmic analysis to refine feeding decisions. In Mediterranean aquaculture, where large cage volumes and high stocking densities complicate direct observation, such systems offer one of the clearest examples of how digitization can improve day-to-day production practice. Already several farms are using commercially available systems for monitoring feeding activity and reduce feed losses.

A related application concerns **non-invasive size estimation and morphology assessment** (Voskakis et al. 2021; Tonachella et al. 2022). Stereoscopic cameras and other image-based systems make it possible to estimate fish size and evaluate selected morphometric features without repeated capture and handling. These methods can contribute to more accurate biomass estimation and provide additional operational welfare indicators (Christofilogiannis et al. 2026). Where external appearance, swimming performance, or body condition deviate from expected patterns, such systems may also contribute to earlier recognition of health or welfare problems. In practical terms, they support better feeding calibration, harvest planning, and welfare-oriented observation while reducing the stress associated with intrusive measurement procedures.

Another major area of application is **site suitability analysis and spatial planning**, where remote sensing, geospatial data, and multi-criteria analytical frameworks can support strategic decisions beyond the individual cage (Porporato et al. 2020). Mediterranean aquaculture increasingly operates within contested marine spaces shaped by environmental limits, coastal uses, infrastructure access, and regulatory constraints. Already advisory bodies (such as consultants of the industry) have started using such tools particularly for spatial planning purposes. Digital methods can help identify areas that are more favorable for fish growth while also considering wave climate, distance to harbor facilities, cumulative ecological impact, vulnerable ecosystems, and possible conflicts with other users. In this sense, precision aquaculture is not limited to production optimization inside farms; it also contributes to more informed spatial governance and long-term sector planning.

Drones, remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs) extend the capacity to inspect cages, nets, moorings, and surrounding conditions in areas where access is difficult, costly, or potentially dangerous for human divers. They are particularly useful for cage-net inspection, infrastructure monitoring, and underwater observation, and their role is likely to grow as farms become larger and move into more exposed locations (Livanos et al. 2018; Paspalakis et al. 2020; Ubina and Cheng 2022; Fabijanić et al. 2023; Vasileiou and Vlontzos 2025). In these environments, robotics can contribute to more frequent inspection routines, earlier problem detection, and safer maintenance practices. By supporting more reliable inspection of nets, moorings, and cage integrity, they may also strengthen biosecurity by reducing escape risk and helping maintain more controlled farming conditions. In the Mediterranean region the use of robots in the industry is very limited at industrial scale and only at research level there are initiatives.

These technologies generate large and heterogeneous datasets, which is why AI, machine learning, and **decision support systems** are becoming increasingly important. AI can help identify patterns, detect anomalies, forecast growth, and optimize management actions, while DSS platforms integrate data streams and model outputs into alerts, dashboards, and recommendations useful for farm managers (Assimakopoulos et al. 2024; Chatziantoniou et al. 2023). Their practical value lies in converting complex information into guidance that is usable at farm level.

At a more advanced level, **digital twins** may allow scenario testing and simulation of farm-environment interactions before interventions are made in the real system (Føre et al. 2024). Although still emerging, they point toward a future in which farms can test management options virtually, compare scenarios, and better assess risk before acting.

The practical development of these applications is already visible in several Mediterranean and European research and innovation initiatives demonstrating that the digital transition of aquaculture is not a distant prospect, but an ongoing process in which research results, prototype systems, and commercial products are gradually converging. Commercial aquaculture technology portfolios also include ROV-supported and imaging-based systems for underwater inspection, net monitoring, and maintenance in cage farming.

The broader technological landscape also includes emerging production concepts such as semi-enclosed systems, submersible systems, recirculating aquaculture systems, mobile aquaculture vessels, and multi-use offshore platforms (Nilsen et al. 2020; Long et al. 2024). These developments do not replace Mediterranean cage farming in the short term, but they indicate the direction in which aquaculture is moving: toward larger, more complex, and more technologically mediated production systems. As this shift continues, precision fish farming will become increasingly central not only because it improves efficiency, but because it provides the informational and analytical infrastructure required to manage complexity itself.

Barriers to Adoption and Implementation Challenges

Although the potential benefits of digital transformation are substantial, adoption is not straightforward. The first obstacle is cost. Sensors, camera systems, network infrastructure, software platforms, robotics, and analytical tools may require significant investment. For fragmented sectors with many small- and medium-sized enterprises, the initial cost of adoption can be prohibitive, especially when return on investment is uncertain or difficult to quantify in the short term.

A second challenge concerns skills and organizational readiness. Digital tools are not self-implementing. Their effective use depends on personnel capable of operating equipment, managing data flows, interpreting outputs, and integrating new information into routine decisions. This requires training, farmer engagement, and a shift in organizational culture. Without adequate human capacity, even technically sophisticated systems may remain underused.

Data-related challenges are equally important. Precision aquaculture depends on robust and reliable data collection. Poor calibration, incomplete coverage, inconsistent measurements, and weak validation procedures can reduce trust in the system and undermine decision quality. In addition, the increasing digitization of farms raises questions about data ownership, access rights, privacy, and cybersecurity. Producers may be hesitant to adopt connected systems if they are uncertain about how sensitive operational data will be stored, shared, or protected.

Interoperability is another major barrier. Many digital tools are developed as stand-alone products or within research projects, which can make integration difficult. If sensor outputs, camera data, modeling platforms, and management software cannot communicate effectively, the full benefits of digital transformation will remain unrealized. The ability to combine data across systems is essential for creating actionable intelligence rather than isolated streams of information.

Artificial intelligence introduces additional concerns. While AI can improve prediction and automation, it must be used responsibly. Issues of transparency, accountability, bias, and human oversight are highly relevant in food production systems. Decisions affecting animal welfare, environmental performance, or economic risk cannot be delegated blindly to opaque algorithms. Trustworthy AI in aquaculture therefore requires technical robustness, explainability where possible, and clear governance arrangements.

Finally, there is the broader issue of adoption strategy. Digital transformation may create fears of disruption, job displacement, or uneven competitive advantage. If innovation is perceived as benefiting only larger or better-capitalized firms, the sector may become even more polarized. Policies supporting scalable tools, targeted subsidies, shared infrastructure, and inclusive training programs may therefore be necessary to ensure that digital transition strengthens rather than fragments the industry.

Future Perspectives

The future of Mediterranean aquaculture will depend on how effectively the sector combines biological knowledge, engineering, data analysis, and management capacity. Climate change alone makes historical experience less reliable as a guide to future conditions. Precision fish farming is therefore likely to move from a promising innovation field to a core element of mainstream aquaculture management.

Environmental monitoring will become more continuous, feeding systems more responsive, and modelling tools more important for risk assessment and spatial planning. Robotics may become standard for certain inspection tasks, particularly in offshore or otherwise demanding installations. Digital twins, although still emerging, may become valuable tools for forecasting and scenario analysis.

At the same time, future progress will depend on more than equipment deployment. The sector will need stronger interoperability among systems, better training, and organizational models that help producers turn data into decisions. For Mediterranean aquaculture in particular, inclusive adoption will be essential so that digital transition does not widen the gap between producers.

Digitalization should therefore be treated not as an end in itself but as a means to improve environmental performance, welfare, productivity, and social legitimacy. Its long-term value will depend on whether it helps aquaculture become not only more efficient, but also more resilient and more transparent. The most successful technologies will likely be those that are not only advanced, but practical, interpretable, and well adapted to the real operational conditions of Mediterranean farms.

Conclusions

Mediterranean aquaculture is entering a period in which conventional management approaches are no longer sufficient to address growing environmental, economic, and operational complexity. Digital transformation and precision fish farming provide a credible pathway toward more informed and adaptive management through monitoring, automation, analytics, and decision support.

Their value lies in improving visibility within farms, enabling earlier responses, strengthening feeding precision, supporting biosecurity and infrastructure control, and contributing to more transparent and sustainable production systems. In this sense, precision aquaculture responds not only to the need for efficiency, but also to the broader need for knowledge-based growth under conditions of increasing uncertainty.

However, the transition is not purely technological. Its success depends on investment capacity, interoperability, data reliability, training, governance, and the responsible use of AI. The Mediterranean sector must therefore approach digital transformation as an integrated socio-technical process rather than as a simple matter of equipment adoption.

Ultimately, the strategic question is not whether Mediterranean aquaculture will digitalize, but how. A resilient and sustainable future for the sector will depend on whether digital tools are deployed in ways that support better decisions, stronger environmental stewardship, improved production performance, and more inclusive innovation. Precision fish farming should thus be understood not as a narrow technical trend, but as part of a broader transformation toward data- and knowledge-based aquaculture.

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