environments

Review

Eco-Sustainability in Aquaculture: Questions and Perspectives

Antonio Calisi [1,*], Davide Gualandris [1], Elisa Gamalero [1], Francesco Dondero [1], Teodoro Semeraro [2,3,*] and Tiziano Verri [2]

[1] Department of Science and Technological Innovation, University of Eastern Piedmont, Viale Michel 11, I-15121 Alessandria, Italy; davide.gualandris@uniupo.it (D.G.); elisa.gamalero@uniupo.it (E.G.); francesco.dondero@uniupo.it (F.D.)
[2] Department of Biological and Environmental Sciences and Technologies, University of Salento, Via Prov.le Lecce-Monteroni, I-73100 Lecce, Italy; tiziano.verri@unisalento.it
[3] Research Institute on Terrestrial Ecosystems (CNR-IRET), National Research Council, Via Prov.le Lecce-Monteroni, I-73100 Lecce, Italy
* Correspondence: antonio.calisi@uniupo.it (A.C.); teodoro.semeraro@unisalento.it or teodoro.semeraro@cnr.it (T.S.)

Abstract

Aquaculture marks the transition from the simple activity of harvesting aquatic animal resources, carried out through the catching practices of fishing, to the farming of aquatic organisms in fresh, brackish and sea waters, carried out through human intervention aimed at increasing production. To date, research is proceeding towards expanding the range of species that can be farmed, improving the number and quality of products, and reducing the environmental impact of aquaculture activities; these efforts are supported by the improvement of our knowledge of the biology of the relevant species, the significant updating/upgrading of the rearing technologies, and the increasing awareness of the importance of water quality in optimising farming conditions. While necessarily dependent on market demand, aquaculture needs to fully leverage its environmental potential; and the relationship between aquaculture and the environment requires a system of production that combines eco-compatibility and eco-sustainability. Here, we report and analyse insights and perspectives in eco-sustainable aquaculture, spanning from sustainability and innovation processes in aquaculture to antibiotic control and aquaculture ecosystem services, in the context of the United Nations Sustainable Development Goals.

Keywords: aquaculture; eco-sustainability; aquaculture ecosystems services; innovative processes

Academic Editor: Chien-Sen Liao

Received: 6 February 2026
Revised: 29 March 2026
Accepted: 7 April 2026
Published: 9 April 2026

1. Introduction

Due to the increased demand for fish and seafood products and the reduction in global wild fisheries, aquaculture has become the major source of food fish production. According to the FAO [1], in 2022, world production of aquatic animals reached 185.4 million tonnes, of which 51% came from aquaculture (94.4 million tonnes, with a first sale value of 296 billion USD); this means that for the first time aquaculture surpassed capture fisheries in aquatic animal production. Based on 2022 estimates, aquatic animals provide ~15% animal protein consumed globally, and for over 40% of the world population, i.e., more than 3.2 billion people, fish contribute at least 20% of per capita protein intake, equivalent to 20.7 kg per capita. Also, it has been predicted that, by 2050, the vast majority of aquatic dietary protein will be supplied by aquaculture [1].

These numbers highlight the growing need to promote (novel forms of) sustainable aquaculture, an approach that has long been established in many low-income countries, where production relies on integrated aquaculture systems, small-scale operations, and traditional extensive technologies, and it is increasingly emphasised in higher-income countries as well [2]. Different motivations converge in shaping the global evolution of aquaculture. In many low-income countries, fish production remains an essential complement to diets often deficient in key nutrients such as high-quality proteins, essential fatty acids, and minerals [2,3]. In contrast, in higher-income societies, where basic nutritional needs are largely met, consumers' expectations have shifted toward product quality, health attributes, and lifestyle-related values, including sustainability and origin [4,5]. At the same time, there is growing awareness that product quality is increasingly linked to the quality of the surrounding environment, reinforcing the importance of sustainable production systems across all regions [2]. Also, for high-income societies, the principles of sustainability, resource conservation, and ecological balance have become central themes across the entire agri-food system, including the fisheries and aquaculture sectors [2,3]. In response, increasingly advanced aquaculture technologies have been developed with the dual objective of protecting the environment and producing high-quality products with nutritional characteristics as close as possible to those of wild fish [6,7].

Within this framework, sustainable aquaculture extends beyond increasing production volumes; it also requires reducing environmental impacts throughout the production cycle. This can be achieved through the adoption of ecosystem-based approaches, nutrient management, biodiversity protection measures, and many other actions [2].

While acknowledging the interconnected implications for both animal and human health, this review examines current knowledge on the sustainability and innovation directions of modern aquaculture systems by principally: (i) outlining the main sustainability dimensions of aquaculture by comparing farming systems and recent innovative processes; (ii) examining antibiotic use in aquaculture and assessing eco-friendly alternatives within the broader context of antimicrobial resistance and the One Health framework; (iii) evaluating the capacity of aquaculture to provide ecosystem services and blue infrastructure benefits, including contributions to climate mitigation, biodiversity conservation, and circular economy strategies; (iv) discussing how aquaculture can support the achievement of the UN Sustainable Development Goals (SDGs) through appropriate policy, governance and innovation measures. The objective is to highlight, and possibly indicate, key technological, managerial and governance drivers that can accelerate the transition toward climate-resilient, low-impact and socially accepted aquaculture.

2. Literature Search, Data Collection, Bibliometric Analysis and Emerging Trends

This narrative review integrates a bibliometric co-occurrence analysis to identify the most recent scientific trends in sustainable aquaculture. A quantitative mapping approach was adopted to examine the evolution of research themes, technological innovations, and sustainability-oriented practices emerging in the periods 2020–2026 (structural relevance), 2022–2026 and 2025–2026 (temporal emergence).

A structured search was conducted in Scopus, selected for its broad coverage of the peer-reviewed literature. The search string used was "aquaculture" AND "sustainability". The query was applied to all keywords (author keywords + index keywords), restricting the time window to January 2020–March 2026 (first dataset), January 2022–March 2026 (second dataset), and January 2025–March 2026 (third dataset) to monitor contemporary developments in sustainable aquaculture. All document types indexed as articles, reviews, book chapters, and conference papers were included to ensure a broad representation of emerging research fronts.

https://doi.org/10.3390/environments13040208

Three Scopus CSV export files were generated (on 15 March 2026) (see Supplementary Materials), which included author keywords, index keywords, combined keyword lists (all keywords), and various bibliographic metadata (publication year, citation counts, source title, etc.). No manual exclusion of studies was performed beyond the dataset filters.

The three datasets were imported into VOSviewer (v.1.6.20) for co-occurrence analysis. Keywords appearing fewer than 5 times were excluded to reduce noise and highlight consolidated or emerging thematic areas.

Co-occurrence networks were generated using the full counting method. VOSviewer automatically grouped keywords into clusters, each representing a coherent macro-thematic area. Core keywords (highest total link strength, TLS), emerging keywords (average publication year, APY), and research intensity indicators (occurrences) were extracted from datasets as needed. Keywords with an APY $\geq$ 2023.8 were classified as emerging trends; keywords with an APY $\geq$ 2025.3 were classified as the most recent trends. This approach allowed the identification of breakthrough macro-themes among current research trajectories.

2.1. Bibliometric Structure and Emerging Trends

The bibliometric analysis of the Scopus-indexed literature published between 2020 and 2026 reveals a highly structured and rapidly evolving research landscape in sustainable aquaculture (Table 1). The VOSviewer co-occurrence map (all keywords, $n \approx$ 2000+) organises the field into four coherent clusters, each corresponding to a major thematic axis.

Table 1. Structural relevance (2020–2026) [§].

Cluster [&]	Macro-Theme	Top Structurally Relevant Keywords (2020–2026) (Occurrences)	Structural Role
1	Environmental sustainability, climate resilience and ecosystem management	aquaculture (2106), climate change (266), biodiversity (128), aquatic ecosystem (24), carbon footprint (51), coastal zone (24), carrying capacity (26)	These terms anchor the environmental dimension: climate impacts, ecosystem functioning, governance, and sustainability metrics.
2	Health, welfare and biosecurity	bacteria (70), *Aeromonas* spp., antioxidant activity (32), apoptosis (20), biomarkers (19), immune response (implied via enzymes, oxidative stress markers)	High-frequency health terms reflect persistent concerns about disease, immunity, and welfare.
3	Circular systems, waste valorisation and water quality	bioremediation (99), wastewater (26), adsorption (17), biochar (13), anaerobic digestion (19), bioflocs (31), bioreactors (12)	Strong engineering–environmental cluster focused on reducing pollution and closing nutrient loops.
4	Innovative feeds, nutrition and resource-efficient production	amino acids (48), aquafeed (46), alternative proteins (15), black soldier fly (19), algae (41), nutritional physiology terms (e.g., amino acid metabolism)	Feed innovation remains the largest driver of sustainability and cost efficiency.

[§] High-frequency, high-link-strength keywords across the full period. Keywords included according to: occurrences from the 2020–2026 file, cluster membership, and semantic grouping into macro-themes. [&] Cluster 1 aggregates terms related to *environmental sustainability*, *climate change*, *biodiversity*, and *ecosystem functioning*. High-frequency keywords such as *aquaculture*, *climate change*, *biodiversity*, *aquatic ecosystem*, *carbon footprint*, and *coastal zone* indicate that environmental performance and climate resilience remain foundational pillars of the field. Cluster 2 centres on *fish health*, *welfare*, and *biosecurity*, with dense co-occurrence around *bacteria*, *Aeromonas*, *antioxidant activity*, *apoptosis*, *biomarkers*, and *immune-related enzymes*. This cluster reflects the persistent centrality of disease management and physiological stress responses in aquaculture sustainability. Cluster 3 captures the *circularity* and *water quality dimension*, dominated by terms such as *bioremediation*, *wastewater*, *adsorption*, *biochar*, *anaerobic digestion*, *bioflocs*, and *bioreactors*. These keywords highlight the growing emphasis on nutrient recovery, pollution mitigation, and low-impact production systems. Cluster 4 focuses on *innovative feeds* and *nutritional strategies*, with strong representation of *amino acids*, *alternative proteins*, *black soldier fly*, *algae*, *aquafeed*, and *nutritional physiology*. Feed innovation emerges as a major driver of sustainability gains and cost efficiency.

The overlay visualisation (2022–2026) reveals a clear temporal shift toward emerging topics (Table 2). Keywords with the highest APY include climate resilience, blue carbon, circular economy, antimicrobial resistance, bacteriophage, β-glucan, biochar, anaerobic digestion, circular bioeconomy, alternative protein source, and black soldier fly larvae.

These terms indicate a transition toward climate-positive aquaculture, precision health approaches, circular resource flows, and biotech-driven feed ingredients.

Table 2. Temporal emergence (2022–2026) [§].

Cluster [&]	Macro-Theme	Emerging/Fast-Growing Keywords (2022–2026) [&]	Trend Direction (Based on APY)
1	Environmental sustainability, climate resilience and ecosystem management	climate resilience (2024.6), blue carbon (2023.6), circular economy (2024.15), coastal protection (2024.6), carbon neutrality (2024.4)	Strong acceleration toward climate-positive aquaculture, mitigation strategies, and ecosystem-based management.
2	Health, welfare and biosecurity	antimicrobial resistance (2024.1), bacteriophage therapy (2024.2), β-glucan (2024), biomarkers (2024.3–2024.5), apoptosis (2024.3)	Shift toward precision health, microbiome-based interventions, and reduced antibiotic use.
3	Circular systems, waste valorisation and water quality	adsorption materials (2023.7), biochar (2023.9), anaerobic digestion (2023.6), bioreactors (2023.7), circular bioeconomy (2024.16)	Rapid growth in waste valorisation, nutrient recovery, and low-impact water treatment.
4	Innovative feeds, nutrition and resource-efficient production	alternative protein source (2023.8), black soldier fly larvae (2024.25), amino acid optimisation (2024.3), algal oils (2023.57)	Biotech-driven feed ingredients and precision nutrition are accelerating.

[§] Keywords with high APY (2023.8–2025.6) and rising link strength. Keywords included according to: APY from the 2022–2026 file with focus on terms with APY $\geq$ 2023.8 and substantial link strength, cluster membership, and semantic grouping into macro-themes. [&] These themes correspond to the yellow-shaded areas in VOSviewer overlay maps (see Supplementary Materials).

Overall, the bibliometric structure shows a mature core (environment, health, and nutrition) accompanied by rapidly expanding frontiers (climate mitigation, microbiome engineering, circular bioeconomy, and novel feed sources).

2.2. Recent (2025–2026) Dynamics in Sustainable Aquaculture Research

Based on the 2025–2026 data (see Supplementary Materials), the VOSviewer map reveals a research landscape that remains structurally anchored in the four macro-themes identified for the broader 2020–2026 period, while showing a marked acceleration in climate-positive strategies, digitalisation, and molecular health diagnostics. This is summarised in Tables 3 and 4 and Figure 1.

High-frequency keywords such as aquaculture (764 occurrences), fish (267), climate change (112), environmental impact (81), bioremediation (36), diet (39), feed conversion ratio (20), and fish disease (44) (see, e.g., Table 3) confirm the continued centrality of environmental performance, feed optimisation, and health management.

The network also highlights a growing emphasis on ecosystem-based approaches, with terms such as ecosystem services, ecosystem health, environmental sustainability, and coastal waters showing strong link strength and high recency. In parallel, the health and welfare cluster shows a shift toward molecular and cellular markers, including apoptosis, differential gene expression, enzyme activity, and erythrocyte count, indicating a move toward precision diagnostics.

A notable development is the rapid rise of AI-enabled aquaculture, with keywords such as deep learning, computer vision, convolutional neural network, data mining, and digital transformation emerging as new hotspots. These terms reflect the integration of automation, monitoring technologies, and decision-support systems into aquaculture operations.

Finally, the circularity cluster shows consolidation around circular bioeconomy, circular economy, eco-friendly, denitrification, biofloc, and effluent treatment, confirming that resource efficiency and waste valorisation remain core sustainability strategies.

Table 3. Structural relevance (2025–2026) §.

Cluster	Macro-Theme	Top Structurally Relevant Keywords (2025–2026) (Occurrences; TLS)	Structural Role
1	Environmental sustainability, climate resilience and ecosystem management	climate change (112; 1319), environmental sustainability (78; 1374), environmental impact (81; 1221), ecosystems (41; 745), biodiversity (50; 825), environmental monitoring (36; 731)	These terms anchor the environmental and climate dimension, showing strong centrality and persistent dominance across the network.
2	Health, welfare and biosecurity	fish disease (44; 928), fish diseases (34; 789), antibiotic resistance (34; 590), enzyme activity (44; 1000), apoptosis (8; 239), disease resistance (30; 434)	Health-related terms remain structurally central, reflecting ongoing concerns about disease management and physiological stress.
3	Circular systems, waste valorisation and water quality	bioremediation (36; 614), effluent (6; 189), denitrification (8; 183), biofloc (12; 129), environmental technology (24; 406), biodegradation (6; 185)	Strong engineering–environmental cluster focused on reducing pollution, nutrient recovery, and water quality management.
4	Innovative feeds, nutrition and resource-efficient production	diet (39; 935), feed conversion ratio (20; 547), dietary supplements (21; 582), fishmeal replacement (7; 23), fatty acids (19; 239), amino acids (10; 68)	Feed optimisation and nutritional biotechnology remain major structural pillars.
5	Technological innovation and digitalisation	deep learning (41; 399), artificial intelligence (52; 639), data mining (13; 181), computer vision (7; 70), decision-support systems (6; 68)	AI-based tools show increasing structural integration into aquaculture systems.

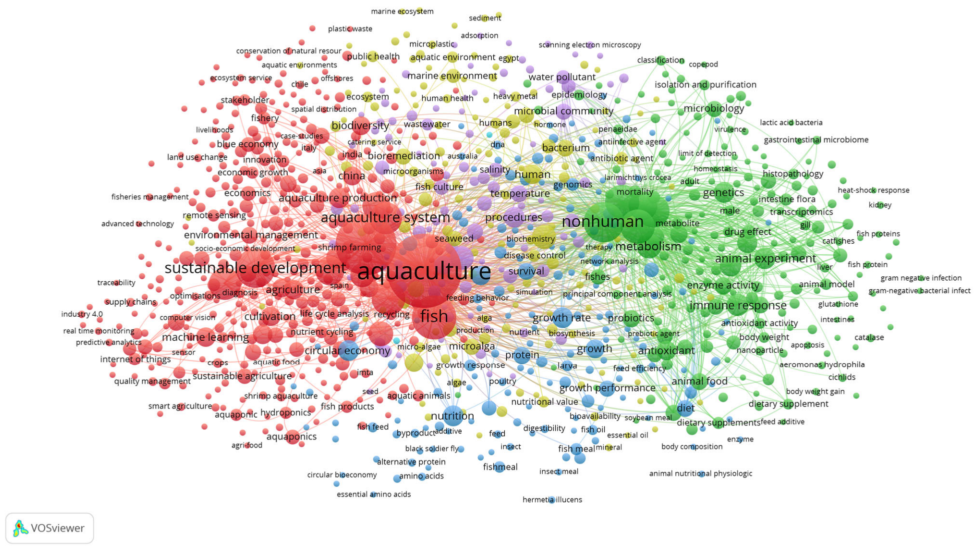
§ High-frequency, high-centrality keywords defining the core structure of sustainable aquaculture in 2025–2026. Keywords included according to: occurrences and TLS from the 2020–2026 file, cluster membership, and semantic grouping into macro-themes.

Table 4. Temporal emergence (2025–2026) §.

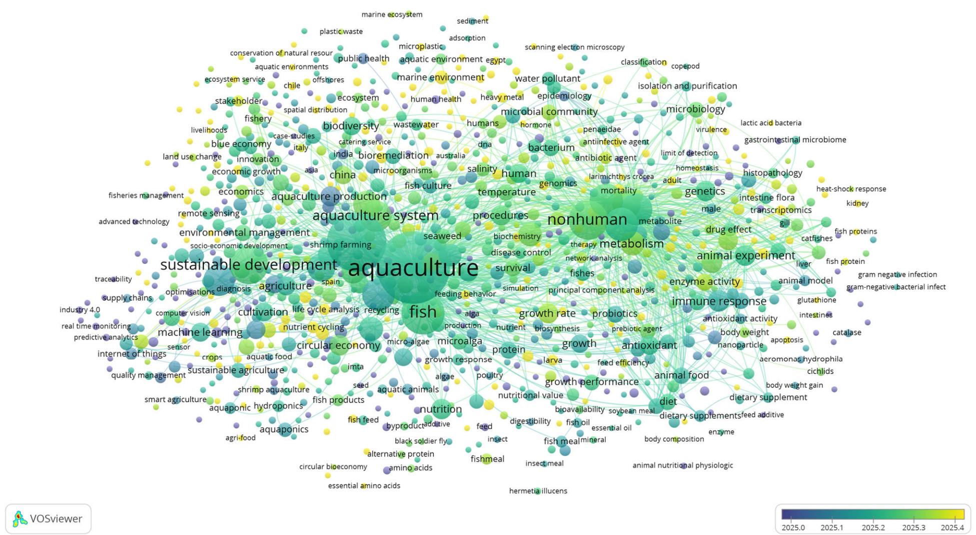
Cluster	Emerging Theme (2025–2026)	Emerging/Fast-Growing Keywords (APY $\geq$ 2025.30)	Trend Direction (Based on APY)
1	Climate-positive and resilience-oriented aquaculture	climate resilience (2025.375), climate change adaptation (2025.2), ecosystem services (2025.333–2025.625), environmental degradation (2025.6667)	Strong acceleration toward climate-positive aquaculture, resilience, and ecosystem-based management.
2	Precision health and molecular diagnostics	apoptosis (2025.5), differential gene expression (2025.3), downregulation (2025.5714), erythrocyte count (2025.0), enzyme activity (2025.3409)	Shift toward molecular, cellular, and immunological indicators of health and welfare.
3	AI-enabled aquaculture and digitalisation	deep learning (2025.2439), data mining (2025.6154), computer vision (2025.0), convolutional neural network (2025.2), digital transformation (2025.2)	Rapid integration of AI for monitoring, automation, and decision support.
4	Circular bioeconomy and resource efficiency	circular bioeconomy (2025.3333), circular economy (2025.2833), eco-friendly (2025.1667), environmental technology (2025.2083), biodegradation (2025.1667)	Circularity becomes a central sustainability pillar, not a peripheral theme.
5	Functional feeds and nutritional biotechnology	essential amino acids (2025.6), dietary intake (2025.1667), feed additives (2025.4286), fishmeal replacement (2025.1429), fatty acids (2025.4211)	Feed innovation shifts toward biotech-enabled, functional, and efficiency-oriented strategies.
6	Production, welfare and performance (cross-cutting)	feeding behaviour (2025.5833), energy metabolism (2025.6667), body composition (2025.3333)	Welfare and metabolic performance indicators show recent methodological innovation.

§ Keywords with the highest recency (APY $\geq$ 2025.30) and substantial link strength, indicating fast-growing research fronts. Keywords included according to: APY from the 2025–2026 file with focus on terms with APY $\geq$ 2025.30 and substantial link strength, cluster membership, and semantic grouping into macro-themes.

In summary, across the full 2020–2026 period, sustainable aquaculture research displays a stable thematic backbone centred on environmental sustainability, fish health and welfare, circular resource flows, and feed innovation. The 2022–2026 overlay reveals a first wave of emerging themes, including climate resilience, circular bioeconomy, antimicrobial resistance mitigation, and biotech-enabled feed ingredients. The most recent (2025–2026) dataset confirms these trajectories while highlighting a decisive shift toward climate-positive strategies, molecular diagnostics, and AI-enabled aquaculture. Together, the three periods illustrate a sector evolving from traditional sustainability concerns toward technologically advanced, climate-resilient, and resource-efficient production systems aligned in a perspective with global sustainability frameworks such as those sustained by the SDGs, the EU Green Deal, FAO Blue Transformation, etc.



(**A**)



(**B**)

Figure 1. (**A**) VOSviewer visualisation map of keyword co-occurrence in sustainable aquaculture research (2025–2026). The network visualisation map highlights emerging frontiers in climate-positive aquaculture (e.g., climate resilience, ecosystem services, and environmental sustainability) (yellow), precision health and molecular diagnostics (e.g., apoptosis, differential gene expression, and enzyme activity) (green), AI-enabled monitoring and automation (e.g., deep learning, computer vision, and digital transformation) (red), circular bioeconomy (e.g., circular economy, eco-friendly, and denitrification), and functional feed innovation (e.g., dietary supplements, essential amino acids, and feed additives) (blue). (**B**) VOSviewer overlay visualisation map of keyword co-occurrence in sustainable aquaculture research (2025–2026). Node colours represent the APY, with yellow tones indicating the most recent research activity. These trends illustrate the sector transition toward technologically advanced, climate-resilient, and resource-efficient aquaculture systems.

3. Towards an Eco-Sustainable Aquaculture

The 2025–2026 analyses (Tables 3 and 4) show that sustainability-oriented terms such as climate change, environmental sustainability, environmental impact, ecosystems, and biodiversity form the structural core of Cluster 1, the most central and interconnected domain in the current aquaculture knowledge network (Figure 2). These keywords also display strong temporal acceleration (APY $\geq$ 2025.30), confirming the emergence of a climate-positive and resilience-oriented aquaculture paradigm.

Manuscript Section	Structural Cluster (Table 3)	Emerging Cluster (Table 4)	Representative Keywords (2025–2026)	Macro-Theme
3.1 Sustainability in aquaculture	Cluster 1	Cluster 1	climate change; environmental sustainability; environmental impact; biodiversity; ecosystem services	Environmental sustainability, climate resilience, ecosystem management
Use of native species	Cluster 1	Cluster 1	biodiversity; ecosystems; environmental impact; conservation	Biodiversity protection, ecosystem integrity
Shellfish farming	Cluster 1	Cluster 1	bivalves; environmental monitoring; ecosystem services; environmental impact	Low-impact farming, ecosystem-based production
3.2 Innovative processes	Clusters 1 & 3	Clusters 1 & 4	bioremediation; environmental technology; ecosystem services; climate resilience	Circular systems + climate-resilient aquaculture
Offshore aquaculture + IMTA	Cluster 1	Cluster 1	climate change; environmental monitoring; ecosystem services	Climate-positive aquaculture, offshore sustainability
Aquaponics	Cluster 3	Cluster 4	denitrification; bioremediation; biodegradation; biofloc; environmental technology	Circular nutrient cycling, integrated systems
Farm wastewater	Cluster 3	Cluster 4	effluent; denitrification; bioremediation; biodegradation; environmental technology; biofloc	Circular bioeconomy, nutrient recovery, water quality
Exploiting algae potential	Cluster 3	Cluster 4	bioremediation; denitrification; effluent; biodegradation; environmental technology; biofloc	Circular systems, waste valorization, water quality
Breeding of fish with vegetable flours	Cluster 4	Cluster 5	diet; feed conversion ratio; dietary supplements; fishmeal replacement; fatty acids; essential amino acids	Innovative feeds, nutrition, resource-efficient production
3.3 Antibiotics and aquaculture	Cluster 2	Cluster 2	fish disease; antibiotic resistance; enzyme activity; apoptosis; differential gene expression	Health, welfare, biosecurity, molecular diagnostics
Vaccination, phage therapy, quorum sensing, probiotics, peptides, phytochemicals, nanotechnologies	Cluster 2	Cluster 2	apoptosis; enzyme activity; erythrocyte count; down regulation; bacterial infection	Precision health, immunology, pathogen control
3.4 Aquaculture ecosystem services	Cluster 1	Cluster 1	ecosystem services; environmental sustainability; environmental impact; biodiversity	Ecosystem-based management, sustainability governance
Aquaculture and blue infrastructures	Cluster 1	Cluster 1	blue economy; ecosystem services; environmental sustainability; coastal waters; coastal zone management; climate resilience	Ecosystem-based spatial planning, blue economy, climate-resilient infrastructures

Figure 2. Trends in eco-sustainable aquaculture. Mapping of manuscript sections to VOSviewer clusters (2025–2026).

Each of the following sections maps to one or more clusters according to the structural relevance (occurrences, TLS) and temporal emergence (APY $\geq$ 2025.30) of the associated keywords, supporting the thematic organisation of the following part of the manuscript on the current state of the art and the emerging research fronts in sustainable aquaculture (see Figure 2).

3.1. Sustainability in Aquaculture

In modern aquaculture, a trending thought is gaining ground, which is reflected (i) in the growing emphasis on "recovering naturality" in all current farming practices and (ii) in expanding the knowledge on cultured aquatic organisms' biology to support sustainable production. As highlighted in the literature, modern aquaculture still relies on intensive and semi-intensive systems that generate environmental pressures, including disease spread and antibiotic use. On the other side, extensive aquaculture, aligned with Cluster 1 (ecosystem management) and Emerging Cluster 1 (see Tables 1–4 and Figure 2), remains the most environmentally compatible approach, though limited by lower yields.

To date, extensive aquaculture is considered the most natural and sustainable form of aquafarming as it tends to exploit exclusively the resources provided by the environment, without any nutritional contribution from man. Marine aquaculture and tinned-seafood-dedicated aquafarming (mainly freshwater aquaculture) are the main forms of breeding, which are generally intended for euryhaline species of coastal waters, such as eel, sea bass, sea bream, and mullet [8,9]. Thus, extensive aquaculture is an example of the interaction between human activity and environmental conservation. Its limit is represented by the rather low yields, but it has quality standards similar to the catch.

Some emerging aspects of eco-sustainability in aquaculture are explored below, i.e., the use of native species and shellfish farming.

Use of native species

The preference for native species to reduce ecological risks aligns with Cluster 1 and Emerging Cluster 1, where biodiversity, ecosystems, and environmental impact are structurally dominant terms (see Tables 1–4 and Figure 2). This reflects the increasing emphasis on genetic integrity, ecological compatibility, and conservation-aligned aquaculture.

Farmed fish are generally selected based on traits such as robustness, resistance and high growth rate, regardless of whether they are native or non-native (i.e., species not naturally present in the farming area). Because a significant number of fish escape from farming basins, both native and non-native species pose distinct threats [3]. Native escapees can mate with wild counterparts, lowering the genetic fitness of the descendants through introgression (genetic impact), particularly because hatchery reproducers are often few in number and highly inbred compared to natural populations. Conversely, non-native escapees can compete with, and often displace, local populations (ecological impact), due to their selection for superior hardiness and, at times, aggressiveness [10].

From a sustainability perspective, it is arguably superior to cultivate local species in aquaculture to minimise the environmental damage caused by accidental releases that can not only disrupt the eco-environmental balance but also introduce pathogens into native ecosystems [10]. However, cultivating native species is not always viable if they do not exhibit the desired zootechnical traits. Moreover, closed-facility breeding programs are often optimised to maximise growth efficiency, a feature that may be compromised if only native fish are used. In this respect, it is worth investing in parallel breeding programs to improve the production characteristics of native species.

Shellfish farming

Shellfish farming aligns with Cluster 1 and Emerging Cluster 1's structural focus on, e.g., ecosystem services, environmental monitoring, and biodiversity (see Tables 1–4 and Figure 2). As filter feeders requiring no external feed inputs, bivalves represent a model of ecosystem-based, low-impact aquaculture, consistent with the most central sustainability trends.

In the context of aquaculture, shellfish farming, i.e., the cultivation of mussels, clams and oysters, has been considered an example of sustainable sea farming. Because these animals feed by filtering the microorganisms present in the water, they require no external feed [11]. However, it is essential that their breeding environment is safe to prevent the accumulation of harmful substances or bacteria in their bodies. To ensure optimal health and welfare, shellfish farming operations should maintain low stocking densities, ensure adequate water exchange, and prioritise environmental hygiene [12].

3.2. Innovative Processes

The development of multitrophic, multispecies, and polyculture systems that has occurred over the last few years corresponds to the intersection of Cluster 1 (ecosystem management) and Cluster 3 (circular systems and water reuse) and related Emerging Clusters 4 and 5, respectively (see Tables 1–4 and Figure 2). Keywords such as bioremediation and environmental technology highlight the structural relevance of these approaches, while emerging terms like resource efficiency and circular bioeconomy confirm their growing prominence clusters.

There has been a natural trend in aquaculture towards recovering the natural biological and ecological relationships among species (animals, plants, bacteria, algae, etc.) kept together in either closed, semi-closed or open-culture systems in (a) multitrophic, multispecies, polyculture configuration(s). The aim is to try and reproduce situations that at best assimilate an artificial system to a quasi-natural environment. This trend is acknowledged as innovative and requires integrated basic and applied research in order to build a modern approach to aquafarming processes. In this framework, it is imperative, e.g., to define species compatibility (i.e., species that can live in the same farming environment without detrimental interactions) and species complementarity (i.e., complementary use of available resources and/or commensalism/mutualism) to achieve efficient and ethical aquaculture [13]. Such innovative production processes are mainly based on the application of the principle of "treatment and reuse" (waste) of a "culture medium" (water), where "different organisms" (bacteria, phyto- and zooplankton, algae, plants, animals, etc.) share a sort of selected "common space" for relatively "long times". The systems work when a sort of equilibrium ("steady state") is achieved [3,14,15]. This is particularly true for semi-closed and closed-circuit systems, which allow water to be treated physically, chemically and bacteriologically, allowing it to be reused by those organisms that produced the wastewater [3,16]. Furthermore, by recreating the natural trophic chain in the same controlled/semi-controlled environment, these systems represent a sort of (multispecies) polyculture (setup) capable of giving consistent and important solutions in the innovation of systems from a biological, productive and ecological point of view [15]. Not only that, they can also represent a true complex ecotoxicological laboratory where tests can be run on a varied and wide battery of marine organisms (bacteria, zooplankton, phytoplankton, and larvae) and for the evaluation of the toxicity (acute, chronic and sub-lethal) of waters of different origin and/or subjected to continuous treatment and reuse.

A couple of examples of emerging integrated system paradigms are described below.

Integrated multi-trophic aquaculture (IMTA) and IMTA-advanced off-shore aquaculture

Offshore systems are embedded in Cluster 1, where climate change, environmental monitoring, and ecosystem services dominate (see Tables 1–4 and Figure 2). Their development reflects the emerging trend toward climate-resilient aquaculture, reducing coastal impacts while improving welfare and product quality.

In recent years, innovative production systems such as recirculating aquaculture systems, offshore aquaculture and integrated multi-trophic aquaculture (IMTA) models have become increasingly popular. These technological solutions enhance the efficiency of water and energy use, while mitigating the environmental impacts of traditional farming methods. Together, these solutions support the transition towards more sustainable, circular and resilient forms of aquaculture, in line with the principles of the blue economy and ecosystem-based management of aquatic resources [17–22].

A recent trend in this field is the use of multi-functionality platform systems in confined offshore marine areas in combination with IMTA practices. This allows for the development of modern mariculture practices in offshore systems [23,24], with the objective of removing aquafarms from the coast, reducing the environmental effects, and, at the same time, overcoming some limits of offshore farming and increasing the competitiveness of aquaculture [23]. Under these conditions, experimental trials could be carried out in the direction of relating the aquafarming technology to the welfare conditions of the fish, using traditional stress indices and evaluating the response of new indicators [23,24]. In this way, with the monitoring of the effects on the quality and safety of the product, it could be assessed how the improvement of the aquafarming conditions affects the well-being of organisms, which is also dependent on the effects of climate change on the production chain [25].

https://doi.org/10.3390/environments13040208

Aquaponics

Aquaponics is tightly linked to Cluster 3 (see Tables 1–4 and Figure 2), with strong representation of keywords such as denitrification, bioremediation, biofloc, and biodegradation. Its pre-eminence aligns with the emerging circularity cluster, confirming aquaponics as a rapidly expanding research frontier in sustainable production.

Within the frames of the two keywords sustainability and aquaculture, in several countries the word aquaponics represents the novel spreading paradigm related to a type of aquatic production activity that primarily allows the integrated production of fish and vegetables [26–32]. Briefly, aquaponics uses water cycling in circuits in a simple way. In particular: (i) the system is based on one or more fish farming tanks; (ii) vegetables are placed above the tanks; (iii) within this system, the vegetables absorb the nutrients released by the fish. The fish–vegetable relationship is reciprocal, i.e., the fish release useful substances to the vegetables and the vegetables give oxygen to the fish [30,31]. In this respect, aquaponics aims to generate an all-natural purification system. By breathing, fish emit ammonia, which contains nitrogen. Nitrogen is the main source of nourishment for plants, which, however, before it is consumed, must be transformed into nitrites and then nitrates. Only after this step will this substance no longer be poisonous for fish and become food for plants [26,31]. The transformation from fish waste to plant nutrition may occur by means of two groups of bacteria: (i) ammonia-oxidising bacteria (such as *Nitrosomonas*) that feed on ammonia and return nitrites; (ii) nitrite-oxidising bacteria (such as *Nitrobacter*) that feed on nitrites and return nitrates. Vegetables, with their roots, extract the nitrates from the water and in return purify the water for the fish. This system in nature is known as the "nitrogen cycle". This process promises to be effective for large-scale crops as well as for vegetable gardens, greenhouses and terraces. To date, aquaponics has been proven to be a useful and environmentally sustainable practice [32].

Farm wastewater

Wastewater management, one of the cornerstones of aquafarming control, is strongly associated with Cluster 3 and Emerging Cluster 4 (see Tables 3 and 4 and Figure 2), where keywords such as effluent, denitrification, bioremediation, and biofloc form the backbone of research on water quality and nutrient recycling. The emergence of environmental technology and biodegradation (APY $\geq$ 2025.16) reinforces the shift toward closed-loop, resource-efficient systems, including IMTA, aquaponics and more structurally integrated agriculture–aquaculture models.

Depending on the type of culture, fish farms produce wastes in various liquid, semi-solid and solid forms, e.g., while extensive culture produces wastes in the form of liquids, intensive culture that typically uses semi-closed or closed water systems produces waste in forms other than liquid. While wastewater discharge into natural water bodies might be a concern, modern land-based aquaculture systems are often situated far from such bodies, such that that this production setup (which is common for intensive culture) reduces pollution.

A problem common to all types of intensive aquaculture concerns waste that contains fish manure, feed waste, and antibiotic residues in various compositions [33–36]. Due to these inputs, the chemical composition of the water changes inside and outside the plant infrastructure and can promote the growth of algae that produce toxins that are dangerous for marine organisms and for humans [7]. The problem of polluting wastewater can be minimised with adequate plant management. Some innovative solutions include filtration, decantation and purification systems, where wastewater is returned with chemical–physical characteristics similar to the incoming water. However, the best solutions are those that provide a "closed cycle" which eliminates the wastewater [35,36]. One solution is based on some particularly innovative systems, such as (i) IMTA (as described above) and

(ii) integrated agricultural farming systems and aquaculture. For example, in IMTA, waste rich in organic matter is used to feed another species, e.g., a sea bass plant in Israel used wastewater to grow seaweed, which in turn was used to feed a shellfish (Japanese abalone) that is marketed [37]. Also, in an integrated agriculture/aquaculture system in which fish manure fertilises rice fields, the fish feed on the grasses that grow in the rice fields, thus eliminating the "weeds". In this "rice/fish" case, the concept ("mutualism") is to improve rice production by letting herbivorous fish eliminate weeds that compete with rice plants for sunshine, fertiliser, and space. At the same time, fish in rice fields feed on weeds, plankton, and benthos and form an optimum ecological system that benefits both the fish and the rice [38].

Exploiting algae potential

Macro- and microalgae play a central role in nutrient assimilation, biofiltration, and feed production, thus exhibiting a very high potential for eco-sustainable and environmentally friendly production applications. These functions correspond to Cluster 3 and Emerging Cluster 4 (see Tables 1–4 and Figure 2), characterised by keywords such as bioremediation, denitrification, effluent, biodegradation, and environmental technology. The emergence of circular bioeconomy and eco-friendly systems (APY $\geq$ 2025.16) confirms that algae-based solutions are a key component of the circularity paradigm.

Most fish farms release nitrates and organic sludge into the environment. Any alteration of the balance between nutrients (e.g., an excessive intake of nitrates or phosphates) leads to an imbalance in the growth of phytoplankton [39,40], which may manifest itself in a numerical explosion of certain species (algal blooms or red tides) and have significantly negative consequences for the entire aquatic ecosystem, with extensive death of organisms [41]. In the modern paradigm of integrated aquaculture, the nutrients in wastewater are currently considered not a burden but a resource for auxiliary crops of plants [34–43]. With this in mind, biofiltration using plants, such as macroalgae, is an assimilative process, and therefore it increases the assimilation capacity of the environment for nutrients [14,44,45]. Plant biofilters can significantly reduce the global environmental impact of cultures. The use of macroalgae as nutrient users in integrated aquaculture thus represents an excellent example of biotechnology, in which the production system is designed in collaboration with nature [44].

Today, microalgae are an object of growing interest due to their considerable potential for exploitation. They are successfully used in many sectors: aquaculture, chemical industry, bioenergetics, cosmetics, etc. Important applications are also in the food industry because microalgal biomasses contain important nutrients (proteins, fats, carbohydrates, carotenoids, vitamins, etc.). In several countries, the interest in marine microalgae crops is relatively recent and arose from the idea of using these crops as a starting point for reconstructing the trophic chain in the processes of artificial reproduction of marine fish species [46,47]. Nowadays, phytoplankton is commonly used (i) as live food for filter-feeding organisms such as bivalve molluscs and penaeid larvae; (ii) as "pabulum" for zooplankton, such as copepods and rotifers, which in turn constitute food for the larvae of many species of fish and crustaceans farmed today; (iii) for the production and enrichment of the nutritional properties of zooplankton (mostly rotifers) administered in turn to fish larvae; and (iv) directly as food (e.g., for tilapias which, having a multipurpose diet, in addition to preying on small animals in sediment, filter the plankton directly from the water) or feed ingredients [46,48]. To date, phytoplankton culture, comparable to current agriculture, requires the "domestication" of useful plant species and the formation of culture environments particularly suited to the physiological necessities of massive algal production. Moreover, while current aquaculture employs standard feed ingredients and feeding protocols mainly selected on the basis of the species and culture method used (extensive, intensive, etc.), it is worth emphasising that to support sustainability ingredients and protocols should be developed in order to fully meet the nutritional needs of the cultured animals in the initial and subsequent phases of their life cycle. In this context, the phytoplankton (and zooplankton) species selected for culture should be selected for breeding, keeping in mind that they have been selected to reproduce the food chain present in nature to scale [46–48]. Finally, the intensive cultivation of phytoplankton is necessary as its presence in the seas is not sufficient to support the optimal growth of larvae and juvenile stages reared at a high density.

Exploring vegetable flour potential

The transition toward plant-based feeds aligns with Cluster 4 and Emerging Cluster 5 (see Tables 3 and 4 and Figure 2), where the keywords diet, feed conversion ratio, dietary supplements, fishmeal replacement, and fatty acids dominate. Emerging terms such as essential amino acids and feed additives (APY $\geq$ 2025.42) highlight rapid innovation in functional feeds and nutritional biotechnology, confirming that feed optimisation is a major structural pillar of sustainable aquaculture.

As universally acknowledged, the breeding of carnivorous fish is very impactful. Indeed, this type of fish are predators that require significant quantities of fish to feed [9,49]. Some authors report that, on average, for 1 kg of final product destined for sale, 5 kg of fish are needed as feed [50,51]. This type of aquaculture produces unacceptable waste and certainly cannot represent an alternative to fishing. To reduce the overexploitation of fish resources, over the last several decades, replacing part of the protein component derived from fish-based flours with vegetable protein raw materials has been considered. More sustainable is the breeding of organisms whose diet is less of a burden on the environment because it is based on vegetable flours. The most suitable omnivorous or herbivorous species are: common carp, herbivorous carp, silver carp, tilapia, tench, and several species of mullet [52]. However, the use of vegetable-derived substances cannot exceed a certain threshold, otherwise the correct growth of the animals will be compromised.

3.3. Antibiotics and Aquaculture

The analysis of the 2022–2026 data (see Tables 1–4 and Figure 2) identified fish disease(s), antibiotic resistance, and enzyme activity as central keywords in Cluster 2 and Emerging Cluster 2, reflecting the structural importance of disease management and biosecurity. Emerging terms such as apoptosis, differential gene expression, downregulation, and erythrocyte count (APY $\geq$ 2025.30) indicate a shift toward molecular diagnostics, immunological markers, and precision health approaches.

Antibiotics

To date, antibiotics are used in aquaculture—it is common practice to add antibiotics to feed—primarily for disease prevention and treatment, managing overcrowding in intensive systems, and enhancing productivity. In this respect, they have been employed for more than 50 years as growth promoters and prophylactic, metaphylactic and/or therapeutic agents [33,39,53,54]. China is among the main producing and consuming countries for antibiotics and ranks first among the 15 major aquaculture-producing countries. According to a recent estimate, half of the total amount of antibiotics produced in China is destined for animal feed, so that ~105,000 tonnes are used for animal growth and care [55,56]. Worldwide, in 11 of the 15 leading aquaculture countries, 67 antibiotic molecules (oxytetracycline, sulphadiazine and florfenicol, but also sulphadimethoxine, erythromycin, amoxicillin and enrofloxacin) are used. In more detail, while the mean number of antimicrobial compounds used by different countries for aquaculture is 15, Vietnam and China were reported to use, respectively, 39 and 33 different antibiotics [39]. While some of these antibiotics are

https://doi.org/10.3390/environments13040208

used for veterinary purposes only, others are important in human medical therapy care, e.g., amoxicillin has been classified by the World Health Organization (WHO) as critically important and oxytetracycline as highly important in human medicine. Collectively, these data suggest that a large amount of antibiotics belonging to different chemical categories being used in aquaculture can result in enormous environmental pressure on resident bacterial populations. Interestingly, 75–80% of the antibiotic fraction used in aquaculture maintains its activity and enters the environment [57]. Thus, the fraction previously used to feed fish can accumulate in the aquaculture environment, leading to an increased amount of antibiotics in sediments, pond water, and animal tissues, with a negative impact on both environmental and human health [33,39,40]. Finally, the occurrence of antibiotic residues in animal tissues affects the complex dynamics of the human gut microbiota [58]. Moreover, aquaculture is often based on open systems that allow the dissemination of antibiotic residues not only in cultured aquatic products, but also in wild fish, sediments, and open waters. In this context, the use of first-line antibiotics for human therapy in aquaculture can lead to the development of antibiotic-resistant microbial strains and the spread of antibiotic resistance genes through horizontal gene transfer from aquaculture microorganisms to human pathogens. Taking into account that antibiotic resistance represents one of the most critical threats for human health [53], considerable attention has been paid to this topic. Based on these premises and under the impetus of the Blue Transformation (a 2030 agenda for sustainable development: https://www.fao.org/3/cc0461en/online/sofia/2022/action-deliver-global-goals.html (Accessed on 6 February 2026), proposing better and more sustainable alternative aquaculture practices to antibiotics is now a priority (for an excellent recent review, see Bondad-Reantaso et al. [59]).

Alternative Practices

All alternative strategies to antibiotics fall within Cluster 2 and Emerging Cluster 2 (see Tables 1–4 and Figure 2), supported by keywords related to immune modulation, pathogen control, and molecular responses. Their alignment with emerging molecular indicators confirms that precision health is one of the fastest-growing research fronts in aquaculture. Here, we describe briefly some of the alternative approaches to antibiotics.

Vaccination

Vaccination is one of the most widely accepted, cost-effective and sustainable tools for both the prevention and the control of fish diseases caused by viruses or bacteria [60,61]. In order to protect against various diseases, both polyvalent and multivalent vaccines containing multiple antigens have been developed and are exploited in large-scale aquaculture, especially for high-value species (e.g., Atlantic salmon). While inactivated whole-cell vaccines show high efficacy against extracellular pathogens, the use of live vaccines ensures strong antibody response and cellular memory, thus avoiding the need for subsequent immunisations. A total of 26 fish vaccines, including inactivated, attenuated, and acellular ones, have been developed and licensed [60]. However, this prevention and control strategy has two main limitations: it is not suitable for crustaceans and molluscs, and it is not very effective in juvenile fish due to their low immune response [62].

Phage therapy

Phage therapy, based on the exploitation of one or a cocktail of lytic bacteriophages able to kill target bacterial cells, has been successfully used to control bacterial diseases in aquatic animals, especially those induced by pathogenic *Vibrio* species, *Lactococcus* and *Aeromonas hydrophila* [59,63,64]. Lytic phages offer a high specificity against their favourite target cells. In order to get an efficient phage cocktail formulation, a large number of different phages should be available in collections. Moreover, regulation of the use of bacteriophages is still lacking in many countries and must be developed together with the methods applied to large-scale production of phages [65,66].

Quorum sensing

Another possible strategy to reduce the use of antibiotics is to hinder bacterial communication that occurs through quorum sensing [67]. Quorum sensing is a mechanism of intra- and inter-species communication involving signalling molecules, collectively called autoinducers. Once the bacterial cell density reaches a threshold level, the autoinducer concentration increases proportionally. The amount of the autoinducer is then sensed by bacterial cells that start to organise and behave in a coordinated manner. As a consequence, the genes that allow better adaptation of bacteria to changing environmental conditions are upregulated, including some virulence genes that in different bacterial species are activated when the bacteria reach a certain density in the host. Quorum quenching is the attenuation of a pathogen's virulence through inhibition of autoinducer synthesis, degradation of the autoinducer or alterations to the sensing of the latter [67–69]. Although quorum quenching offers fascinating perspectives in disease control, it should be considered that it does not remove a pathogen but rather reduces the pathogen's virulence. Consequently, animals will be asymptomatic while carrying the pathogen, thus representing a reservoir for potential pathogen spread. Moreover, silencing of cell-to-cell communication is non-selective, so that even non-target functions in bacterial cells belonging to the same species or to others could be impaired [33,70].

Probiotics

As in humans, the gut microbiome is critical to maintaining fish health; in fact, very often, the onset of disease is related to intestinal dysbiosis. In this context, once administered as a food supplement, probiotics belonging to the group of lactic acid bacteria (LAB) and *Bacillus* species are able to reduce the incidence of diseases mainly through modulation of the immune system; competition with pathogens for nutrients and space; reduction in intestinal pH; and the production of antimicrobial compounds, including antibiotics and bacteriocins [71–73]. The efficacy of probiotics in disease prevention can be enhanced by simultaneous treatment with prebiotics (usually oligosaccharides not assimilated by humans but stimulating the growth of probiotic microorganisms) in formulations known as symbiotic. The use of whole-cell probiotics coupled to prebiotics shows beneficial effects on organisms but induces qualitative and quantitative changes in the intestinal microbiome. To minimise the possible impact of prebiotics on the structure of the intestinal community, parabiotics, consisting of dead cells of probiotics, and postbiotics, represented by probiotic supernatants, were recently developed and evaluated for their efficacy in the prevention of diseases in aquaculture [74,75].

Bioactive peptides

In order to circumvent the use of living bacterial cells, a possible approach is to focus on bacteriocins. These are bioactive peptides with antimicrobial activity (bacteriostatic and/or bactericidal) synthesised by bacteria at the ribosomal level. Since bacteriocins are inactive against eukaryotic cells; they are considered safe and have no side effects on human health. Moreover, being gene products, they can be modified to improve their efficacy, especially against bacteria resistant to bacteriocins [76]. Consequently, they have been proposed as a sustainable and promising alternative to the use of antibiotics in aquaculture systems [77,78].

Phytochemicals

Plants provide a rich source of compounds, including terpenoids, phenolic metabolites and alkaloids, which can be used as phytochemicals and phytopharmaceuticals in aquaculture. They find application in this field through their therapeutic use against bacterial, viral, fungal and parasitic infections and their prophylactic effects due to their immunostimulant properties which are valuable for disease prevention [79,80].

Nanotechnologies

Nanotechnology devices represent recent tools proposed as an alternative to antibiotics. Nanoparticles of silver, zinc oxide, gold and titanium dioxide exhibit antimicrobial effects by multiple mechanisms, including membrane and cell envelope damage, inhibition of transport systems, inactivation of essential enzymes, and induction of oxidative damage [81]. However, concerns have been raised due to the limited knowledge available on the toxicology of these nanoparticles and the possible harmful effects that nanoparticle uptake can have on DNA metabolism [82,83]. Conversely, nanobubble technology, which is based on the use of bubbles with a diameter < 200 nm characterised by a long residence time in a solution, is considered an efficient and safe tool for treating water systems. In fact, oxygen nanobubbles increase the amount of dissolved oxygen, leading to increased cellular metabolic rates and improved animal growth. Moreover, after the collapse of the nanobubble, shock waves induce the release of ROS capable of destroying bacterial macromolecules, including proteins, lipids and DNA, thus behaving as disinfectant compounds [84,85]. Similarly, treatment of water with ozone nanobubbles reduces pathogen density, increases the amount of dissolved oxygen and modulates the immune system in fish. For example, 10 min water treatment with ozone nanobubbles induced a 97% reduction in the bacterial load of pathogenic *Streptococcus agalactiae* and *Aeromonas veronii* [86].

3.4. Aquaculture Ecosystem Services

This section corresponds directly to Cluster 1 and Emerging Cluster 1 (Tables 1–4 and Figure 2), where ecosystem services, environmental sustainability, environmental impact, and biodiversity are structurally dominant. The recency of ecosystem services (APY up to 2025.625) highlights the growing recognition of aquaculture as a provider of ecological, economic, and social benefits.

Aquaculture focuses on the cultivation under human control of aquatic organisms to grow aquatic biomass (fish, algae, etc.) that can be used for human consumption, e.g., as seafood or as a raw material for commercial and industry production and recreational purposes [1]. Thus, it comprehensively represents a management system in ponds, estuaries, and coastal and marine areas that provides direct and indirect benefits to human society and biodiversity conservation in terms of [87–91]:

- Food production: It improves global food security by providing a major source of protein. It helps meet the increasing demand for seafood as wild fish stocks dwindle.
- Employment and economic benefits: It creates employment opportunities, especially in rural and coastal areas. It supports livelihoods and contributes to the economy through fish production, processing and related industries.
- Reduced pressure on wild stocks: Pressure on wild fish populations is reduced, allowing them to recover and maintain their ecological balance.
- Controlled production: It reduces the risk of overfishing, habitat destruction and bycatch associated with traditional fishing methods.

However, aquaculture farming systems in water ecosystems on the land or sea need space and resource input for production; therefore, they can be linked to negative impacts on human well-being in terms of [88,92–94]:

- Environmental degradation: Problems such as water pollution from fish waste and excess feed, habitat alteration, and escape of farmed animals can affect local ecosystems.

- Transmission of diseases and parasites: Fish farms with high stocking densities can be susceptible to diseases and parasites. If not properly controlled, these can spread to wild populations and threaten their health and genetic diversity.
- Feed requirements: Many farmed fish species require feed consisting of other fish species, thus contributing to the depletion of wild fish populations. The development of sustainable and alternative feed sources is an ongoing challenge.
- Escapes and genetic interactions: The escape of farmed (non-native) fish into the wild can lead to interbreeding with wild populations, which can alter their genetic integrity and affect their adaptations and survival strategies.

As a semi-natural ecosystem [95], aquaculture is characterised by both "natural capital", which is composed of natural biotic and abiotic components that sustain ecological processes over time, and "human-derived capital", which is the social and economic involvement required to provide the human inputs and abiotic components to make the system function for human purposes over time [90,96]. The combination of natural and human-derived capital can thus be called a social–ecological–technological system, and it is on such a combination that the provision of ecosystem services that support benefits to human society depends [96–100]. So, there is not only one vision for the provision of ecosystem services by aquaculture; rather, the benefits to human society can depend on the different types of social–ecological–technological aquaculture developed and its ability to strike a positive balance between the quantity and quality of ecosystem service provision and environmental impact (Table 5).

The sustainability of aquaculture depends on different factors, such as farm management practices, feed sources, species selection and regulatory frameworks. By adopting responsible and sustainable practices, aquaculture can enhance the provision of ecosystem services and help meet the growing global demand for aquatic biomass for human consumption and industrial applications. This is in line with global policies to mitigate climate change while minimising negative ecosystem impacts [100–102].

Aquaculture and blue infrastructures

Severe overfishing and human exploitation of aquatic resources have led to habitat loss. It is recognised that aquaculture may play an essential role in ecological restoration by creating ecological functions and structures that maintain a wide range of ecosystem services and safeguard the wild fish stock [103–106]. However, the extent of these benefits varies greatly depending on the context, species, management practices and environmental conditions [107]. For example, marine macroalgae have a robust capacity to increase carbon cycling and can provide a carbon sink that is important for a good climate change mitigation strategy [87,108–110]. Nevertheless, the scale and longevity of carbon sequestration are still the subject of ongoing scientific debate, depending as they do on the specific ecological dynamics of each site [111,112]. Thus, if an aquaculture system is well set, it can constitute a "blue infrastructure", which refers to "a network of natural and human-made water systems that are strategically planned, designed and managed to provide a wide range of ecosystem services and deliver various social, economic and environmental benefits, such as water purification, air quality, space for recreation and climate change mitigation and adaptation" [100,113]. In aquaculture, a blue infrastructure can be characterised by a variety of natural and engineered water-related features and assets that can play an important role in ecosystem services delivery, such as nutrient excretion, water purification, biodiversity conservation, food supply, carbon sequestration and human recreation [89,102,104].

Aquaculture's ability to represent a blue infrastructure lies in its capacity to develop multifunctional applications in social–ecological–technological systems by integrating species from different nutrient stages of the trophic chain into the same system [114], in line with the circular economy approach to maximise the use of resources by keeping products and materials in a continuous cycle of use and reuse [115,116]. Integrated multi-trophic aquaculture (IMTA) is one approach that has been suggested as a way of putting this concept into practice. However, its effectiveness can vary depending on the design of the system and local environmental constraints [117]. Assimilation and storage of nutrients, including through secondary microbial activity, can convert nutrients from one state to another and make them accessible to other biota or reduce excess loads [87,118]. Although these processes are well documented at the experimental and pilot stages, further empirical validation is required to demonstrate their scalability and long-term performance under commercial conditions [119,120]. This can increase economic opportunities by converting the pollutant of one system into a resource of another system, nesting systems within each other, creating a strong synergy between different types of aquaculture production, such as fish, microalgae, macroalgae, phytoplankton and others, reducing the negative impacts of resource extraction and contributing to biodiversity conservation and natural capital, as well as valorisation [95]. However, the following potential trade-offs should also be considered: competition for space, disease transmission and increased management complexity [14,109]. For example, aquaculture ponds can be designed for a dual purpose of economically sustainable production of fish and shrimp, but also to enhance the regulation and support of ecosystem services to increase nutrient cycling for pollutant reduction and bird habitat restoration and regeneration [121]. The success of such multifunctional systems depends on appropriate design, governance, and long-term monitoring [120].

The ability to design aquaculture as blue infrastructure and reduce negative impacts depends on abiotic and biotic aspects at global and local scales [87]. Location is a key factor in determining the synergies of different semi-natural systems and the cumulative effects of costs, benefits and risks. The selection of a site influences not only productivity, but also environmental externalities. Poorly planned locations may exacerbate ecological pressures rather than mitigating them [14,109]. The provision of ecosystem services could be enhanced through the design of specific aquaculture systems that take into account the typology of habitat degradation and pollutants and other stressors characteristic of specific environmental contexts and that promote social–ecological–technological systems to maintain "provisioning services" for social and economic purposes and "regulating services" to reduce pollutants and increase environment health and promote habitat restoration to sustain biodiversity and related cultural services [87,122]. However, the availability of empirical evidence linking specific system designs to quantified outcomes of ecosystem services remains uneven across regions and production systems [14]. Therefore, aquaculture planning and design as part of the blue infrastructure vision needs to strengthen the inherent link between aquaculture and the environmental context at the local and regional level and build integrated management of ecosystem services at the global level across the marine, coastal, terrestrial and atmospheric domains to support sustainable aquaculture in line with the United Nations Sustainable Development Goals. In this context, it is important to explicitly evaluate the trade-offs between the provision of goods and services and the regulation and cultural aspects, rather than assuming that these will occur simultaneously [14]. In such cases, it is useful to apply an ecosystem services valuation framework that includes abiotic and biotic aspects developed in the proposed social–ecological–technological system scenarios and is able to estimate the net positive or negative effect on ecosystem services compared to natural habitats that could be replaced or have been degraded or displaced in the past [123,124]. Such frameworks should incorporate transparent criteria, reproducible indicators and, where possible, quantitative benchmarks in order to support comparability across studies and improve decision-making [109,125].

Table 5. Ecosystem services delivered by aquaculture systems (modified by Le Gouvello et al. 2022 [95]) and integrated biotic/abiotic components that influence the delivery of ecosystem services (modified by Alleway et al. 2019 [87]. The ecosystem services were categorised in agreement with the MEA classification.

Ecosystem Services Category	Ecosystem Services	Local and Regional Scale		Global Scale	
		Abiotic Components	Biotic Components	Abiotic Components	Biotic Components
Supporting Services	Involvement in nutrient cycles (N, P, C)	Cultivation method, infrastructure and gear used, and farming input; Local and regional hydrodynamics; Depth or elevation of cultivation; Benthic sediment type—sediment stability and nutrient absorption capacity; Water quality and chemistry parameters and ranges (e.g., pH, dissolved oxygen, nitrogen, phosphorus, carbon dioxide, and turbidity); Benthic habitat type (e.g., baskets, bags or rack oyster culture); Water temperature and salinity ranges; Weather patterns (e.g., rainfall, prevailing wind direction); Distance between and density of aquaculture operations; Distance from and discharge magnitude of nutrient and pollutant sources; Solar irradiance	Stocking density of species; Coculture and interaction with multiple species; Benthic habitat type; Benthic community structure and biodiversity; Pathogen dissemination pathways; Marine pest presence and dissemination pathways; Phytoplankton availability	Nutrient status of ecosystem (e.g., oligotrophic, eutrophic); Additional anthropogenic inputs (e.g., land-based runoff, estuarine or delta inputs); Water temperature and salinity Ranges; Weather patterns (e.g., rainfall, prevailing wind direction); Vulnerability to climate-related disturbances; Solar irradiance	Culture of endemic or naturalised species; Population status of existing wild harvest resources; Conservation status of existing coastal habitat and biodiversity
	Plankton production				
	Biodiversity protection				
	Coastal protection				
	Refuge areas for wild species				
	Reproduction areas for wild species				
Regulating Services	Climate regulation				
	Hydrodynamic regulations				
	Protection from erosion				
	Wave submersion				
	Sediment regulation				
	Nutrient regulation				
Provisioning Services	Seafood				
	Nutraceuticals				
	Fertilisers				
	Fibers				
	Raw materials				
	Biofuels, combustible materials				
Cultural Services	Preserving traditional practices				
	Preserving religious practices				
	Sentimental value				
	Source of knowledge				
	Sentinel role				
	Source of environment education				
	Seascape quality				
	Ecotourism, recreational services, leisure				

3.5. Aquaculture in the Context of UN Goals

Aquaculture is increasingly being discussed as a potential contributor to multiple Sustainable Development Goals (SDGs) [1,107,108]. However, its contribution should not be considered positive in all cases; rather, it depends on system design, governance and the local environmental context [1,109]. From this perspective, the concept of aquaculture as "blue infrastructure" is useful for framing its multifunctional role, although its implementation remains uneven and context-specific. The alignment of aquaculture with the SDGs is fully consistent with Cluster 1 and Emerging Cluster 1 (Tables 1–4 and Figure 2), which integrates environmental sustainability, climate resilience, ecosystem services, and environmental protection. These terms form the backbone of the global governance and sustainability discourse, confirming the strategic relevance of aquaculture to achieving the 2030 Agenda.

Aquaculture may help create direct and indirect benefits for people, and when planned, designed, and managed within the framework of blue infrastructure it may contribute to such achievements:

- Zero Hunger (SDG 2) and Good Health and Well-Being (SDG 3): The "provisioning services" of aquaculture systems may maintain food security through the direct provision of seafood and nutritious food essential for human health and indirectly through the provision of raw materials for the food industry, such as medical resources for the health industry and others, e.g., substrates for restoration, the cosmetics industry, pharmaceuticals, texturants, agar and biofuel. Aquaculture can meet the growing demand for seafood due to population growth while reducing negative impacts on fish stocks in natural habitats [87,89,90,117]. However, the nutritional and environmental benefits can vary significantly across regions depending on species selection, feed composition, and production practices [1,14,108].
- Gender Equality (SDG 5): The "cultural services" of aquaculture may be linked to the development of an inclusive business model to increase social cohesion and equality between male and female workers [90,118,119]. Nevertheless, evidence on gender equity outcomes remains inconsistent, with benefits often influenced by local socioeconomic conditions, access to resources and governance frameworks [1,126].
- Clean Water and Sanitation (SDG 6): The "regulating services" of aquaculture systems may support nutrient cycling of water; indeed, aquaculture can involve marine bivalves and algae, which benefit from the environment by absorbing organic matter, including waste from foraged species, thus removing the organic matter and other particulates and reducing nutrient loads in the water (e.g., nitrogen, phosphate, and carbon). By reducing excess anthropogenic nutrients, the mariculture of shellfish and algae can combat eutrophication [95,100,104,115,118,127–133]. However, these benefits depend on the scale of the system, the hydrodynamics and the background nutrient levels. In some cases, aquaculture can also contribute to localised pollution if it is not managed properly [109,134].
- Decent Work and Economic Growth (SDG 8) and Industry, Innovation, and Infrastructure (SDG 9): The "provisioning and cultural services" of aquaculture systems can support economic growth with livelihood production and social development through the creation of employment opportunities in a sustainable manner. Aquaculture can provide income for small farmers at the local level in rural and coastal communities in different countries and contribute to poverty reduction at the global level, as it can be applied in different environmental conditions and for the extraction of specific commodities in the industrial sectors. Ecotourism is a specific activity linked to the rising seafood industry that is useful in sustaining local community identity in disadvantaged and impoverished communities [87,89,95,104,135,136]. However, the distribution of economic benefits is not uniform and may be limited by factors such as market access, capital requirements and governance structures [14,107,137].
- Sustainable Cities and Communities (SDG 11): The "provisioning and regulating services" of aquaculture systems can contribute to sustainable urban growth by providing a local and environmentally friendly source of food. It supports the development of resilient and sustainable seafood chain systems in cities reducing the need for long-distance transportation. Moreover, aquaculture design in terms of blue infrastructure for water cleaning can contribute to reducing the urban pollutants, increasing urban biodiversity [95,104,127]. Nevertheless, to avoid conflicts with other land and water uses and ensure net environmental benefits, urban aquaculture systems require careful spatial planning and resource management [109,138].

- Responsible Consumption and Production (SDG 12) and Climate Action (SDG 13): The "regulating services" of aquaculture systems can reduce environmental impacts and contribute to climate change mitigation efforts. Multifunctional application of aquaculture can generate integrated multitrophic aquaculture systems that can utilise nutrient-rich waste from one species to fertilise another, reducing pollution and greenhouse gas emissions. Moreover, by influencing carbon cycling, the cultivation of algae and bivalves can play an important role in carbon sequestration; therefore, an aquaculture system can represent a strong carbon sink or stock, contributing to reducing carbon dioxide in the atmosphere and mitigating climate change [87,89,95,101,115,118,127,135]. However, the extent of these mitigation benefits remains uncertain and depends on life cycle assessments, system design and wider environmental interactions [14,111,112,139].
- Life Below Water (SDG 14): The "provisioning services" of aquaculture systems may contribute to the conservation and sustainable use of marine and aquatic ecosystems. They can help reduce overfishing and habitat destruction by offering an alternative to wild-caught seafood. Moreover, well-planned and -designed aquaculture systems can be applied as strategies for the restoration of marine habitats that have been destroyed [89,90,95,104,117,128,129,131]. However, if aquaculture is not managed properly, it can put pressure on marine ecosystems. This can include altering habitats, spreading diseases and cultivated species interacting genetically with wild populations [14,140].
- Partnerships for the Goals (SDG17): The "regulating, provisioning and cultural services" of aquaculture may be combined to develop integration between marine conservation strategies, climate strategies and coastal management and the planning and design of aquaculture operations at local and global levels. Payment for ecosystem services is a policy incentive tool that provides economic benefits for actions designed to increase the provision of ecosystem services in a given location at the local or regional level [88,141] and can be applied to sustainable aquaculture that favours human well-being. This strategy can drive the realisation of blue infrastructure to conserve biodiversity and increase seafood stocks while minimising environmental impacts, involving private and public stakeholders [89,95,104,142]. Nevertheless, the effectiveness of such policy instruments hinges on governance capacity, stakeholder coordination, and robust monitoring and evaluation frameworks [1,125].

Connections between aquaculture systems and UN Goals can be achieved over time with the growth of sustainable and responsible aquaculture practices that depend on proper environmental management, social responsibility, adherence to regulatory frameworks, and the development of new biological and engineering applications. Therefore, rather than assuming universal contributions, it is crucial to evaluate aquaculture systems using context-specific, evidence-based assessments that consider the benefits and trade-offs across multiple SDGs [14,107–109].

4. Perspectives

The development of the sector will increasingly face a series of challenges requiring integrated approaches and informed decision-making. On the one hand, the trade-off between production intensification and environmental sustainability requires a careful balance to be struck between efficiency, ecosystem protection and animal welfare [90,142,143]. On the other hand, adapting to climate change will become increasingly important in terms of both production resilience and the mitigation of environmental impacts [144]. Additionally, growing competition for limited resources such as water, land and space will demand managerial innovations and more strategic territorial planning [145,146]. Finally, social acceptability and consumer perception introduce an additional layer of complexity: transparency, traceability and scientifically grounded communication are key to building trust and guiding choices towards more responsible, widely adopted production models [147,148].

Integrating life cycle assessment (LCA), advanced traceability and certification systems, and artificial intelligence (AI) tools is key to systematically improving the production performance and environmental, social and economic sustainability of aquaculture systems [7,149,150]. The LCA approach, developed in accordance with ISO 14040/14044 standards [151], makes it possible to quantify the environmental impact of aquaculture systems across their entire life cycle, from feed production and the grow-out phase to processing and distribution. This allows the main "hotspots" in terms of water consumption, energy use, greenhouse gas emissions and nutrient release to be identified [110,152,153]. Recent studies demonstrate that applying LCA to aquaculture facilitates the transition to more efficient production models by enabling improvements in feed formulations and reducing losses throughout the supply chain [154,155]. In parallel, the adoption of digital traceability systems and blockchain technologies, as well as voluntary certification schemes such as ASC, Global G.A.P. and Friend of the Sea, strengthens supply-chain transparency and governance. It also reduces sanitary risks, promotes responsible farming practices and facilitates the international market recognition of sustainable products [156–159]. Certifications also foster convergence between life cycle assessment (LCA) evaluations and socioeconomic indicators, contributing to the development of integrated metrics for monitoring the environmental, social and governance (ESG) performance of aquaculture companies [160,161].

The Sustainable Development Goals also address three emerging issues (Tables 1–4 and Figure 3) which are important for maintaining environmental sustainability, climate resilience, ecosystem services and environmental protection.

Manuscript Section	Structural Cluster (Table 3)	Emerging Cluster (Table 4)	Representative Keywords (2025–2026)	Macro-Theme
3.5 Aquaculture and the UN Goals	Cluster 1	Cluster 1	environmental sustainability; climate resilience; ecosystem services	Sustainability governance, SDG alignment
Digitalization and AI in aquaculture *(NEW)*	Cluster 5	Cluster 3	deep learning; artificial intelligence; data mining; computer vision; digital transformation; decision support systems	AI-enabled aquaculture, automation, precision monitoring
Biosecurity and environmental risk (beyond antibiotics) *(NEW)*	Clusters 2 & 1	Cluster 2	biosecurity; environmental risk; environmental monitoring; disease detection; ecosystem health	Holistic biosecurity, environmental risk management
Blue food systems and food security *(NEW)*	Cluster 1	Cluster 1	blue food; food production; food safety; food quality; environmental sustainability	Blue food systems, global nutrition, sustainable protein supply

Figure 3. Emerging issues in eco-sustainable aquaculture.

The increasing digitalisation of the supply chain allows these instruments to be integrated with AI- and machine learning-based solutions and IoT sensor systems. These systems enable real-time monitoring of farming parameters, the early diagnosis of stress and diseases, the optimisation of feeding practices, and the predictive management of water quality [162–164]. These systems help to reduce feed waste and energy inputs, lower antibiotic use and improve animal welfare, thereby generating synergistic effects on productivity and the environmental footprint [110,153]. Integrating data from sensors, digital twins and decision-support platforms further facilitates the alignment of operational indicators and LCA metrics. This enables data-driven management models and circular economy approaches in RAS, offshore and IMTA systems [101,114,115].

The convergence of life cycle assessment (LCA), traceability and certification systems, and artificial intelligence (AI) is giving rise to a new generation of intelligent, transparent, and low-emission aquaculture systems. These systems are capable of supporting business competitiveness, protecting ecosystems, and aligning with the principles of the blue economy, as well as with European and international policies on the ecosystem-based management of aquatic resources [100,102,165]. Certain emerging issues concerning biosecurity and food systems require separate consideration. Future biosecurity strategies will increasingly adopt a "One Health" approach, integrating disease prevention, environmental monitoring, and ecosystem management. The real challenge will be to shift from reactive measures to preventive, system-based risk management supported by continuous monitoring technologies and standardised global protocols. Effective management of cross-border environmental risks will require strengthened international cooperation. A key future direction will be developing inclusive and resilient value chains that improve access to blue foods, particularly in vulnerable regions, thereby promoting food security and justice. This will require integrated policy frameworks and stronger links between local production systems and global markets.

5. Conclusions

This review has spanned from sustainability and innovation processes in aquaculture to antibiotics control and aquaculture ecosystem services. All of these represent highly relevant and trendy topics in aquaculture, but taken individually they fail to fully reveal the potential of aquaculture and related aquatic technologies. For example, there are several eco-friendly and sustainable tools to contrast the development of diseases in aquaculture environments that are currently available. However, the need for strict regulation, possibly uniform across countries, regarding the prudent and conscious use of antibiotics (which represent a fragile resource) cannot be underestimated. According to the principles of the One Health strategy, the antibiotic resistance issue must be faced holistically, considering aquatic systems as strictly interconnected with food security and human and environmental health. When analysing aquaculture not only as a system for the production of high amounts of animal protein for human consumption but as a multitrophic, multispecies eco-based system that aims to be integrated under the keyword sustainability, the very perception of the impact of aquaculture itself changes significantly and this human production activity becomes part of a comprehensive system of environmental problem eco-solutions rather than a problem itself. Again, the possibilities are many, but limitations due to local politics, i.e., different countries having different regulations, will reduce the effect of the ecological approach in aquaculture. In this respect, aquaculture can be used to remove environmental challenges, not necessarily producing food for humans at the same time. Utilising the products of aquaculture in the direction of biotechnology might be an option for the valorisation of the whole production sector.

In a wider perspective, aquaculture has the potential to contribute significantly to human and planetary well-being when aligned with the SDGs. It plays a crucial role in achieving most if not all of the 17 SDGs, but its impact cannot be limited to eliminating hunger, improving health, increasing environmental sustainability, and reducing poverty. Better linkages between aquaculture, health, the food system, and natural resource management policy are required for greater impact. Integrating land- and ocean-based aquaculture with renewable energy and agricultural systems is also essential to accelerate its contributions. Key institutions should monitor aquaculture SDG indicators and develop new tools to capture wider benefits.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/environments13040208/s1: Figure S1: VOSviewer keyword co-occurrence maps for sustainable aquaculture research (2020–2026 vs. 2022–2026 data); Dataset (S1a, S1b, S1c, S2, S3, S4), Table S1: VOSviewer bibliometric workflow.

Author Contributions: Conceptualisation, A.C.; methodology, T.S.; software, T.S.; validation, A.C., T.V. and T.S.; formal analysis, T.S.; investigation, A.C.; resources, F.D.; data curation, A.C.; writing—original draft preparation, A.C., E.G. and T.S.; writing—review and editing, A.C., T.V., D.G., F.D. and T.S.;

visualisation, A.C.; supervision, F.D.; project administration, T.V. and F.D.; funding acquisition, T.V., T.S. and F.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the PON Ricerca e Innovazione 2014–2020 project, grant number ARS01_01053—"Remote, Intelligent & Sustainable aquaculturE system for Fish" (Fish-RISE). The publication was also supported by EU—Next Generation EU Mission 4 "Education and Research"—Component 2: "From research to business"—Investment 3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures"—Project IR0000032—ITINERIS—Italian Integrated Environmental Research Infrastructures System—CUP B53C22002150006.

Data Availability Statement: No new data were created or analyzed in this study.

Acknowledgments: The authors acknowledge the research infrastructures participating in the ITINERIS project with their Italian nodes: ACTRIS, ANAEE, ATLaS, CeTRA, DANUBIUS, DISSCO, e-LTER, ECORD, EMPHASIS, EMSO, EUFAR, Euro-Argo, EuroFleets, Geoscience, IBISBA, ICOS, JERICO, LIFEWATCH, LNS, N/R Laura Bassi, SIOS, SMINO.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. FAO. *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*; FAO: Rome, Italy, 2024.
2. Boyd, C.E.; D'Abramo, L.R.; Glencross, B.D.; Huyben, D.C.; Juarez, L.M.; Lockwood, G.S.; McNevin, A.A.; Tacon, A.G.J.; Teletchea, F.; Tomasso, J.R., Jr.; et al. Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *J. World Aquac. Soc.* **2020**, *51*, 578–633. [CrossRef]
3. Subasinghe, R.; Soto, D.; Jia, J. Global aquaculture and its role in sustainable development. *Rev. Aquac.* **2009**, *1*, 2–9. [CrossRef]
4. Cantillo, J.; Martín, J.C.; Román, C. Determinants of fishery and aquaculture products consumption at home in the EU28. *Food Qual. Prefer.* **2021**, *88*, 104085. [CrossRef]
5. Banovic, M.; Reinders, M.J.; Claret, A.; Guerrero, L.; Krystallis, A. A cross-cultural perspective on impact of health and nutrition claims, country-of-origin and eco-label on consumer choice of new aquaculture products. *Food Res. Int.* **2019**, *123*, 36–47. [CrossRef]
6. Pazmiño, M.L.; Chico-Santamarta, L.; Boero, A.; Ramirez, A.D. Environmental life cycle assessment and potential improvement measures in the shrimp and prawn aquaculture sector: A literature review. *Aquac. Fish.* **2025**, *10*, 183–201. [CrossRef]
7. Chambers, P. Standard methods for the examination of water and wastewater. In *Scientific e-Resources*; ED-Tech Press: Waltham Abbey, UK, 2019; pp. 8–34.
8. Watanabe, W.O.; Alam, M.S.; Carroll, P.M.; Daniels, H.V.; Hinshaw, J.M. Marine finfish aquaculture. In *Aquaculture: Farming Aquatic Animals and Plants*; Lucas, J.S., Southgate, P.C., Tucker, C.S., Eds.; John Wiley and Sons: Hoboken, NJ, USA, 2019; pp. 437–482.
9. Lall, S.P.; Tibbetts, S.M. Nutrition, feeding, and behavior of fish. *Vet. Clin. N. Am. Exot. Anim. Pract.* **2009**, *12*, 361–372. [CrossRef]
10. Clavelle, T.; Lester, S.E.; Gentry, R.; Froehlich, H.E. Interactions and management for the future of marine aquaculture and capture fisheries. *Fish Fish.* **2019**, *20*, 368–388. [CrossRef]
11. Altaff, K. Indigenous live feed for aqua hatchery larval rearing of finfish and shellfish: A review. *Int. J. Zool. Investig.* **2020**, *6*, 162–173. [CrossRef]
12. Hernroth, B.E.; Baden, S.P. Alteration of host-pathogen interactions in the wake of climate change-increasing risk for shellfish associated infections? *Environ. Res.* **2018**, *161*, 425–438. [CrossRef] [PubMed]
13. Thomas, M.; Pasquet, A.; Aubin, J.; Nahon, S.; Lecocq, T. When more is more: Taking advantage of species diversity to move towards sustainable aquaculture. *Biol. Rev. Camb. Philos. Soc.* **2021**, *96*, 767–784. [CrossRef] [PubMed]
14. Naylor, R.L.; Hardy, R.W.; Buschmann, A.H.; Bush, S.R.; Cao, L.; Klinger, D.H.; Little, D.C.; Lubchenco, J.; Shumway, S.E.; Troell, M. A 20-year retrospective review of global aquaculture. *Nature* **2021**, *591*, 551–563. [CrossRef]
15. Martinez-Cordova, L.R.; López-Elías, J.; Martinez-Porchas, M.; Bringas-Burgos, B.; Naranjo-Paramo, J. A preliminary evaluation of an integrated aquaculture-agriculture systems (tilapia and peppers) at mesocosm scale. *J. Aquac. Mar. Biol.* **2020**, *9*, 19–22. [CrossRef]
16. Mordenti, O.; Casalini, A.; Mandelli, M.; Di Biase, A. A closed recirculating aquaculture system for artificial seed production of the European eel (*Anguilla anguilla*): Technology development for spontaneous spawning and eggs incubation. *Aquac. Eng.* **2014**, *58*, 88–94. [CrossRef]
17. Luiz, D.d.B.; Kato, H.d.A.; Schneider, M.; dos Santos, V.R.V.; Moreira, R.d.F.P.M. Technological approaches to enhance water efficiency in aquaculture: Aiming towards sustainable intensification. *Aquac. Eng.* **2026**, *113*, 102679. [CrossRef]

18. Ruiz-Vanoye, J.A.; Diaz-Parra, O.; Márquez Vera, M.A.; Fuentes-Penna, A.; Barrera-Cámara, R.A.; Ruiz-Jaimes, M.A.; Toledo-Navarro, Y.; Bernábe-Loranca, M.B.; Simancas-Acevedo, E.; Trejo-Macotela, F.R.; et al. A Comprehensive Review of Quality of Aquaculture Services in Integrated Multi-Trophic Systems. *Fishes* **2025**, *10*, 54. [CrossRef]
19. Goda, A.M.A.S.; Mohammady, E.Y.; Aboseif, A.M.; Aboushabana, N.M.; Helal, A.M.; Abdelaty, B.S.; Ashour, M.; El-Haroun, E. Comparative socioeconomic, environmental and technical analysis of conventional versus smart sustainable integrated multi-trophic aquaponics systems. *Sci. Rep.* **2025**, *15*, 39414. [CrossRef]
20. Grandez-Yoplac, D.E.; Pachas-Caycho, M.; Cristobal, J.; Chapa-Gonza, S.; Mori-Zabarburu, R.C.; Guadalupe, G.A. Recirculating Aquaculture Systems (RAS) for Cultivating ncorhynchus mykiss and the Potential for IoT Integration: A Systematic Review and Bibliometric Analysis. *Sustainability* **2025**, *17*, 6729. [CrossRef]
21. Mihailov, S. Integrated Multi-Trophic Aquaculture in freshwater and marine contexts: Opportunities for circular economy. *Anim. Sci. Biotechnol.* **2025**, *58*, 2.
22. Haque, M.M.; Mahmud, N. Potential Role of Aquaculture in Advancing Sustainable Development Goals (SDGs) in Bangladesh. *Aquac. Res.* **2025**, *2025*, 6035730. [CrossRef]
23. Lounas, R.; Kasmi, H.; Chernai, S.; Amarni, N.; Ghebriout, L.; Meslem-Haoui, N.; Hamdi, B. Towards sustainable mariculture: Some global trends. *Thalass. Int. J. Mar. Sci.* **2020**, *36*, 447–456. [CrossRef]
24. Oyinlola, M.A.; Reygondeau, G.; Wabnitz, C.C.; Troell, M.; Cheung, W.W. Global estimation of areas with suitable environmental conditions for mariculture species. *PLoS ONE* **2018**, *13*, e0191086. [CrossRef]
25. Rajee, O.; Alicia, T.K.M. Biotechnological application in aquaculture and its sustainability constraints. *Int. J. Adv. Biotechnol. Res.* **2019**, *10*, 1.
26. Lennard, W.; Goddek, S. Aquaponics: The basics. In *Aquaponics Food Production Systems*; Goddek, S., Kotzen, B., Joyce, A., Burnell, G.M., Eds.; Springer: Cham, Switzerland, 2019; pp. 113–143.
27. Okomoda, V.T.; Oladimeji, S.A.; Solomon, S.G.; Olufeagba, S.O.; Ogah, S.I.; Ikhwanuddin, M. Aquaponics production system: A review of historical perspective, opportunities, and challenges of its adoption. *Food Sci. Nutr.* **2022**, *11*, 1157–1165. [CrossRef]
28. Rakocy, J.E. Aquaponics-integrating fish and plant culture. In *Aquaculture Production Systems*; Tidwell, J.H., Ed.; John Wiley & Sons: Oxford, UK, 2012; pp. 344–386. [CrossRef]
29. Schneider, P.; Rochell, V.; Plat, K.; Jaworski, A. Circular Approaches in Small-Scale Food Production. *Circ. Econ. Sustain.* **2021**, *1*, 1231–1255. [CrossRef]
30. Palm, H.W.; Knaus, U.; Appelbaum, S.; Goddek, S.; Strauch, S.M.; Vermeulen, T.; Jijakli, M.H.; Kotzen, B. Towards commercial aquaponics: A review of systems, designs, scales and nomenclature. *Aquac. Int.* **2018**, *26*, 813–842. [CrossRef]
31. Wei, Y.; Li, W.; An, D.; Li, D.; Jiao, Y.; Wei, Q. Equipment and intelligent control system in aquaponics: A review. *IEEE Access* **2019**, *7*, 169306–169326. [CrossRef]
32. Greenfeld, A.; Becker, N.; Bornman, J.F.; Spatari, S.; Angel, D.L. Is aquaponics good for the environment?—Evaluation of environmental impact through life cycle assessment studies on aquaponics systems. *Aquac. Int.* **2022**, *30*, 305–322. [CrossRef]
33. Chen, J.; Sun, R.; Pan, C.; Sun, Y.; Mai, B.; Li, Q.X. Antibiotics and food safety in aquaculture. *J. Agric. Food Chem.* **2020**, *68*, 11908–11919. [CrossRef] [PubMed]
34. Odoemena, K.I.; Rowshon, M.D.K.; Binti, H.C.M. Advances in utilization of wastewater in agricultural practice: A technical note. *Irrig. Drain.* **2020**, *69*, 149–163. [CrossRef]
35. Ahmad, A.L.; Chin, J.Y.; Harun, M.H.Z.M.; Low, S.C. Environmental impacts and imperative technologies towards sustainable treatment of aquaculture wastewater: A review. *J. Water Process Eng.* **2022**, *46*, 102553. [CrossRef]
36. Tom, A.P.; Jayakumar, J.S.; Biju, M.; Somarajan, J.; Ibrahim, M.A. Aquaculture wastewater treatment technologies and their sustainability: A review. *Energy Nexus* **2021**, *4*, 100022. [CrossRef]
37. Neori, A.; Chopin, T.; Troell, M.; Buschmann, A.H.; Kraemer, G.P.; Halling, C.; Shpigel, M.; Yarish, C. Integrated aquaculture: Rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture* **2004**, *231*, 361–391. [CrossRef]
38. Frei, M.; Becker, K. Integrated rice-fish culture: Coupled production saves resources. *Nat. Resour. Forum* **2005**, *29*, 135–143. [CrossRef]
39. Lulijwa, R.; Rupia, E.J.; Alfaro, A.C. Antibiotic use in aquaculture, policies and regulation, health and environmental risks: A review of the top 15 major producers. *Rev. Aquac.* **2020**, *12*, 640–663. [CrossRef]
40. Yuan, X.; Lv, Z.; Zhang, Z.; Han, Y.; Liu, Z.; Zhang, H. A Review of Antibiotics, Antibiotic Resistant Bacteria, and Resistance Genes in Aquaculture: Occurrence, Contamination, and Transmission. *Toxics* **2023**, *11*, 420. [CrossRef]
41. Glibert, P.M.; Wilkerson, F.P.; Dugdale, R.C.; Raven, J.A.; Dupont, C.L.; Leavitt, P.R.; Parker, A.E.; Burkholder, J.A.M.; Kana, T.M. Pluses and minuses of ammonium and nitrate uptake and assimilation by phytoplankton and implications for productivity and community composition, with emphasis on nitrogen-enriched conditions. *Limnol. Oceanogr.* **2016**, *61*, 165–197. [CrossRef]

42. Nhu, D.T.; Hoang, Y.N.T.; Lieu, P.K.; Harada, H.; Brion, N.; Hieu, D.V.; Van Hop, N.; Venterink, H.O. Effects of nutrient supply and nutrient ratio on diversity–productivity relationships of phytoplankton in the Cau Hai lagoon, Vietnam. *Ecol. Evol.* **2019**, *9*, 5950–5962. [CrossRef]
43. Zohdi, E.; Abbaspour, M. Harmful algal blooms (red tide): A review of causes, impacts and approaches to monitoring and prediction. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 1789–1806. [CrossRef]
44. Ingrao, C.; Faccilongo, N.; Di Gioia, L.; Messineo, A. Food waste recovery into energy in a circular economy perspective: A comprehensive review of aspects related to plant operation and environmental assessment. *J. Clean. Prod.* **2018**, *184*, 869–892. [CrossRef]
45. Araújo, R.; Vázquez Calderón, F.; Sánchez López, J.; Azevedo, I.C.; Bruhn, A.; Fluch, S.; Garcia, T.M.; Ghaderiardakani, F.; Ilmjärv, T.; Laurans, M.; et al. Current status of the algae production industry in Europe: An emerging sector of the blue bioeconomy. *Front. Mar. Sci.* **2021**, *7*, 626389. [CrossRef]
46. García-Poza, S.; Leandro, A.; Cotas, C.; Cotas, J.; Marques, J.C.; Pereira, L.; Gonçalves, A.M. The evolution road of seaweed aquaculture: Cultivation technologies and the industry 4.0. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6528. [CrossRef] [PubMed]
47. Yarnold, J.; Karan, H.; Oey, M.; Hankamer, B. Microalgal aquafeeds as part of a circular bioeconomy. *Trends Plant Sci.* **2019**, *24*, 959–970. [CrossRef]
48. Das, P.; Mandal, S.C.; Bhagabati, S.K.; Akhtar, M.S.; Singh, S.K. Important live food organisms and their role in aquaculture. In *Frontiers in Aquaculture*; Sundaray, J.K., Sukham, M., Mohanty, R.K., Otta, S.K., Eds.; Narendra Publishing House: New Delhi, India, 2012; pp. 69–86.
49. Prabu, E.; Felix, S.; Felix, N.; Ahilan, B.; Ruby, P. An overview on significance of fish nutrition in aquaculture industry. *Int. J. Fish. Aquat. Stud.* **2017**, *5*, 349–355.
50. De Silva, S.S.; Anderson, T.A. *Fish Nutrition in Aquaculture*; Chapman & Hall: London, UK, 1995.
51. FAO (United Nations Food and Agriculture Organization). *The Production of Fishmeal and Oil*; FAO Fisheries Technical Paper No. 142; FAO: Rome, Italy, 1986.
52. Fiorentino, F.; Vitale, S. How can we reduce the overexploitation of the Mediterranean resources? *Front. Mar. Sci.* **2021**, *8*, 674633. [CrossRef]
53. Hossain, A.; Habibullah-Al-Mamun, M.; Nagano, I.; Masunaga, S.; Kitazawa, D.; Matsuda, H. Antibiotics, antibiotic-resistant bacteria, and resistance genes in aquaculture: Risks, current concern, and future thinking. *Environ. Sci. Pollut. Res. Int.* **2022**, *29*, 11054–11075. [CrossRef]
54. Schar, D.; Klein, E.Y.; Laxminarayan, R.; Gilbert, M.; Van Boeckel, T.P. Global trends in antimicrobial use in aquaculture. *Sci. Rep.* **2020**, *10*, 21878. [CrossRef]
55. Liu, X.; Steele, J.; Meng, X. Usage, residue, and human health risk of antibiotics in Chinese aquaculture: A review. *Environ. Pollut.* **2017**, *223*, 161–169. [CrossRef] [PubMed]
56. Mo, W.Y.; Chen, Z.; Leung, H.M.; Leung, A.O. Application of veterinary antibiotics in China's aquaculture industry and their potential human health risks. *Environ. Sci. Pollut. Res. Int.* **2017**, *24*, 8978–8989. [CrossRef]
57. Watts, J.E.; Schreier, H.J.; Lanska, L.; Hale, M.S. The rising tide of antimicrobial resistance in aquaculture: Sources, sinks and solutions. *Mar. Drugs* **2017**, *15*, 158. [CrossRef]
58. Monteiro, S.H.; Andrade, G.C.; Garcia, F.; Pilarski, F. Antibiotic Residues and Resistant Bacteria in Aquaculture. *Pharm. Chem. J.* **2018**, *5*, 127–147.
59. Bondad-Reantaso, M.G.; MacKinnon, B.; Karunasagar, I.; Fridman, S.; Alday-Sanz, V.; Brun, E.; Le Groumellec, M.; Li, A.; Surachetpong, W.; Karunasagar, I.; et al. Review of alternatives to antibiotic use in aquaculture. *Rev. Aquac.* **2023**, *15*, 1421–1451. [CrossRef]
60. Ma, J.; Bruce, T.J.; Jones, E.M.; Cain, K.D. A Review of Fish Vaccine Development Strategies: Conventional Methods and Modern Biotechnological Approaches. *Microorganisms* **2019**, *7*, 569. [CrossRef] [PubMed]
61. Mondal, H.; Thomas, J.A. Review on the recent advances and application of vaccines against fish pathogens in aquaculture. *Aquac. Int.* **2022**, *30*, 1971–2000. [CrossRef] [PubMed]
62. Du, Y.; Hu, X.; Miao, L.; Chen, J. Current status and development prospects of aquatic vaccines. *Front. Immunol.* **2022**, *13*, 1040336. [CrossRef]
63. Ramos-Vivas, J.; Superio, J.; Galindo-Villegas, J.; Acosta, F. Phage Therapy as a Focused Management Strategy in Aquaculture. *Int. J. Mol. Sci.* **2021**, *22*, 10436. [CrossRef]
64. Silva, Y.J.; Costa, L.; Pereira, C.; Mateus, C.; Cunha, A.; Calado, R.; Gomes, N.C.; Pardo, M.A.; Hernandez, I.; Almeida, A. Phage therapy as an approach to prevent *Vibrio anguillarum* infections in fish larvae production. *PLoS ONE* **2014**, *9*, e114197. [CrossRef]
65. Fauconnier, A. Phage Therapy Regulation: From Night to Dawn. *Viruses* **2019**, *11*, 352. [CrossRef]
66. Liu, R.; Han, G.; Li, Z.; Cun, S.; Hao, B.; Zhang, J.; Liu, X. Bacteriophage therapy in aquaculture: Current status and future challenges. *Folia Microbiol.* **2022**, *67*, 573–590. [CrossRef]

67. Gupta, D.S.; Kumar, M.S. The implications of quorum sensing inhibition in bacterial antibiotic resistance-with a special focus on aquaculture. *J. Microbiol. Meth.* **2022**, *203*, 106602. [CrossRef]
68. Jayaprakashvel, M.; Subramani, R. Implications of Quorum Sensing and Quorum Quenching in Aquaculture Health Management. In *Implication of Quorum Sensing and Biofilm Formation in Medicine, Agriculture and Food Industry*; Bramhachari, P., Ed.; Springer: Singapore, 2019; pp. 299–312.
69. Zhao, J.; Chen, M.; Quan, C.S.; Fan, S.D. Mechanisms of quorum sensing and strategies for quorum sensing disruption in aquaculture pathogens. *J. Fish Dis.* **2015**, *38*, 771–786. [CrossRef] [PubMed]
70. Shaheer, P.; Sreejith, V.N.; Joseph, T.C.; Murugadas, V.; Lalitha, K.V. Quorum quenching *Bacillus* spp.: An alternative biocontrol agent for *Vibrio harveyi* infection in aquaculture. *Dis. Aquat. Organ.* **2021**, *146*, 117–128. [CrossRef]
71. Chauhan, A.; Singh, R. Probiotics in aquaculture: A promising emerging alternative approach. *Symbiosis* **2019**, *77*, 99–113. [CrossRef]
72. El-Saadony, M.T.; Alagawany, M.; Patra, A.K.; Kar, I.; Tiwari, R.; Dawood, M.A.O.; Dhama, K.; Abdel-Latif, H.M.R. The functionality of probiotics in aquaculture: An overview. *Fish Shellfish Immunol.* **2021**, *117*, 36–52. [CrossRef]
73. Hoseinifar, S.H.; Sun, Y.Z.; Wang, A.; Zhou, Z. Probiotics as Means of Diseases Control in Aquaculture, a Review of Current Knowledge and Future Perspectives. *Front. Microbiol.* **2018**, *9*, 2429. [CrossRef]
74. Goh, J.X.; Tan, L.T.; Law, J.W.; Ser, H.L.; Khaw, K.Y.; Letchumanan, V.; Lee, L.H.; Goh, B.H. Harnessing the potentialities of probiotics, prebiotics, synbiotics, paraprobiotics, and postbiotics for shrimp farming. *Rev. Aquacul.* **2022**, *14*, 1478–1557. [CrossRef]
75. Wee, W.; Abdul Hamid, N.K.; Mat, K.; Ili, R.; Khalif, A.R.; Rusli, N.D.; Rahman, M.M.; Kabir, M.A.; Wei, L.S. The effects of mixed prebiotics in aquaculture: A review. *Aquacul. Fish.* **2022**, *9*, 28–34. [CrossRef]
76. Cotter, P.D.; Ross, R.P.; Hill, C. Bacteriocins—A viable alternative to antibiotics? *Nat. Rev. Microbiol.* **2013**, *11*, 95–105. [CrossRef] [PubMed]
77. Nayak, A.; Karunasagar, I.; Chakraborty, A. Potential application of bacteriocins for sustainable aquaculture. *Rev. Aquacul.* **2022**, *14*, 1234–1248. [CrossRef]
78. Wang, J.; Zhang, S.; Ouyang, Y.; Li, R. Current developments of bacteriocins, screening methods and their application in aquaculture and aquatic products. *Biocatal. Agric. Biotechnol.* **2019**, *22*, 101395. [CrossRef]
79. Rahimi, N.N.M.N.; Natrah, I.; Loh, J.Y.; Ervin Ranzil, F.K.; Gina, M.; Lim, S.E.; Lai, K.S.; Chong, C.M. Phytocompounds as an Alternative Antimicrobial Approach in Aquaculture. *Antibiotics* **2022**, *11*, 469. [CrossRef] [PubMed]
80. Reverter, M.; Reverter, M.; Bontemps, N.; Lecchini, D.; Banaigs, B.; Sasal, P. Use of plant extracts in fish aquaculture as an alternative to chemotherapy: Current status and future perspectives. *Aquaculture* **2014**, *433*, 50–61. [CrossRef]
81. Okeke, E.S.; Chukwudozie, K.I.; Nyaruaba, R.; Ita, R.E.; Oladipo, A.; Ejeromedoghene, O.; Atakpa, E.O.; Agu, C.V.; Okoye, C.O. Antibiotic resistance in aquaculture and aquatic organisms: A review of current nanotechnology applications for sustainable management. *Environ. Sci. Pollut. Res.* **2022**, *29*, 69241–69274. [CrossRef]
82. Fajardo, C.; Martinez-Rodriguez, G.; Blasco, J.; Mancera, J.M.; Thomas, B.; De Donato, M. Nanotechnology in aquaculture: Applications, perspectives and regulatory challenges. *Aquacult. Fish.* **2022**, *7*, 185–200. [CrossRef]
83. Hetta, H.F.; Ramadan, Y.N.; Al-Harbi, A.I.; Ahmed, E.A.; Battah, B.; Abd Ellah, N.H.; Zanetti, S.; Donadu, M.G. Nanotechnology as a Promising Approach to Combat Multidrug Resistant Bacteria: A Comprehensive Review and Future Perspectives. *Biomedicines* **2023**, *11*, 413. [CrossRef]
84. Agarwal, A.; Ng, W.J.; Liu, Y. Principle and applications of microbubble and nanobubble technology for water treatment. *Chemosphere* **2011**, *84*, 1175–1180. [CrossRef]
85. Ebina, K.; Shi, K.; Hirao, M.; Hashimoto, J.; Kawato, Y.; Kaneshiro, S.; Morimoto, T.; Koizumi, K.; Yoshikawa, H. Oxygen and air nanobubble water solution promote the growth of plants, fishes, and mice. *PLoS ONE* **2013**, *8*, e65339. [CrossRef]
86. Jhunkeaw, C.; Khongcharoen, N.; Rungrueng, N.; Sangpo, P.; Panphut, W.; Thapinta, A.; Senapin, S.; St-Hilaire, S.; Dong, H.T. Ozone nanobubble treatment in freshwater effectively reduced pathogenic fish bacteria and is safe for Nile tilapia (*Oreochromis niloticus*). *Aquaculture* **2021**, *534*, 736286. [CrossRef]
87. Alleway, H.K.; Gillies, C.L.; Bishop, M.J.; Gentry, R.R.; Theuerkauf, S.J.; Jones, R. The Ecosystem Services of Marine Aquaculture: Valuing Benefits to People and Nature. *BioScience* **2019**, *69*, 59–68. [CrossRef]
88. Weitzman, J. Applying the ecosystem services concept to aquaculture: A review of approaches, definitions, and uses. *Ecosyst. Serv.* **2019**, *35*, 194–206. [CrossRef]
89. Zhou, X.; Fang, J.; Shi, S.; Yang, L.; Xie, B.; Huang, L. Ecosystem Services of Ecosystem Approach to Mariculture: Providing an Unprecedented Opportunity for the Reform of China's Sustainable Aquaculture. *Front. Mar. Sci.* **2022**, *9*, 909231. [CrossRef]
90. EC-European Commission. *The EU Blue Economy Report 2025*; EC-European Commission: Brussels, Belgium, 2025. Available online: https://medblueconomyplatform.org/wp-content/uploads/2025/05/the-eu-blue-economy-report-2025.pdf (accessed on 5 March 2026).

91. Rodríguez, M.C.B.; González, C.E.M.; Almanza, E.D.C.; Rodríguez, C.G.; Regino-Vergara, J.Á.; López-Padilla, A. Benefits and challenges of the internet of things in aquaculture production: A literature review. *Front. Sustain. Food Syst.* **2025**, *9*, 1590153. [CrossRef]
92. Froehlich, H.E.; Runge, C.A.; Gentry, R.R.; Gaines, S.D.; Halpern, B.S. Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 5295–5300. [CrossRef] [PubMed]
93. Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **2018**, *360*, 987–992. [CrossRef] [PubMed]
94. Xu, C.; Su, G.; Brosse, S.; Zhao, K.; Zhang, M.; Xu, J. Social benefits and environmental performance of aquaculture need to improve worldwide. *Commun. Earth Environ.* **2024**, *5*, 698. [CrossRef]
95. Le Gouvello, R.; Brugere, C.; Simard, F. *Aquaculture and Nature-Based Solutions. Identifying Synergies Citation: Between Sustainable Development of Coastal Communities, Aquaculture, and Marine and Coastal Conservation*; IUCN: Gland, Switzerland, 2022.
96. Tan, P.Y.; Zhang, J.; Masoudi, M.; Alemu, J.B.; Edwards, P.J.; Grêt-Regamey, A.; Richards, D.R.; Saunders, J.; Song, X.P.; Wong, L.W. A conceptual framework to untangle the concept of urban ecosystem services. *Landsc. Urban Plann.* **2020**, *200*, 103837. [CrossRef]
97. Costanza, R.; d'Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]
98. Daily, G. *Nature's Services: Societal Dependence on Natural Ecosystems*; Island Press: Washington, DC, USA, 1997.
99. Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being. A Framework for Assessment*; Island Press: Washington, DC, USA, 2005.
100. EUROPEAN COMMISSION-Directorate-General for Maritime Affairs and Fisheries. *Unit D.3 (2025): FAMENET Ecosystem Services and Aquaculture Report*; EUROPEAN COMMISSION-Directorate-General for Maritime Affairs and Fisheries: Brussels, Belgium, 2025. Available online: https://webgate.ec.europa.eu/circabc-ewpp/d/d/workspace/SpacesStore/622d7fba-14a1-4057-a4e4-3d0c72d55f41/download (accessed on 5 March 2026).
101. Thomsen, M.; Bruhn, A.; Kotta, J.; Buck, B.H.; Hall, J.R.; Martin, G.; Agüera, A.; Maar, M.; Chakraborty, M.; Ekoule, M.; et al. Advancing a restorative blue Economy: A DPSIR–Ecosystem services framework for sustainable seaweed aquaculture. *Ecosyst. Serv.* **2026**, *77*, 101800. [CrossRef]
102. Eu-Com. *Communication from the Commission to the European Parliament the Council the European Economic and Social Committee and the Committee of the Regions. A New Circular Economy Action Plan*; Eu-Com: Brussels, Belgium, 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN (accessed on 5 March 2026).
103. Golden, C.D.; Allison, E.H.; Cheung, W.W.L.; Dey, M.M.; Halpern, B.S.; McCauley, D.J.; Smith, M.D.; Vaitla, B.; Zeller, D.; Myers, S.S. Nutrition: Fall in fish catch threatens human health. *Nature* **2016**, *534*, 317–320. [CrossRef]
104. Overton, K.; Dempster, T.; Swearer, S.; Morris, R.; Barret, L. Achieving conservation and restoration outcomes through ecologically beneficial aquaculture. *Conserv. Biol.* **2023**, *38*, e14065. [CrossRef]
105. Duarte, C.M.; Wu, J.; Xiao, X.; Bruhn, A.; Krause-Jensen, D. Can seaweed farming play a role in climate change mitigation and adaptation? *Front. Mar. Sci.* **2017**, *4*, 100. [CrossRef]
106. CE. *Green Infrastructure (GI)-Enhancing Europe's Natural Capital*; Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions (COM/2013/0249 final); CE: Brussels, Belgium, 2013.
107. Garlock, T.M.; Asche, F.; Anderson, J.L.; Eggert, H.; Anderson, T.M.; Che, B.; Chávez, C.A.; Chu, J.; Chukwuone, N.; Dey, M.M.; et al. Environmental, economic, and social sustainability in aquaculture: The aquaculture performance indicators. *Nat. Commun.* **2024**, *15*, 5274. [CrossRef]
108. Golden, C.D.; Koehn, J.Z.; Shepon, A.; Passarelli, S.; Free, C.M.; Viana, D.F.; Matthey, H.; Eurich, J.G.; Gephart, J.A.; Fluet-Chouinard, E.; et al. Aquatic foods to nourish nations. *Nature* **2021**, *598*, 315–320. [CrossRef]
109. Boyd, C.E.; McNevin, A.A.; Davis, R.P.; Godumala, R.; Mohan, A.B.C.; Clay, J. Production methods and resource use at *Litopenaeus vannamei* and *Penaeus monodon* farms in India compared with previous findings from Thailand and Vietnam. *J. World Aquac. Soc.* **2020**, *51*, 674–688. [CrossRef]
110. Chopin, T.; Robinson, S. Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practices: Introduction to the workshop and positioning of the issues. *Bull. Aquac. Assoc. Can.* **2004**, *104*, 4–10.
111. Krause-Jensen, D.; Duarte, C.M. Substantial role of macroalgae in marine carbon sequestration. *Nat. Geosci.* **2016**, *9*, 737–742. [CrossRef]
112. Duarte, C.M.; Losada, I.J.; Hendriks, I.E.; Mazarrasa, I.; Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* **2017**, *3*, 961–968. [CrossRef]
113. Aubin, J.; Callier, M.; Rey-Valette, H.; Mathè, S.; Wilfart, A.; Legendre, M.; Slembrouck, J.; Caruso, D.; Chia, E.; Masson, G.; et al. Implementing ecological intensification in fish farming: Definition and principles from contrasting experiences. *Rev. Aquac.* **2019**, *11*, 149–167. [CrossRef]

114. Valenti, W.C.; Kimpara, J.M.; Preto, B.D.L.; Moraes-Valenti, P. Indicators of sustainability to assess aquaculture systems. *Ecol. Indic.* **2018**, *88*, 402–413. [CrossRef]
115. Humphries, A.T.; Ayvazian, S.G.; Carey, J.C.; Hancock, B.T.; Grabbert, S.; Cobb, D.; Strobel, C.J.; Fulweiler, R.W. Directly Measured Denitrification Reveals Oyster Aquaculture and Restored Oyster Reefs Remove Nitrogen at Comparable High Rates. *Front. Mar. Sci.* **2016**, *3*, 74. [CrossRef]
116. Walton, M.E.M.; Vilas, C.; Canavate, J.P.; Gonzalez-Ortegon, E.; Prieto, A.; van Bergeijk, S.A.; Green, A.J.; Librero, M.; Mazuelos, N.; Le Vay, L. A model for the future: Ecosystem services provided by the aquaculture activities of Veta la Palma, Southern Spain. *Aquaculture* **2015**, *448*, 382–390. [CrossRef]
117. Chopin, T.; Cooper, J.A.; Reid, G.; Cross, S.; Moore, C. Open-water integrated multi-trophic aquaculture: Environmental biomitigation and economic diversification. *Aquaculture* **2012**, *4*, 209–220. [CrossRef]
118. Carlozo, N. *Integrating Water Quality and Coastal Resources into Marine Spatial Planning in the Chesapeake and Atlantic Coastal Bays*; Report n 8192014–724; Maryland Department of Natural Resources Chesapeake Coastal Service: Annapolis, MD, USA, 2014.
119. Barrington, K.; Ridler, N.; Chopin, T.; Robinson, S.; Robinson, B. Social and economic dimensions of an integrated multi-trophic aquaculture system: A Canadian case study. *Aquac. Econ. Manag.* **2009**, *13*, 290–306. [CrossRef]
120. Buck, B.H.; Troell, M.F.; Krause, G.; Angel, D.L.; Grote, B.; Chopin, T. State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA). *Front. Mar. Sci.* **2018**, *5*, 165. [CrossRef]
121. Semeraro, T.; Aretano, R.; Barca, A.; Pomes, A.; Del Giudice, C.; Gatto, E.; Lenucci, M.; Buccolieri, R.; Emmanuel, R.; Gao, Z.; et al. A Conceptual Framework to Design Green Infrastructure: Ecosystem Services as an Opportunity for Creating Shared Value in Ground Photovoltaic Systems. *Land* **2020**, *9*, 238. [CrossRef]
122. Semeraro, T.; Scarano, A.; Santino, A.; Emmanuel, R.; Lenucci, M. An innovative approach to combine solar photovoltaic gardens with agricultural production and ecosystem services. *Ecosyst. Serv.* **2022**, *56*, 101450. [CrossRef]
123. Cohen-Shacham, E.; Walters, G.; Janzen, C.; Maginnis, S. *Nature-Based Solutions to Address Global Societal Challenges*; IUCN: Gland, Switzerland, 2016.
124. Brugere, C.; Aguilar-Manjarrez, J.; Beveridge, M.C.M.; Soto, D. The ecosystem approach to aquaculture 10 years on-a critical review and consideration of its future role in blue growth. *Rev. Aquac.* **2018**, *11*, 493–514. [CrossRef]
125. Costanza, R.; de Groot, R.; Braat, L.; Kubiszewski, I.; Fioramonti, L.; Sutton, P.; Farber, S.; Grasso, M. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosyst. Serv.* **2017**, *28*, 1–16. [CrossRef]
126. Kruijssen, F.; McDougall, C.L.; van Asseldonk, I.J.M. Gender and aquaculture value chains: A review of key issues and implications for research. *Aquaculture* **2018**, *493*, 328–337. [CrossRef]
127. Kaminski, A.M.; Krujissen, F.; Cole, S.M.; Beveridge, M.C.M.; Dawson, C.; Mohan, C.V.; Suri, S.; Karim, M.; Chen, O.L.; Phillips, M.J.; et al. A review of inclusive business models and their application in aquaculture development. *Rev. Aquac.* **2020**, *12*, 1881–1902. [CrossRef]
128. Petersen, J.K.; Saurel, C.; Nielsen, P.; Timmermann, K. The use of shellfish for eutrophication control. *Aquac. Int.* **2016**, *24*, 857–878. [CrossRef]
129. Theuerkauf, S.J.; Morris, J.A., Jr.; Waters, T.J.; Wickliffe, L.C.; Alleway, H.K.; Jones, R.C. Global spatial analysis reveals where marine aquaculture can benefit nature and people. *PLoS ONE* **2019**, *14*, e0222282. [CrossRef]
130. Allison, E.H. *Aquaculture, Fisheries, Poverty, and Food Security*; Working paper no. 2011-65; World Fish Centre: Penang, Malaysia, 2011.
131. OECD. *OECD Review of Fisheries 2025*; OECD Publishing: Paris, France, 2025. [CrossRef]
132. Carranza, A.; Zu Ermgassen, P.S.E. A Global Overview of Restorative Shellfish Mariculture. *Front. Mar. Sci.* **2020**, *7*, 722. [CrossRef]
133. Fitzsimons, J.A.; Branigan, S.; Gillies, C.L.; Btumbaugh, R.D.; Cheng, J.; De Angelis, B.M.; Geselbracht, L.; Hancock, B.; Jeffs, A.; McDonald, T.; et al. Shellfish reefs: Global guidelines for practitioners and scientists. *Conserv. Sci. Pract.* **2020**, *2*, e198. [CrossRef]
134. Hughes, A.D.; Black, K.D.; Campbell, I.; Davidson, K.; Kelly, M.S.; Stanley, M.S. Does seaweed offer a solution for bioenergy with biological carbon capture and storage? *Greenh. Gases Sci. Technol.* **2012**, *2*, 402–407. [CrossRef]
135. Jack, B.K.; Kousky, C.; Sims, K.R.E. Designing payments for ecosystem services: Lessons from previous experience with incentive-based mechanisms. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 9465–9470. [CrossRef]
136. Petersen, J.K.; Hasler, B.; Timmermann, K.; Nielsen, P.; Bruunshøj Tørring, D.; Larsen, M.M.; Holmer, M. Mussels as a tool for mitigation of nutrients in the marine environment. *Mar. Pollut. Bull.* **2014**, *82*, 137–143. [CrossRef]
137. Asche, F.; Cojocaru, A.L.; Roth, B. The development of large scale aquaculture production: A comparison of the supply chains for chicken and salmon. *Aquaculture* **2018**, *493*, 446–455. [CrossRef]
138. Badiola, M.; Mendiola, D.; Bostock, J. Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. *Aquac. Eng.* **2012**, *51*, 26–35. [CrossRef]
139. Gephart, J.A.; Henriksson, P.J.G.; Parker, R.W.R.; Shepon, A.; Gorospe, K.D.; Bergman, K.; Eshel, G.; Golden, C.D.; Halpern, B.S.; Hornborg, S.; et al. Environmental performance of blue foods. *Nature* **2021**, *597*, 360–365. [CrossRef]

140. Gentry, R.R.; Froehlich, H.E.; Grimm, D.; Kareiva, P.; Parke, M.; Rust, M.; Gaines, S.D.; Halpern, B.S. Mapping the global potential for marine aquaculture. *Nat. Ecol. Evol.* **2017**, *1*, 1317–1324. [CrossRef] [PubMed]
141. ASviS–Alleanza Italiana per lo Sviluppo Sostenibile. *La "Nature Restoration Law": Un'opportunità per l'Italia*; Position Paper; AsviS: Roma, Italy, 2025. Available online: https://asvis.it/public/asvis2/files/Pubblicazioni/PositionPaper/2025/PP_Nature_Restoration_Law.pdf (accessed on 5 March 2026).
142. FAO. *The State of World Fisheries and Aquaculture 2020: Sustainability in Action*; FAO: Rome, Italy, 2020. Available online: https://openknowledge.fao.org/items/b752285b-b2ac-4983-92a9-fdb24e92312b (accessed on 5 March 2026).
143. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S., III; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. A safe operating space for humanity. *Nature* **2009**, *461*, 472–475. [CrossRef]
144. IPCC. *Climate Change 2022: Impacts, Adaptation and Vulnerability*; Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 2022. Available online: https://www.ipcc.ch/report/ar6/wg2/ (accessed on 5 March 2026).
145. OECD. *Making Better Policies for Food Systems*; Organisation for Economic Co-operation and Development; OECD: Paris, France, 2021. Available online: https://www.oecd.org/content/dam/oecd/en/publications/reports/2021/01/making-better-policies-for-food-systems_0fd8c682/ddfba4de-en.pdf (accessed on 5 March 2026).
146. UNESCOWWAP. *The United Nations World Water Development Report 2024: Water for Prosperity and Pace*; United Nations World Water Assessment Programme; UNESCOWWAP: Paris, France, 2024. Available online: https://www.unesco.org/en/articles/united-nations-world-water-development-report-2024-water-prosperity-and-peace (accessed on 5 March 2026).
147. Grunert, K.G. Food quality and safety: Consumer perception and demand. *Food Sci. Hum. Wellness* **2015**, *4*, 136–143. [CrossRef]
148. Verbeke, W.; Sans, P.; Van Loo, E.J. Challenges and prospects for consumer acceptance of cultured meat. *J. Integr. Agric.* **2020**, *19*, 431–438. [CrossRef]
149. Yang, H.; Feng, Q.; Xia, S.; Wu, Z.; Zhang, Y. AI-driven aquaculture: A review of technological innovations and their sustainable impacts. *Artif. Intell. Agric.* **2025**, *15*, 508–525. [CrossRef]
150. Popowicz, M.; Katzer, N.J.; Kettele, M.; Schöggl, J.-P.; Baumgartner, R.J. Digital technologies for life cycle assessment: A review and integrated combination framework. *Int. J. Life Cycle Assess.* **2025**, *30*, 405–428. [CrossRef]
151. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006. Available online: https://www.cscses.com/uploads/2016328/20160328110518251825.pdf (accessed on 5 March 2026).
152. Henchion, M.; Hayes, M.; Mullen, A.M.; Fenelon, M.; Tiwari, B. Future protein supply and demand: Strategies and sustainability analyses using LCA approaches. *Foods* **2017**, *6*, 53. [CrossRef] [PubMed]
153. Henriksson, P.J.; Guinée, J.B.; Kleijn, R.; de Snoo, G.R. Life cycle assessment of aquaculture systems—A review of methodologies. *Int. J. Life Cycle Assess.* **2012**, *17*, 304–313. [CrossRef]
154. Boyd, C.E.; McNevin, A. *Aquaculture, Resource Use, and the Environment*; Wiley-Blackwell: Oxford, UK, 2015. [CrossRef]
155. FAO. *The State of Food and Agriculture 2020: Overcoming Water Challenges in Agriculture*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2020. Available online: https://openknowledge.fao.org/items/a2dc7490-735d-4b5d-92a2-a36bfb380e02 (accessed on 5 March 2026).
156. MSC—Marine Stewardship Council. *MSC Fisheries Standard and Guidance*; MSC—Marine Stewardship Council: London, UK, 2019. Available online: https://www.msc.org/it (accessed on 5 March 2026).
157. OECD. *Review of Fisheries 2020*; OECD: Paris, France, 2020. Available online: https://www.oecd.org/content/dam/oecd/en/publications/reports/2020/12/oecd-review-of-fisheries-2020_ea7a669d/7946bc8a-en.pdf (accessed on 5 March 2026).
158. ASC–Aquaculture Stewardship Council. *ASC Standards and Certification Programme: Principles and Criteria for Responsible Aquaculture*; ASC: Utrecht, The Netherlands, 2021. Available online: https://asc-aqua.org/producers/asc-standards/ (accessed on 5 March 2026).
159. Bush, S.R.; Belton, B.; Hall, D.; Vandergeest, P.; Murray, F.J.; Ponte, S.; Oosterveer, P.; Islam, M.S.; Mol, A.P.; Hatanaka, M.; et al. Certify sustainable aquaculture? *Science* **2013**, *341*, 1067–1068. [CrossRef]
160. Masi, M.; Adinolfi, F.; Vecchio, Y.; Agnusdei, G.P.; Coluccia, B. Toward the Circular Economy in the Aquaculture Sector: Bibliometric, Network and Content Analyses. *Sustainability* **2024**, *16*, 5405. [CrossRef]
161. Føre, M.; Frank, K.; Norton, T.; Svendsen, E.; Alfredsen, J.A.; Dempster, T.; Eguiraun, H.; Watson, W.; Stahl, A.; Sunde, L.M.; et al. Precision fish farming: A new framework to improve production in aquaculture. *Biosyst. Eng.* **2018**, *173*, 176–193. [CrossRef]
162. Chelladurai, S.P.; Shiny, G.S.; Jeevitha, S.V.; Swapna, P.; Pavithra, R.; Arulraj, S. Revolutionizing Aquaculture Practices: IoT and Deep Learning-based Remote Monitoring for Sustainable Fish Farming. In Proceedings of the 2024 5th International Conference on Smart Electronics and Communication (ICOSEC), Trichy, India, 18–20 September 2024; pp. 547–553. [CrossRef]
163. Haque, S.A.; Jufaili, S.M.A. Applications of Artificial Intelligence in Fisheries: From Data to Decisions. *Big Data Cogn. Comput.* **2026**, *10*, 19. [CrossRef]

164. Bostock, J.; Lane, A.; Hough, C.; Yamamoto, K. An assessment of the economic contribution of EU aquaculture production and the influence of policies for its sustainable development. *Aquac. Int.* **2016**, *24*, 699–733. [CrossRef]
165. FAO. *Blue Transformation: Roadmap for FAO's Work on Aquatic Food Systems*; FAO: Rome, Italy, 2022. Available online: https://openknowledge.fao.org/items/467191e5-111b-4191-a4d3-843e491fd418 (accessed on 5 March 2026).