

HAEDES

Digital twinning & sensing

Industry needs

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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 seaweed-based systems across Europe. It consolidates the most recent research insights, emerging market trends, and identified industry needs, while actively encouraging engagement with stakeholders from academia, the private sector, and the broader public. Its mission is to accelerate the development of a resilient, competitive, and sustainable blue bioeconomy, with a particular focus on seaweed and seaweed-based solutions and aquaculture.

The present report addresses a set of concrete **needs identified in the industry**, with a specific focus on the **design and implementation of a digital twinning solution tailored for seaweed farming**. This effort represents a tangible response to sector-specific challenges identified in aquaculture and reflects how digital innovation can be directed to meet operational demands. The digital twin system creates a real-time virtual model of seaweed farms, allowing producers to continuously monitor environmental conditions, forecast biomass growth, and optimise decision-making.

Developed in close collaboration with seaweed farmers, the system incorporates smart monitoring capabilities, adaptable configurations for diverse farm setups, and an intuitive, user-friendly interface. By integrating digital technologies into the aquaculture value chain, this business case promotes a shift towards smarter and low-impact practices - crucial for enabling sustainable growth and reinforcing Europe's leadership in the global seaweed sector.

Beyond this case, the report also contributes to understanding the current state of the industry and the aquaculture sector more broadly, highlighting key challenges it faces. It is equally important to assess the existing legal and regulatory frameworks governing the sector, to identify what is still lacking and what steps are needed to address the industry's needs and support its development.

1. Contextualization

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 relatively new, with the first small-scale farms being 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 (MacMonagail et al., 2018), feedstock for the bio based economy (Stévant et al., 2017; Helmes 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 CO₂ 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 were first used not only as fertilizers but also in medicines 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 (EC) has been encouraging the development of seaweed farming across its marine territories (European Commission, 2021). Nevertheless, there is still a significant gap in fundamental knowledge regarding the potential of this activity in European waters.

Hunger remains a global socioeconomic challenge, persisting despite significant technological progress. A central aim of the United Nations' 2030 Sustainable Development Agenda is to implement strategies that effectively address and mitigate the widespread impacts of this issue. Aquaculture stands out as one such initiative, aiming to produce high-quality food for human consumption while minimizing environmental impact (FAO, 2018). The 2024 edition of The State of World Fisheries and Aquaculture (SOFIA) said global fisheries and aquaculture production in 2022 surged to 223.2 million tonnes, a 4.4 percent increase from the year 2020. Production comprised 185.4 million tonnes of aquatic animals and 37.8 million tonnes of algae (FAO, 2024).

1.1. Aquaculture challenges

The aquaculture industry in Europe faces many challenges, some of them related to the fact that it is a relatively new sector. Problems sometimes associated with traditional aquaculture are pollution, particularly in terms of water use, feed efficiency and waste management. Therefore, aquaculture is under increasing pressure to reduce its impact on the environment, with a simultaneous demand to ensure quality levels of its products (Behroozi & Couturier, 2019; Che et al., 2023; Føre et al., 2024). Other challenges are labour intensiveness, environmental pollution, disease outbreaks and limited product traceability. The control of all the operation involved in the monitoring process heavily relies on human intervention, which limits full system optimization. To address this, automation and advanced data analysis are being introduced to enhance decision-making and system efficiency (Biazi et al., 2023).

Therefore, there is an urgent need for innovative approaches and improvements to facilitate operations, reduce environmental impacts and improve the efficiency of the aquaculture industry. There are also some challenges related with the economic pressure (Chen et al., 2025). The costs

associated with energy, maintenance and labour account for a significant portion of operating expenses. Coupled to volatile market prices, it is difficult for aquaculture enterprises to remain profitable.

Some parameters such as temperature, oxygen, pH, ammonia, nitrite and nitrate levels, which are directly related to water quality, need to be controlled as means to achieve good product management and an appropriate growth of the cultured species (Dupont et al., 2018). To address this problem, Industry 4.0—also known as the Fourth Industrial Revolution—represents the latest stage of industrialization. It focuses on the use of smart devices to create a physical–digital connection between the components of the production flow, enabling a fully optimized and integrated process. Some technological trends in this phase that can act as key tools to produce more sustainable food options are the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), computer vision (CV), and optimized sensors (Vaidya et al., 2018).

2. Industry current situation

2.1. Industrial Challenges

The aquaculture sector is an emerging industry that has experienced significant growth in recent years. Consequently, the innovation demanded by this sector is continuous and has been increasingly evident in recent times. New technologies are being developed and tested to meet these evolving needs. As a result, there are several challenges and requirements intrinsic to the ongoing development of this field.

The roadmap for the Blue economy published by the Blue Bioeconomy Forum in 2019 identified bottlenecks and made recommendations in four main areas, based on a consultation with around 300 relevant stakeholders. Among the identified areas are Policy, environmental and regulations; finance and business development; consumers and value chains and science, technology and innovation (COM (2022) 592 final). In the current EU seaweed sector, Forum outputs lead to the conclusion that the development of seaweed cultivation has been hindered by factors such as high production costs, low-scale production, limited knowledge of the markets consumers' needs and the risk and environmental impacts of seaweed cultivation, as well as a fragmented governance framework.

Figure 1 highlights the problems, objectives and action areas related to EU seaweed initiatives, identified by the communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions (COM (2022) 592 final).

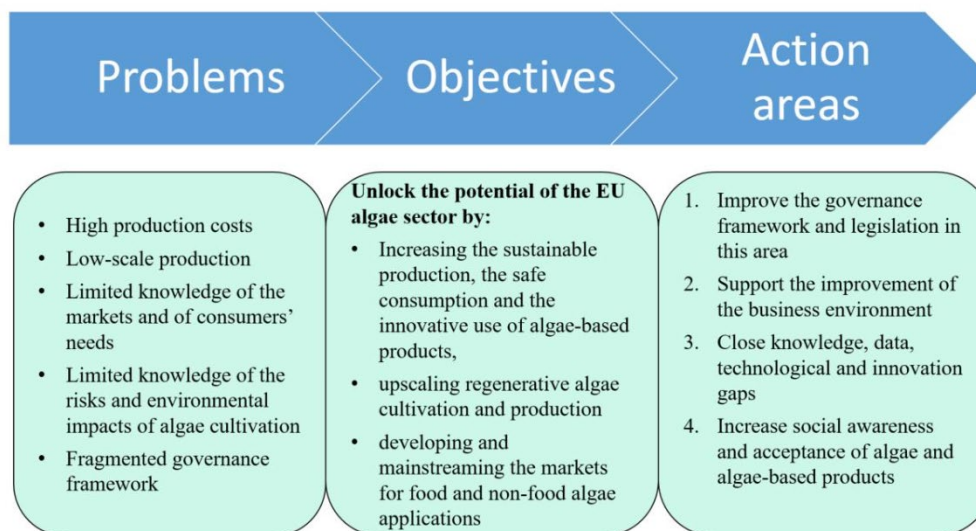


Figure 1. Problems, objectives and proposed action areas for EU seaweed-related initiatives (COM (2022) 592 final; DG MARE).

Currently, **99%** of seaweed production volumes in the EU depend on seaweed **harvesting from wild population at sea**, which will not be able to sustain the growing demand for seaweed products in the future (European Commission, 2022). It is **urgent to accelerate sustainable seaweed cultivation** systems to increase the seaweed production volumes in the EU. Another identified problem is the **high production cost** to cultivate seaweed in the EU today, which explains why many producers are not competitive in the global market.

Seaweed are not traditionally part of the Europeans' diet, and many consumers are hesitant to include them in their regular meals. Increasing public knowledge about seaweed's nutritional benefits, low environmental impact, and safe consumption is essential to boost demand. Currently, consumers lack information on preparation methods, product availability, and potential risks such as heavy metals or iodine content. In the business sector, many are unaware of the diverse applications of seaweed, as well as the environmental advantages of seaweed production. Besides **raising social and consumer awareness**, better **connections between suppliers and buyers** are needed. Clear commercial channels and harmonized pricing for seaweed biomass could help introduce these products to new markets willing to experiment.

There is also the need to ensure the sustainability of the sector, and for that it is crucial to understand the environmental impacts of a growing seaweed industry. Detailed assessments are needed, including effects on local biodiversity, environmental footprints, and compensation measures, especially for seaweed cultivation. Increased knowledge about the environmental benefits of seaweed, such as carbon and nutrient capture, is also important. Potential negative impacts, like reduced genetic diversity (reported in countries like Chile and Tanzania) and ocean colour changes causing increased heat absorption and warming (Bach et al., 2021), must be carefully evaluated. Therefore, further research and monitoring programs are necessary to better understand these risks and develop mitigation strategies, which can also help improve consumer acceptance of seaweed products in the EU (European Commission, 2022).

Seaweed aquaculture at sea and seaweed cultivation on land must follow various national regulations, which differ across Member States and cover aspects like licensing, marine space access, and species allowed for farming. Although experts advise against moving species between different marine areas or spreading identical seedlings widely to avoid disrupting local genetic diversity, such events can still occur. **Access to marine space depends on national Marine Spatial Planning and is granted via temporary licenses managed by national authorities, with processes that vary greatly and are often complex and resource demanding.** This can hinder new investments. Furthermore, **differences in downstream legislation**, such as inconsistent food safety

limits on iodine content in seaweed biomass among Member States, have caused disputes between suppliers and buyers across borders, creating commercial tensions.

Several initiatives aim to enhance knowledge and awareness of seaweed, including the European Marine Data and Observation Network, the Commission's Knowledge Centre for the Bioeconomy, and studies by the Joint Research Centre on seaweed's role in climate goals and nutrient cycles. The EU Mission "Restore our Ocean and Waters by 2030" highlights ocean regeneration as essential for human well-being. The Food 2030 initiative promotes a systemic approach linking land and sea food systems, emphasizing seaweed farming as key for sustainable food from aquatic resources. The European Blue Forum facilitates dialogue among blue economy sectors, including seaweed, to align interests in climate neutrality and marine conservation. Although seaweed aquaculture is governed by numerous EU and national regulations, a more unified regulatory framework could better support sector growth. In this sense, the seaweed sector could benefit from a more coherent approach (European Commission. 2022; COM(2022)592 final).

3. EU regulation

Recently, the European Commission has launched and supported several initiatives focused on algae. These efforts encompass the EU4Algae project, which aims to establish a collaborative European Algae Stakeholder Platform. Additionally, EU research and innovation funding programs like Horizon 2020 and Horizon Europe, along with investments facilitated by the European Maritime and Fisheries Fund and the European Regional Development Fund, underscore the Commission's commitment to foster growth in the algae sector. Furthermore, support mechanisms such as Blue Invest and the Aquaculture Assistance Mechanism are pivotal in advancing blue economy initiatives.

The Treaty on the Functioning of the European Union (TFEU) provides for the following distribution of responsibilities between the EU and the Member States in the algae sector:

- 1) The European Union has exclusive competence with regard to the conservation of marine biological resources within the framework of the common fisheries policy (see Article 3 (1d) TFEU) (Regulation (EU) No 1380/2013).
- 2) The European Union shared competence with the Member States in matters of agriculture and fisheries (including aquaculture, thus covering the production of seaweed, the common organization of the markets in fisheries) to the exclusion conservation of living marine resources, and Union policy will contribute to pursuing objectives in the main areas of:
 - Common public safety concerns for the aspects defined in the TFEU;
 - Consumer protection
 - Environment

However, there is currently a **lack of harmonized algae-related legislative framework** between Member States. Some of the main legal guidelines for seaweed aquaculture are presented below (Figure 6).



Figure 2. Overview of legal acts relevant to seaweed aquaculture.

The EU Algae Initiative¹ also describes a set of challenges preventing the development of the sector, identifying a fragmented governance framework as one of the key obstacles. An overview of the present EU governance framework is summarized in Figure 3.

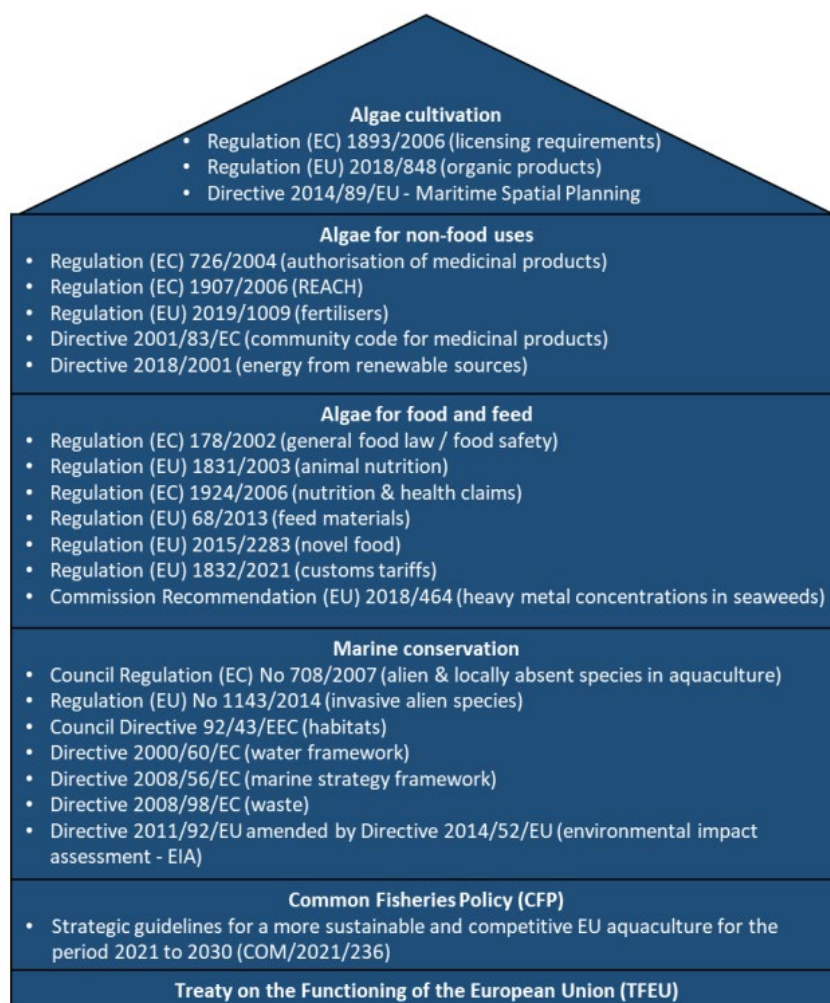


Figure 3. EU governance framework of the algae sector. Source (Policy Department for Structural and Cohesion Policies, 2023).

¹ <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:592:FIN>

Regarding the innovation and the digitalization of the sector, there's no specific legislation ruling the sector. However, the EU is a model of good practice in sharing marine data and ocean observations. **The obligation for EU countries to share marine data and to cooperate at EU and regional level to improve data collection and monitoring is well-established in the EU Marine Strategy Framework Directive (MSFD). This could be complemented by an ocean observation initiative to structure and harmonise the collection of marine data within Europe.** Systems such as EMODnet and Copernicus have these data available (European Commission & High Representative of the Union for Foreign Affairs and Security Policy, 2022). To digitalize and modernize the aquaculture sector, it is mandatory to innovate and bring technology to the processes involved.

There are **many reporting obligations** on the sector under different pieces of EU and national legislation. However, the data collected are mostly socioeconomic data regarding marine aquaculture or animal health, with limited data reported on environmental indicators specific to aquaculture. Therefore, it will be necessary to **coordinate better reporting obligations and streamline reporting procedures** between different services. It will also be necessary to provide more structured guidance to EU Member States on how to obtain and report data. Data reporting should also apply to environmental indicators and cover aquaculture production beyond marine aquaculture (European Commission, 2021).

Although legislation for the use of artificial intelligence in the EU is already being drafted, it is important to ensure its harmonization for the aquaculture sector – something that is already starting to happen in agriculture through the Agricultural Data Space. From a legislative perspective, **the digitalization of aquaculture in the EU requires a clearer and more harmonized framework to enable the adoption of technologies such as digital twins, IoT, and AI.** The sector **needs common technical standards and transparent rules on data sharing and protection.** It is also essential to establish regulatory sandboxes that foster innovation and to adapt EU regulations on data, AI, and cybersecurity to the operational realities of aquaculture, while ensuring competitiveness, sustainability, and streamlined legal compliance.

Conclusion

Seaweed production is increasingly recognized as a strategic sector with the potential to address multiple global challenges, including food security, climate change mitigation, and the sustainable development of coastal regions. This project has highlighted that seaweed aquaculture offers a promising pathway to diversify food sources, replace high-impact raw materials, and develop high-value products.



However, despite its acknowledged potential, the sector still faces significant barriers to expansion. The absence of a harmonized regulatory framework at the European level generates uncertainty; creates disparities between Member States; and discourages investment. Technological adoption is also **hindered by high costs for integrating and developing advanced tools such as Digital Twins, as well as by limited digital skills within the industry.** Furthermore, the potential contribution of **Earth Observation data**, such as that from the Copernicus

program, is currently constrained by spatial resolution limitations, reducing its applicability for site-specific aquaculture operations.

In conclusion, unlocking the full potential of seaweed production in Europe will require coordinated and cross-sectoral action. Stronger policy alignment, targeted investment in innovation and enhanced digital infrastructure will be essential to improve efficiency, competitiveness, and environmental sustainability. By addressing regulatory, technological, and capacity gaps, the EU can position itself as a global leader in this emerging sector, ensuring that its growth contributes meaningfully to the blue economy and to broader European objectives in climate, biodiversity and food policy.

Reference list

Alevizos, E., & Barille, L. (2023). Global Ocean spatial suitability for macroalgae offshore cultivation and sinking. *Frontiers in Marine Science*, 10, 1320642. <https://doi.org/10.3389/fmars.2023.1320642>.

Araújo, R., Vázquez Calderón, F., Sánchez López, J., Azevedo, I. C., Bruhn, A., Fluch, S., ... & Dias, J. M. (2021). Current status of the algae production industry in Europe: an emerging sector of the blue bioeconomy. *Frontiers in Marine Science*, 7, 626389. <https://doi.org/10.3389/fmars.2020.626389>.

Bach, L. T., Tamsitt, V., Gower, J., Hurd, C. L., Raven, J. A., & Boyd, P. W. (2021). Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt. *Nature Communications*, 12(1), 2556. <https://doi.org/10.1038/s41467-021-22837-2>.

Barbier, M., Araújo, R., Rebours, C., Jacquemin, B., Holdt, S. L., & Charrier, B. (2020). Development and objectives of the PHYCOMORPH European guidelines for the sustainable aquaculture of Seaweeds (PEGASUS). *Botanica Marina*, 63(1), 5–16. <https://doi.org/10.1515/bot-2019-0051>.

Behroozi, L., & Couturier, M. F. (2019). Prediction of water velocities in circular aquaculture tanks using an axisymmetric CFD model. *Aquacultural Engineering*, 85, 114–128.

Biazi, V., & Marques, C. (2023). Industry 4.0-based smart systems in aquaculture: A comprehensive review. *Aquacultural Engineering*, 103, 102360. <https://doi.org/10.1016/j.aquaeng.2023.102360>.

Brito, A. C., Pereira, H., Picado, A., Cruz, J., Cereja, R., Biguino, B., ... & Dias, J. M. (2023). Increased oyster aquaculture in the Sado Estuary (Portugal): How to ensure ecosystem sustainability? *Science of The Total Environment*, 855, 158898. <https://doi.org/10.1016/J.SCITOTENV.2022.158898>.

Che, Z., Zhou, Y., Zhao, C., Ren, X., Liu, H., Sun, W., Liu, H., & Li, M. (2023). Experimental study on sewage collection and related performance of square arc angle aquaculture tank. *Aquaculture International*, 32, 3017–3040.

Chen, J., Xu, Y., Li, H., Zhao, X., Su, Y., Qi, C., Qu, K., & Cui, Z. (2025). The Application of Digital Twin Technology in the Development of Intelligent Aquaculture: Status and Opportunities. *Fishes*, 10(8), 363. <https://doi.org/10.3390/fishes10080363>.

Couteau, C., & Coiffard, L. (2016). Seaweed applications in cosmetics. In: Fleurence, J., Levine, I. (Eds.), *Seaweed in Health and Disease Prevention*. Elsevier, Amsterdam, pp. 423–441.

Dupont, C., Cousin, P., & Dupont, S. (2018). IoT for aquaculture 4.0 smart and easy-to-deploy real-time water monitoring with IoT. In 2018 Global Internet of Things Summit (GloTS). IEEE, pp. 1–5.

Elizondo-González, R., Quiroz-Guzmán, E., Escobedo-Fregoso, C., Magallon-Servín, P., & Pena-Rodríguez, A. (2018). Use of seaweed *Ulva lactuca* for water bioremediation and as feed additive for white shrimp *Litopenaeus vannamei*. *PeerJ*, 6, e4459.

European Commission. (2018). Commission Recommendation (EU) 2018/464 of 19 March 2018 on the monitoring of metals and iodine in seaweed, halophytes and products based on seaweed. *Official Journal of the European Union*, L 78, 16–18. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018H0464>



European Commission. (2021). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Sustainable blue economy – Harnessing the potential of our oceans and seas* (COM(2021) 236 final). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0236>

European Commission, & High Representative of the Union for Foreign Affairs and Security Policy. (2022, June 24). *Joint communication to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – Setting the course for a sustainable blue planet* (JOIN(2022) 28 final). https://oceans-and-fisheries.ec.europa.eu/document/download/77056529-c1fe-49e4-9776-11c54b060a97_en?filename=join-2022-28_en.pdf

European Commission. (2021, May 17). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – A new approach for a sustainable blue economy in the EU – Transforming the EU's blue economy for a sustainable future* (COM(2021) 240 final). https://eur-lex.europa.eu/resource.html?uri=cellar:bab1f9a7-b30b-11eb-8aca-01aa75ed71a1.0022.02/DOC_1&format=PDF

European Commission. (2022). Staff working document on the state of play of the Common Fisheries Policy and consultation on the fishing opportunities for 2023 (SWD(2022) 361 final). https://oceans-and-fisheries.ec.europa.eu/document/download/d2b345d5-9c66-4eca-aa43-6b135293bac8_en?filename=swd-2022-361_en.pdf

Eurostat. (2024, April 30). EU aquaculture 2022: 1.08 million tonnes farmed. <https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240430-3>

FAO. (2018). Meeting the Sustainable Development Goals. The State of World Fisheries and Aquaculture 2018. Food and Agriculture Organization of the United Nations.

Food and Agriculture Organization of the United Nations. (2024a). The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action. <https://openknowledge.fao.org/items/3bffafd3-c474-437b-afd4-bb1182feeea6>

Food and Agriculture Organization of the United Nations. (2024b). FAO report: Global fisheries and aquaculture production reaches a new record high. <https://www.fao.org/newsroom/detail/fao-report-global-fisheries-and-aquaculture-production-reaches-a-new-record-high/en>

Føre, M., Alver, M. O., Alfredsen, J. A., Rasheed, A., Hukkelås, T., Bjelland, H. V., ... & Papandroulakis, N. (2024). Digital twins in intensive aquaculture – Challenges, opportunities and future prospects. *Computers and Electronics in Agriculture*, 218, 108676. <https://doi.org/10.1016/j.compag.2024.108676>

He, B., & Bai, K.-J. (2020). Digital twin-based sustainable intelligent manufacturing: A review. *Advanced Manufacturing*, 9, 1–21.

Helmes, R. J., Lopez-Contreras, A. M., Benoit, M., Abreu, H., Maguire, J., Moejes, F., & van den Burg, S. W. (2018). Environmental impacts of experimental production of lactic acid for bioplastics from *Ulva* spp. *Sustainability*, 10, 1–15.

Kang, J. Y., Chun, B. S., Lee, M. C., Choi, J. S., Choi, I. S., & Hong, Y. K. (2016). Anti-inflammatory activity and chemical composition of essential oil extracted with supercritical CO₂ from the brown seaweed *Undaria pinnatifida*. *Journal of Essential Oil Bearing Plants*, 19, 46–51.

Le, N.-B.-V., Huh, J.-H. (2024). AgTech: Building Smart Aquaculture Assistant System Integrated IoT and Big Data Analysis. *IEEE Transactions on AgriFood Electronics*, 2, 471–482.

Le, N.-B.-V., Woo, H., Lee, D., & Huh, J.-H. (2024). AgTech: A survey on digital twins based aquaculture systems. IEEE Access. <https://doi.org/10.1109/ACCESS.2024.3443859>

MacMonagail, M., Cummins, E., Bermejo, R., Daly, E., Costello, D., & Morrison, L. (2018). Quantification and feed to food transfer of total and inorganic arsenic from a commercial seaweed feed. *Environment International*, 118, 314–324.

Porterfield, W. M. (1922). References to the Algae in the Chinese Classics. *Bulletin of the Torrey Botanical Club*, 49(10). <https://www.jstor.org/stable/2480100>

Stévant, P., Rebours, C., & Chapman, A. (2017). Seaweed aquaculture in Norway: recent industrial developments and future perspectives. *Aquaculture International*, 25, 1373–1390.

United Nations Conference on Trade and Development. (n.d.). Seaweed holds huge potential to bring economic, climate, and gender benefits. UNCTAD. <https://unctad.org/news/seaweed-holds-huge-potential-bring-economic-climate-and-gender-benefits>

Vaidya, S., Ambad, P., & Bhosle, S. (2018). Industry 4.0—a glimpse. *Procedia Manufacturing*, 20, 233–238.

Wu, J., Keller, D. P., & Oschlies, A. (2023). Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an earth system modeling study. *Earth System Dynamics*, 14, 185–221. <https://doi.org/10.5194/esd-14-185-2023>

Yang, Y., Yu, H., Zhang, X., Zhang, P., Tu, W., & Gu, L. (2024). Fish behavior recognition based on an audio-visual multimodal interactive fusion network. *Aquacultural Engineering*, 107, 102471.



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Alves J. and Proença B. (2025). Digital twinning & sensing - Industry needs (I3-4-Seaweed Project Knowledge Hub Reports). HAEDES Portugal.



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