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Microalgae Technology in Aquaculture Applications: A Comprehensive Literature Review

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Abstract: Microalgae are highly valuable across various industries due to their rich nutritional content and positive environmental impact. In the fast-growing field of aquaculture aimed at meeting global food needs, integrating microalgae technology can be highly beneficial. This literature review explores the diverse roles of microalgae in enhancing aquaculture, focusing on their nutritional benefits, water quality management, larviculture, Integrated Multi-Trophic Aquaculture (IMTA) systems, and bioremediation. Microalgae are excellent natural nutrient sources, offering high protein content, omega-3 fatty acids, vitamins, minerals, and antioxidants, vital for aquatic organism growth and health. Their contributions to water quality maintenance, larval stage nutrition, and waste nutrient uptake are critical. Additionally, microalgae play a pivotal role in IMTA by acting as primary producers and minimizing environmental impact. The review emphasizes challenges like economic constraints and strain optimization, underscoring the need for further research to fully leverage microalgae's potential in aquaculture, promising advancements to revolutionize the industry and enhance global food security.

Keywords:
Aquaculture applications; Bioremediation Integrated Multi-Trophic Aquaculture; Larviculture; Microalgae technology; Nutritional benefits; Water quality management

Introduction

Microalgae, small photosynthetic microorganisms, have garnered significant attention across industries due to their versatile applications and diverse bioactive compounds (Ahmed & Azra, 2022a). They find utility in aquaculture feed, biofuel production, food additives, and pharmaceuticals (von Alvensleben et al., 2016a). These applications extend to biofuels, cosmetics, and bioremediation (Balasubramaniam et al., 2021). Cultivation of microalgae on a large scale with a rapid growth rate positions them as a sustainable biomass source for numerous industries (Soto-Sánchez et al., 2023). Phytosterols, a vital bioactive compound found in microalgae, have been incorporated as food additives in various products like spreads, dairy items, and salad dressings (X. Luo et al., 2015). Microalgae are also rich in polyunsaturated fatty acids (PUFAs), acknowledged for their health-promoting properties (Soto-Sánchez et al., 2023). However, challenges persist in commercial microalgae production and bioactive compound extraction, necessitating research for optimal yield and genetic enhancements (Kumar et al., 2020).

Shifting to aquaculture, microalgae present a sustainable solution for wastewater treatment, nutrient assimilation, and pollutant reduction (Li et al., 2021). Moreover, they serve as a nutritious and sustainable feed source, enhancing the health and performance of aquatic organisms (L. Yang et al., 2021). The antimicrobial properties of microalgae offer a

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sustainable alternative to conventional antibiotics in aquaculture, aiding in disease prevention (Falaise et al., 2016). Additionally, microalgae exhibit promise in the development of immunostimulants and vaccines, advancing disease resistance in aquaculture (K. Ma et al., 2020).

However, challenges such as optimization of cultivation systems, suitable species selection, and cost-effective harvesting technologies require further research and development for seamless integration of microalgae technology into aquaculture practices (Li et al., 2021). This literature review aims to explore the potential of microalgae in enhancing aquaculture efficiency and sustainability, addressing challenges and proposing avenues for further research (Falaise et al., 2016). It will delve into microalgae-bacteria interactions, sustainable feed production, wastewater treatment, and overall water quality enhancement in aquaculture. Through a comprehensive examination of existing literature, the review seeks to shed light on the valuable role of microalgae in improving aquaculture practices and promoting sustainability.

The objective of this literature review is to explore the role of microalgae in improving aquaculture efficiency and sustainability. (Falaise et al., 2016). Microalgae-bacteria interactions have also been investigated for their impacts on the productivity, efficiency, and sustainability of aquaculture (Natrah et al., 2014). Additionally, the use of microalgae as a sustainable feed source in aquaculture has been studied, with findings suggesting that microalgae can be safely used as growth and immune stimulants for aquatic animals (Pantami et al., 2020). Furthermore, microalgae technology has been explored for wastewater treatment in aquaculture, biomass production, and water quality control (Han et al., 2019). The review will also discuss the challenges and potential solutions associated with the application of microalgae in aquaculture, such as biomass harvesting technologies and the need for further research and development (Li et al., 2021; K. Ma et al., 2020; L. Yang et al., 2021). By examining the existing literature, this review aims to provide a comprehensive understanding of the role of microalgae in improving aquaculture practices and promoting sustainability.

Method

In this study, a literature review methodology is utilized, concentrating on a range of international journals investigating microalgae technology in aquaculture. The research delves into the effects of microalgae on aquatic organisms and their potential in developing a sustainable and nutritionally balanced feed. Additionally, the study examines how microalgae can aid in nutrient uptake from wastewater generated by fish in aquaculture and evaluates its impact as a feed for aquatic species.

Result and Discussion

Microalgae as a natural source of essential nutrients for aquatic organisms

Microalgae, a natural nutrient source for aquatic organisms, play a vital role in aquaculture due to their rich content of essential proteins, omega-3 fatty acids, valuable lipids, vitamins, minerals, and antioxidants (Yaakob et al., 2014). These nutrients are fundamental for the growth, development, and overall well-being of aquatic life. Proteins are crucial for growth, and microalgae offer a plentiful supply of high-quality proteins, containing a diverse range of essential amino acids necessary for protein synthesis and physiological functions (Chen et al., 2022). Omega-3 fatty acids like eicosapentaenoic acid and docosahexaenoic acid are essential for aquatic organisms' growth, reproduction, and overall health, with microalgae being a primary source in aquatic ecosystems (Fang et al., 2022). These omega-3 fatty acids can be enhanced in aquaculture feed by incorporating microalgae, improving the nutritional value for farmed species.

Additionally, microalgae contain other valuable lipids, such as monounsaturated and polyunsaturated fatty acids, critical for energy storage, membrane structure, and various physiological processes in aquatic organisms (Yaakob et al., 2014). The nutritional composition of microalgae can be optimized through cultivation strategies, offering tailored nutrient profiles for different aquaculture species (Chen et al., 2022). Cultivating microalgae using sustainable methods underscores their potential as an eco-friendly solution to meet the nutritional needs of aquatic organisms in aquaculture, further promoting sustainability (Chacón-Lee & González-Mariño, 2010; Kumar et al., 2020). In essence, microalgae represent a natural and crucial nutrient source for aquatic organisms, significantly enhancing aquaculture's sustainability and overall success.

Importance of balanced and sustainable feed in aquaculture

Balanced and sustainable feed is vital for aquaculture growth, health, and environmental sustainability (Gatlin et al., 2007). It optimizes growth, development, and overall aquatic organism health. Microalgae, a natural nutrient source, contributes significantly to balanced nutrition in aquaculture, rich in essential proteins, omega-3 fatty acids, lipids, vitamins, minerals, and antioxidants. These nutrients are crucial for metabolic processes, immune function, and overall well-being.

Utilizing plant-based and alternative protein sources, including microalgae, reduces reliance on finite resources, enhances feed efficiency, and minimizes environmental impacts. Incorporating these ingredients promotes sustainability, reducing pressure on wild fish stocks. Enhancing feed efficiency through dietary interventions and understanding gut microbiome interactions optimize nutrient utilization and reduce waste, contributing to economic viability. Balanced and sustainable feed ultimately supports aquaculture's profitability and long-term sustainability in an eco-friendly manner (Hancz, 2020; Madkour et al., 2023; Röthig et al., 2023; Tarnecki et al., 2017).

The positive effects of microalgae-based feeds on growth, survival, and overall health of aquatic species

Studies consistently demonstrate the favorable impact of microalgae-based feeds on aquatic species, enhancing growth, survival, immune response, and nutritional quality. Microalgae exhibit potential as a sustainable and nutritious feed source in aquaculture. Notably, research by Kiron et al. (2016) revealed that microalgae can replace fishmeal in aquafeeds without compromising growth and survival in Atlantic salmon (Kiron et al., 2016). Another study by Hassan et al. (2022) underscored the influence of microalgae diets on hard clam juveniles, affecting growth and survival positively (Hassan et al., 2023). Furthermore, microalgae-based feeds enhance immune response and disease resistance, attributed to their bioactive compounds (Hai, 2015). Microalgae, rich in omega-3 fatty acids, enhance the nutritional quality of aquatic organisms, offering a healthier product for consumers (Kiron et al., 2016). These findings emphasize the multifaceted benefits of integrating microalgae into aquafeeds, from growth and immunity to improved nutritional value, reinforcing their potential in sustainable aquaculture practices.

Water Quality Management and Microalgae

Microalgae play a critical role in managing water quality, serving as bioindicators for water body assessment and control. Their capacity to absorb and convert nutrients into biomass aids in environmental purification, wastewater treatment, and maintaining water quality across aquatic ecosystems. Effective water quality management is vital for environmental sustainability, particularly in aquatic systems. Microalgae, acting as primary producers and bioindicators, are key in evaluating and controlling water quality (Japa et al., 2022). Losses in phytoplankton populations adversely affect fish production, emphasizing the importance of a thriving microalgal community.

Microalgae are also instrumental in maintaining water quality in lakes, rivers, and coastal areas, aiding in nutrient regulation and averting eutrophication (Wang et al., 2022). Additionally, microalgae exhibit promise in wastewater treatment, especially for organic-rich wastewater like brewery effluents (Amenorfenyo et al., 2019). Their ability to absorb nutrients and convert them into biomass makes them an eco-friendly and cost-effective solution for wastewater treatment. The harvested microalgal biomass has various valuable applications, including animal feed, biofertilizer, and biodiesel production. Overall, microalgae-based wastewater treatment presents a sustainable, economically viable approach for addressing wastewater challenges, emphasizing the environmental benefits and cost-effectiveness of this method.

Role of microalgae in maintaining water quality parameters

Effective water quality management is vital for sustaining aquatic ecosystems. Microalgae, with their nutrient uptake and bioremediation capabilities, significantly contribute to this aspect. Studies demonstrate their ability to efficiently remove excess nutrients like nitrogen and phosphorus, preventing eutrophication and maintaining water quality (von Alvensleben et al., 2016b). Microalgae store surplus nutrients as polyphosphate, a reserve source utilized when external nutrients are scarce, aiding in balanced nutrient levels in aquatic environments.

Furthermore, microalgae enhance water quality by producing oxygen and sequestering carbon dioxide through photosynthesis (Liber et al., 2020). Oxygen release supports aquatic organism survival and ecosystem health. Concurrently, their carbon dioxide absorption contributes to carbon capture, potentially mitigating climate change. Microalgae-based wastewater treatment is also promising, effectively removing organic pollutants and heavy metals, remediating contaminated water (Fernandes et al., 2022). The resulting microalgal biomass holds value for biofuel production or nutrient-rich feed in aquaculture, presenting an eco-friendly solution for wastewater treatment and valuable byproduct creation.

In conclusion, microalgae's multifaceted contributions, from nutrient regulation to bioremediation and carbon sequestration, underscore their critical role in water quality management and environmental sustainability. Further research and development are imperative to optimize their application in water treatment systems, addressing global water challenges effectively.

Enhancing Water Quality and Waste Management: Synergizing Biofloc Systems with Microalgae Cultivation

Microalgae cultivation within biofloc systems significantly contributes to nutrient uptake, bioremediation, oxygen production, and carbon dioxide removal. Microalgae efficiently absorb and assimilate nutrients, enhancing nutrient cycling and stabilizing the aquaculture environment (Chen et al., 2022). Furthermore, they provide a continuous source of live food, promoting the growth, survival, and health of cultured organisms (Emerenciano et al., 2012).

Beyond aquaculture, microalgae play a pivotal role in water quality and waste management. Studies showcase their ability to thrive in various environmental conditions while effectively utilizing carbon dioxide (Chinnasamy et al., 2009). Microalgae aid in removing organic pollutants from wastewater, demonstrating promise in waste management and water quality improvement (Mulbry et al., 2008). Additionally, the integration of microalgae cultivation with waste anaerobic digestion enhances system stability and methane production, highlighting the potential for sustainable waste treatment and biomass generation (Ferreira et al., 2022).

Moreover, microalgae contribute to the biorefinery concept, valorizing algal biomass for high-value product production (Katiyar et al., 2021). This holistic approach maximizes resource utilization and promotes a circular economy.

In addition, the integration of microalgae in biofloc systems and broader water and waste management endeavors showcases considerable potential in enhancing water quality, reducing waste, and producing valuable products. Ongoing research and development are critical to fully unlock the potential of microalgae in addressing environmental challenges and promoting sustainable practices.

Microalgae in Larviculture and Hatchery Operations: Enhancing Survival and Nutrition

Microalgae-based larviculture and hatchery operations provide a sustainable and effective approach to raising aquatic larvae. Integrating microalgae as live feed ensures a continuous and nutritious food source, supporting larval growth, survival, and overall health. Furthermore, microalgae contribute to water quality management and offer economic and environmental advantages.

The use of microalgae in larviculture and hatchery operations has garnered significant attention within the aquaculture industry, especially during the critical larval stage. Larvae require high-quality live feed for successful rearing, and microalgae play a pivotal role in providing nutritious and sustainable nourishment. Microalgae are rich in essential nutrients like proteins, lipids, vitamins, and minerals, making them an ideal food source for developing larvae (DANTAS et al., 2022).

Integration of microalgae in larviculture and hatchery operations offers numerous benefits. Microalgae serve as a reliable source of live feed, reducing dependency on costly and variable natural food sources. Cultivated in controlled environments, microalgae ensure consistent feed quality and quantity for the larvae (Sales et al., 2022). Additionally, microalgae can be enriched with specific nutrients to meet the dietary needs of different larval species, enhancing growth, survival, and overall health (Cardoso et al., 2019).

Microalgae-based larviculture also aids water quality management in hatchery systems. Microalgae help maintain water quality by absorbing excess nutrients like nitrogen and phosphorus, mitigating the risk of water pollution and eutrophication (Li et al., 2021). They also contribute to oxygen production through photosynthesis, ensuring adequate oxygen levels for the developing larvae (Cardoso et al., 2019), creating a conducive environment for larval growth and development.

Moreover, utilizing microalgae in larviculture and hatchery operations presents economic and environmental advantages. Microalgae cultivation can be cost-effective compared to traditional live feed sources such as Artemia nauplii, which can be expensive and subject to supply limitations (Rato et al., 2018). On-site microalgae production reduces reliance on external sources and provides a sustainable feed option. Additionally, using microalgae as live feed reduces the environmental impact associated with collecting and transporting natural food sources (Gamboa-Delgado & Márquez-Reyes, 2018).

However, larviculture and hatchery practices face diverse challenges, including supply chain issues, water quality management, disease outbreaks, genetic and reproductive performance of broodstock, the COVID-19 pandemic impact, and technical complexities in maintaining pure cultures and producing essential larval feed (Ahmed & Azra, 2022b; Ragasa et al., 2021). Addressing these challenges requires collaborative efforts, supportive policies, and continuous research and innovation to enhance the efficiency and resilience of larviculture and hatchery practices in aquaculture (Kourkouta et al., 2022).

Ensuring suitable live feed for larval stages is pivotal in larviculture and hatchery operations. Size-appropriate feed is essential to enable larvae to effectively capture and consume prey, promoting growth and survival (Snell et al., 2019). Nutritional enhancement of live prey through microalgae enrichment provides a balanced and nutritious diet, supporting larval development and overall health (Uribe-Wandurraga et al., 2020). Ongoing research and development are necessary to optimize microalgae use in larviculture and hatchery practices, considering specific nutritional requirements and the potential for sustainable and cost-effective microalgae biomass production (Hashmi et al., 2023; Rocha et al., 2008).

Additionally, microalgae-enriched diets have demonstrated success in increasing survival rates and reducing mortality in various aquatic species. The nutritional enhancement offered by microalgae improves diet quality and balance, leading to enhanced larval development, growth, and survival. Further research and development are needed to refine the formulation and application of microalgae-enriched diets in larviculture and hatchery practices, considering specific nutritional requirements and the potential for sustainable and cost-effective production of microalgae biomass.

Microalgae: Bioremediation, Nutrient Uptake, and Wastewater Treatment in Aquaculture

Bioremediation and wastewater treatment using microalgae are sustainable and cost-effective solutions for managing aquaculture wastewater. Microalgae efficiently remove excess nutrients, organic matter, and pollutants from wastewater, enhancing water quality and mitigating environmental impacts (Smith et al., 2006). Integrating microalgae-based wastewater treatment with resource recovery and biorefinery processes promotes circular bioeconomy and sustainability in aquaculture practices (Mulbry et al., 2008).

Aquaculture operations generate wastewater with high nutrient and pollutant levels, posing risks to water quality and ecosystems (Posadas et al., 2014). Microalgae, adept at nutrient assimilation and pollutant removal, provide a natural and cost-effective approach to treating aquaculture wastewater (L. Luo et al., 2016). By utilizing microalgae's capacity to assimilate nutrients like nitrogen and phosphorus, excess nutrients are effectively reduced, preventing eutrophication and minimizing environmental harm. Microalgae also assimilate organic matter and pollutants, further improving water quality (Hashmi et al., 2023).

Studies demonstrate microalgae's potential in removing various pollutants from aquaculture wastewater, depending on factors like microalgae species, wastewater load, and supplemental carbon dioxide (Liu et al., 2019). Optimization of cultivation conditions and the selection of appropriate microalgae species are crucial for effective wastewater treatment (Singh et al., 2023). Moreover, the biomass generated during microalgae cultivation can be utilized for biofuel production (Kapoore et al., 2021), animal feed, high-value compound extraction, and adsorption processes, promoting circular bioeconomy and sustainability (Han et al., 2019; Hawrot-Paw et al., 2019).

Microalgae's role as a tool for nutrient removal in aquaculture effluents holds immense potential, benefiting water quality, the environment, and sustainable aquaculture development (Liu et al., 2019; Mulbry et al., 2008). Research highlights their ability to efficiently remove excess nutrients, reducing eutrophication risk and enhancing water quality (Han et al., 2019). Understanding nutrient uptake and assimilation mechanisms is vital for predicting algal growth, nutrient cycling, and ecosystem functioning (Kapoore et al., 2021). Algae's contribution to biogeochemical cycles, especially the carbon cycle through photosynthetic carbon fixation, highlights their significant role in addressing climate-related challenges.

Applications of microalgae-based systems in treating aquaculture wastewater show promise in reducing nitrogen and phosphorus loads and improving water quality (Litchman et al., 2007). Algae-based constructed wetlands and microalgae assimilation capabilities contribute to efficient nutrient and pollutant removal from wastewater (Hessen et al., 2004). The integration of microalgae in aquaculture practices not only enhances wastewater treatment but also offers opportunities for resource recovery and sustainable wastewater management (Falkowski et al., 1998).

However, challenges such as bacterial contamination, unfavorable effluent conditions, and technological assessments can hinder the wide-scale application of microalgae biotechnology in wastewater treatment. Addressing these challenges and advancing research in this field will further optimize the use of microalgae-based systems for sustainable aquaculture wastewater management.

Challenges, Research Gaps, and Future Advancements in Microalgae Technology for Aquaculture

The limitations of microalgae technology in aquaculture encompass economic challenges (Vieira & Pecchia, 2022), scaling production (Han et al., 2019), and optimizing strains (Han et al., 2019). Economic constraints arise due to high production costs and infrastructure investments. Scaling production from lab to commercial scale requires complex optimization of cultivation systems (Han et al., 2019). Strain selection is critical for efficient nutrient removal while maintaining high biomass productivity (L. Yang et al., 2021). Collaboration is essential to overcome these limitations and integrate microalgae sustainably in aquaculture (Wikfors & Ohno, 2001).

Additionally, there are some research gaps include understanding nutrient assimilation (Kosten et al., 2020; X. Yang et al., 2020)., algal-bacterial cooperation (Falaise et al., 2016), economic assessments (Soto-Sánchez et al., 2023), biomass harvesting optimization (BASHIR et al., 2022), scaling production (Han et al., 2019), strain selection, and region-specific studies (Ayswaria et al., 2023). Advancements like natural antibiotics, improved biomass production, genetic engineering, economic assessments, biomass valorization, algal-bacterial interactions, and disease prevention applications hold potential to enhance microalgae technology for sustainable aquaculture (Y. Ma et al., 2019).

Conclusion

The literature review emphasizes microalgae's role in boosting aquaculture sustainability. It discusses extensive studies on microalgae-assisted aquaculture, covering nutrient assimilation, algae cultivation, wastewater treatment, and more. Microalgae are seen as a sustainable feed for aquaculture, with ongoing efforts to enhance production systems and quality control. Rapidly growing microalgae strains hold promise for various technologies. Addressing challenges in microalgae tech involves biomass production advancements, strain selection, genetic engineering, and disease prevention strategies. Beyond aquaculture, microalgae are potential biofuel feedstocks, with ongoing research to scale up lipid production. Microalgae are rich sources of high-value compounds like pharmaceuticals and natural colorants, but optimization is needed for economical production. These organisms also yield macromolecules with commercial applications. The productivity and composition of microalgae depend on cultivation conditions and nutrient profiles, including fatty acid composition. In conclusion, microalgae offer sustainability benefits through biofuel and high-value compound production, natural colorants, and regulation of fatty acid composition. Optimizing processes and conducting further research is vital to fully utilize microalgae's potential in aquaculture.

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References

Ahmed, N., & Azra, M. N. (2022a). Aquaculture Production and Value Chains in the COVID-19 Pandemic. *Current Environmental Health Reports*, *9*(3), 423–435. https://doi.org/10.1007/s40572-022-00364-6

Ahmed, N., & Azra, M. N. (2022b). Aquaculture Production and Value Chains in the COVID-19 Pandemic. *Current Environmental Health Reports*, *9*(3), 423–435. https://doi.org/10.1007/s40572-022-00364-6

Amenorfenyo, D. K., Huang, X., Zhang, Y., Zeng, Q., Zhang, N., Ren, J., & Huang, Q. (2019). Microalgae Brewery Wastewater Treatment: Potentials, Benefits and the Challenges. *International Journal of Environmental Research and Public Health*, *16*(11), 1910. https://doi.org/10.3390/ijerph16111910

Ayswaria, R., Vijayan, J., & Nathan, V. K. (2023). Antimicrobial peptides derived from microalgae for combating antibiotic resistance: Current status and prospects. *Cell Biochemistry and Function*, *41*(2), 142–151. https://doi.org/10.1002/cbf.3779

Balasubramaniam, V., Gunasegavan, R. D.-N., Mustar, S., Lee, J. C., & Mohd Noh, M. F. (2021). Isolation of Industrial Important Bioactive Compounds from Microalgae. *Molecules*, *26*(4), 943. https://doi.org/10.3390/molecules26040943

Bashir, M., Farooq, M., Khalid, S., & Ali, Q. (2022). The Role Of Microalgae In Different Biotechnology Applications. *Bulletin of Biological and Allied Sciences Research*, *2022*(1), 25. https://doi.org/10.54112/bbasr.v2022i1.25

Cardoso, C., Gomes, R., Rato, A., Joaquim, S., Machado, J., Gonçalves, J. F., Vaz-Pires, P., Magnoni, L., Matias, D., Coelho, I., Delgado, I., Castanheira, I., Matos, J., Ozório, R., Bandarra, N., & Afonso, C. (2019). Elemental composition and bioaccessibility of farmed oysters (*Crassostrea gigas*) fed different ratios of dietary seaweed and microalgae during broodstock conditioning. *Food Science & Nutrition*, *7*(8), 2495–2504. https://doi.org/10.1002/fsn3.1044

Chacón-Lee, T. L., & González-Mariño, G. E. (2010). Microalgae for "Healthy" Foods-Possibilities and Challenges. *Comprehensive Reviews in Food Science and Food Safety*, *9*(6), 655–675. https://doi.org/10.1111/j.1541-4337.2010.00132.x

Chen, F., Qian, J., He, Y., Leng, Y., & Zhou, W. (2022). Could Chlorella pyrenoidosa be exploited as an alternative nutrition source in aquaculture feed? A study on the nutritional values and anti-nutritional factors. *Frontiers in Nutrition*, *9*. https://doi.org/10.3389/fnut.2022.1069760

Chinnasamy, S., Ramakrishnan, B., Bhatnagar, A., & Das, K. (2009). Biomass Production Potential of a Wastewater Alga Chlorella vulgaris ARC 1 under Elevated Levels of CO2 and Temperature. *International Journal of Molecular Sciences*, *10*(2), 518–532. https://doi.org/10.3390/ijms10020518

Dantas, F. De M., Santana, T. M., Kojima, J. T., Fonseca, F. A. L. Da, Lopes, A. C. C., Carvalho, T. B., & Gonçalves, L. U. (2022). Pirarucu Larviculture in green water provides heavier fish and modulates locomotor activity. *Acta Amazonica*, *52*(2), 114–121. https://doi.org/10.1590/1809-4392202100932

Emerenciano, M., Ballester, E. L. C., Cavalli, R. O., & Wasielesky, W. (2012). Biofloc technology application as a food source in a limited water exchange nursery system for pink shrimp Farfantepenaeus brasiliensis (Latreille, 1817). *Aquaculture Research*, *43*(3), 447–457. https://doi.org/10.1111/j.1365-2109.2011.02848.x

Falaise, C., François, C., Travers, M.-A., Morga, B., Haure, J., Tremblay, R., Turcotte, F., Pasetto, P., Gastineau, R., Hardivillier, Y., Leignel, V., & Mouget, J.-L. (2016). Antimicrobial Compounds from Eukaryotic Microalgae against Human Pathogens and Diseases in Aquaculture. *Marine Drugs*, *14*(9), 159. https://doi.org/10.3390/md14090159

Falkowski, P. G., Barber, R. T., & Smetacek, V. (1998). Biogeochemical Controls and Feedbacks on Ocean Primary Production. *Science*, *281*(5374), 200–206. https://doi.org/10.1126/science.281.5374.200

Fang, H., Zhuang, Z., Huang, L., Zhao, W., & Niu, J. (2022). Dietary Klebsormidium sp. Supplementation Improves Growth Performance, Antioxidant and Anti-Inflammatory Status, Metabolism, and Mid-Intestine Morphology of Litopenaeus Vannamei. *Frontiers in Nutrition*, *9*. https://doi.org/10.3389/fnut.2022.857351

Fernandes, F., Silkina, A., Gayo-Peláez, J. I., Kapoore, R. V., de la Broise, D., & Llewellyn, C. A. (2022). Microalgae Cultivation on Nutrient Rich Digestate: The Importance of Strain and Digestate Tailoring under PH Control. *Applied Sciences*, *12*(11), 5429. https://doi.org/10.3390/app12115429

Ferreira, L. O., Astals, S., & Passos, F. (2022). Anaerobic co-digestion of food waste and microalgae in an integrated treatment plant. *Journal of Chemical Technology & Biotechnology*, *97*(6), 1545–1554. https://doi.org/10.1002/jctb.6900

Gamboa-Delgado, J., & Márquez-Reyes, J. M. (2018). Potential of microbial-derived nutrients for aquaculture development. *Reviews in Aquaculture*, *10*(1), 224–246. https://doi.org/10.1111/raq.12157

Gatlin, D. M., Barrows, F. T., Brown, P., Dabrowski, K., Gaylord, T. G., Hardy, R. W., Herman, E., Hu, G., Krogdahl, Å., Nelson, R., Overturf, K., Rust, M., Sealey, W., Skonberg, D., J Souza, E., Stone, D., Wilson, R., & Wurtele, E. (2007). Expanding the utilization of sustainable plant products in aquafeeds: a review. *Aquaculture Research*, *38*(6), 551–579. https://doi.org/10.1111/j.1365-2109.2007.01704.x

Hai, N. V. (2015). The use of probiotics in aquaculture. *Journal of Applied Microbiology*, *119*(4), 917–935. https://doi.org/10.1111/jam.12886

Han, P., Lu, Q., Fan, L., & Zhou, W. (2019). A Review on the Use of Microalgae for Sustainable Aquaculture. *Applied Sciences*, *9*(11), 2377. https://doi.org/10.3390/app9112377

Hancz, C. (2020). Feed efficiency, nutrient sensing and feeding stimulation in aquaculture: A review. *Acta Agraria Kaposváriensis*, *24*(1), 35–54. https://doi.org/10.31914/aak.2375

Hashmi, Z., Bilad, M. R., Fahrurrozi, Zaini, J., Lim, J. W., & Wibisono, Y. (2023). Recent Progress in Microalgae-Based Technologies for Industrial Wastewater Treatment. *Fermentation*, *9*(3), 311. https://doi.org/10.3390/fermentation9030311

Hassan, M. M., Perri, E., Parks, V., & Laramore, S. (2023). Growth, survival and fatty acid profile of hard clam, *Mercenaria mercenaria* , juveniles fed live microalgae diets. *Aquaculture, Fish and Fisheries*, *3*(1), 51–60. https://doi.org/10.1002/aff2.80

Hawrot-Paw, M., Koniuszy, A., Gałczyńska, M., Zając, G., & Szyszlak-Bargłowicz, J. (2019). Production of Microalgal Biomass Using Aquaculture Wastewater as Growth Medium. *Water*, *12*(1), 106. https://doi.org/10.3390/w12010106

Hessen, D. O., Ågren, G. I., Anderson, T. R., Elser, J. J., & de Ruiter, P. C. (2004). CARBON SEQUESTRATION IN ECOSYSTEMS: THE ROLE OF STOICHIOMETRY. *Ecology*, *85*(5), 1179–1192. https://doi.org/10.1890/02-0251

Japa, L., Karnan, K., & Handayani, B. S. (2022). Quality Status of Coastal Waters of Special Economic Zone of Mandalika Central Lombok Based on the Community of Microalgae as Bioindicator. *Jurnal Penelitian Pendidikan IPA*, *8*(6), 2864–2871. https://doi.org/10.29303/jppipa.v8i6.2740

Kapoore, R. V., Wood, E. E., & Llewellyn, C. A. (2021). Algae biostimulants: A critical look at microalgal biostimulants for sustainable agricultural practices. *Biotechnology Advances*, *49*, 107754. https://doi.org/10.1016/j.biotechadv.2021.107754

Katiyar, R., Banerjee, S., & Arora, A. (2021). Recent advances in the integrated biorefinery concept for the valorization of algal biomass through sustainable routes. *Biofuels, Bioproducts and Biorefining*, *15*(3), 879–898. https://doi.org/10.1002/bbb.2187

Kiron, V., Sørensen, M., Huntley, M., Vasanth, G. K., Gong, Y., Dahle, D., & Palihawadana, A. M. (2016). Defatted Biomass of the Microalga, Desmodesmus sp., Can Replace Fishmeal in the Feeds for Atlantic salmon. *Frontiers in Marine Science*, *3*. https://doi.org/10.3389/fmars.2016.00067

Kosten, S., Almeida, R. M., Barbosa, I., Mendonça, R., Santos Muzitano, I., Sobreira Oliveira-Junior, E., Vroom, R. J. E., Wang, H.-J., & Barros, N. (2020). Better assessments of greenhouse gas emissions from global fish ponds needed to adequately evaluate aquaculture footprint. *Science of The Total Environment*, *748*, 141247. https://doi.org/10.1016/j.scitotenv.2020.141247

Kourkouta, C., Tsipourlianos, A., Power, D. M., Moutou, K. A., & Koumoundouros, G. (2022). Variability of key-performance-indicators in commercial gilthead seabream hatcheries. *Scientific Reports*, *12*(1), 17896. https://doi.org/10.1038/s41598-022-23008-z

Kumar, G., Shekh, A., Jakhu, S., Sharma, Y., Kapoor, R., & Sharma, T. R. (2020). Bioengineering of Microalgae: Recent Advances, Perspectives, and Regulatory Challenges for Industrial Application. *Frontiers in Bioengineering and Biotechnology*, *8*. https://doi.org/10.3389/fbioe.2020.00914

Li, H., Chen, S., Liao, K., Lu, Q., & Zhou, W. (2021). Microalgae biotechnology as a promising pathway to ecofriendly aquaculture: a state-of-the-art review. *Journal of Chemical Technology & Biotechnology*, *96*(4), 837–852. https://doi.org/10.1002/jctb.6624

Liber, J. A., Bryson, A. E., Bonito, G., & Du, Z. (2020). Harvesting Microalgae for Food and Energy Products. *Small Methods*, *4*(10), 2000349. https://doi.org/10.1002/smtd.202000349

Litchman, E., Klausmeier, C. A., Schofield, O. M., & Falkowski, P. G. (2007). The role of functional traits and trade-offs in structuring phytoplankton communities: scaling from cellular to ecosystem level. *Ecology Letters*, *10*(12), 1170–1181. https://doi.org/10.1111/j.1461-0248.2007.01117.x

Liu, Y., Lv, J., Feng, J., Liu, Q., Nan, F., & Xie, S. (2019). Treatment of real aquaculture wastewater from a fishery utilizing phytoremediation with microalgae. *Journal of Chemical Technology & Biotechnology*, *94*(3), 900–910. https://doi.org/10.1002/jctb.5837

Luo, L., Zhao, Z., Huang, X., Du, X., Wang, C., Li, J., Wang, L., & Xu, Q. (2016). Isolation, Identification, and Optimization of Culture Conditions of a Bioflocculant-Producing Bacterium *Bacillus megaterium* SP1 and Its Application in Aquaculture Wastewater Treatment. *BioMed Research International*, *2016*, 1–9. https://doi.org/10.1155/2016/2758168

Luo, X., Su, P., & Zhang, W. (2015). Advances in Microalgae-Derived Phytosterols for Functional Food and Pharmaceutical Applications. *Marine Drugs*, *13*(7), 4231–4254. https://doi.org/10.3390/md13074231

Ma, K., Bao, Q., Wu, Y., Chen, S., Zhao, S., Wu, H., & Fan, J. (2020). Evaluation of Microalgae as Immunostimulants and Recombinant Vaccines for Diseases Prevention and Control in Aquaculture. *Frontiers in Bioengineering and Biotechnology*, *8*. https://doi.org/10.3389/fbioe.2020.590431

Ma, Y., Liu, J., Li, M., Tao, W., Yu, Z., & Liu, Y. (2019). The use of *Pseudoalteromonas* sp. F15 in larviculture of the Yesso scallop, *Patinopecten yessoensis*. *Aquaculture Research*, *50*(7), 1844–1850. https://doi.org/10.1111/are.14066

Madkour, K., Dawood, M. A. O., & Sewilam, H. (2023). The Use of Artemia for Aquaculture Industry: An Updated Overview. *Annals of Animal Science*, *23*(1), 3–10. https://doi.org/10.2478/aoas-2022-0041

Mulbry, W., Kondrad, S., & Buyer, J. (2008). Treatment of dairy and swine manure effluents using freshwater algae: fatty acid content and composition of algal biomass at different manure loading rates. *Journal of Applied Phycology*, *20*(6), 1079–1085. https://doi.org/10.1007/s10811-008-9314-8

Natrah, F. M. I., Bossier, P., Sorgeloos, P., Yusoff, F. Md., & Defoirdt, T. (2014). Significance of microalgal-bacterial interactions for aquaculture. *Reviews in Aquaculture*, *6*(1), 48–61. https://doi.org/10.1111/raq.12024

Pantami, H. A., Ahamad Bustamam, M. S., Lee, S. Y., Ismail, I. S., Mohd Faudzi, S. M., Nakakuni, M., & Shaari, K. (2020). Comprehensive GCMS and LC-MS/MS Metabolite Profiling of Chlorella vulgaris. *Marine Drugs*, *18*(7), 367. https://doi.org/10.3390/md18070367

Posadas, E., Bochon, S., Coca, M., García-González, M. C., García-Encina, P. A., & Muñoz, R. (2014). Microalgae-based agro-industrial wastewater treatment: a preliminary screening of biodegradability. *Journal of Applied Phycology*, *26*(6), 2335–2345. https://doi.org/10.1007/s10811-014-0263-0

Ragasa, C., Amewu, S., & Asante, S. (2021). *Immediate impacts of COVID-19 on the aquaculture value chain in Ghana*. https://doi.org/10.2499/p15738coll2.134374

Rato, A., Joaquim, S., Tavares, T. G., Martins, Z. E., Guedes, A. C., Pereira, L. F., Machado, J., Matias, A. M., Gonçalves, J. F. M., Vaz-Pires, P., Magnoni, L. J., Ozório, R. O. A., & Matias, D. (2018). Viability of dietary substitution of live microalgae with dry *Ulva rigida* in broodstock conditioning of Pacific oyster (*Crassostrea gigas*). *Biology Open*. https://doi.org/10.1242/bio.035923

Rocha, R. J., Ribeiro, L., Costa, R., & Dinis, M. T. (2008). Does the presence of microalgae influence fish larvae prey capture? *Aquaculture Research*, *39*(4), 362–369. https://doi.org/10.1111/j.1365-2109.2007.01746.x

Röthig, T., Barth, A., Tschirner, M., Schubert, P., Wenning, M., Billion, A., Wilke, T., & Vilcinskas, A. (2023). Insect feed in sustainable crustacean aquaculture. *Journal of Insects as Food and Feed*, 1–24. https://doi.org/10.3920/JIFF2022.0117

Sales, R., Lopes, R. G., Derner, R. B., & Tsuzuki, M. Y. (2022). Concentrated microalgal biomass as a substitute for fresh microalgae produced on site at hatcheries. *Aquaculture Research*, *53*(17), 5771–5786. https://doi.org/10.1111/are.16072

Singh, A., Shourie, A., & Mazahar, S. (2023). Integration of Microalgae-Based Wastewater Bioremediation–Biorefinery Process to Promote Circular Bioeconomy and Sustainability: A Review. *CLEAN – Soil, Air, Water*, *51*(3), 2100407. https://doi.org/10.1002/clen.202100407

Smith, V. H., Joye, S. B., & Howarth, R. W. (2006). Eutrophication of freshwater and marine ecosystems. *Limnology and Oceanography*, *51*(1part2), 351–355. https://doi.org/10.4319/lo.2006.51.1_part_2.0351

Snell, T. W., Johnston, R. K., & Matthews, A. B. (2019). Utilizing Brachionus biodiversity in marine finfish larviculture. *Hydrobiologia*, *844*(1), 149–162. https://doi.org/10.1007/s10750-018-3776-8

Soto-Sánchez, O., Hidalgo, P., González, A., Oliveira, P. E., Hernández Arias, A. J., & Dantagnan, P. (2023). Microalgae as Raw Materials for Aquafeeds: Growth Kinetics and Improvement Strategies of Polyunsaturated Fatty Acids Production. *Aquaculture Nutrition*, *2023*, 1–19. https://doi.org/10.1155/2023/5110281

Tarnecki, A. M., Burgos, F. A., Ray, C. L., & Arias, C. R. (2017). Fish intestinal microbiome: diversity and symbiosis unravelled by metagenomics. *Journal of Applied Microbiology*, *123*(1), 2–17. https://doi.org/10.1111/jam.13415

Uribe-Wandurraga, Z. N., Igual, M., García-Segovia, P., & Martínez-Monzó, J. (2020). *In vitro* bioaccessibility of minerals from microalgae-enriched cookies. *Food & Function*, *11*(3), 2186–2194. https://doi.org/10.1039/C9FO02603G

Vieira, F. R., & Pecchia, J. A. (2022). Bacterial Community Patterns in the Agaricus bisporus Cultivation System, from Compost Raw Materials to Mushroom Caps. *Microbial Ecology*, *84*(1), 20–32. https://doi.org/10.1007/s00248-021-01833-5

von Alvensleben, N., Magnusson, M., & Heimann, K. (2016a). Salinity tolerance of four freshwater microalgal species and the effects of salinity and nutrient limitation on biochemical profiles. *Journal of Applied Phycology*, *28*(2), 861–876. https://doi.org/10.1007/s10811-015-0666-6

von Alvensleben, N., Magnusson, M., & Heimann, K. (2016b). Salinity tolerance of four freshwater microalgal species and the effects of salinity and nutrient limitation on biochemical profiles. *Journal of Applied Phycology*, *28*(2), 861–876. https://doi.org/10.1007/s10811-015-0666-6

Wang, J., Zhang, Q., Chen, N., Chen, J., Zhou, J., Li, J., Wei, Y., & Bu, D. (2022). A new Desmodesmus sp. from the Tibetan Yamdrok Lake. *PLOS ONE*, *17*(10), e0275799. https://doi.org/10.1371/journal.pone.0275799

Wikfors, G. H., & Ohno, M. (2001). Impact Of Algal Research In Aquaculture. *Journal of Phycology*, *37*(6), 968–974. https://doi.org/10.1046/j.1529-8817.2001.01136.x

Yaakob, Z., Ali, E., Zainal, A., Mohamad, M., & Takriff, M. S. (2014). An overview: biomolecules from microalgae for animal feed and aquaculture. *Journal of Biological Research-Thessaloniki*, *21*(1), 6. https://doi.org/10.1186/2241-5793-21-6

Yang, L., Li, H., Lu, Q., & Zhou, W. (2021). Emerging trends of culturing microalgae for fish-rearing environment protection. *Journal of Chemical Technology & Biotechnology*, *96*(1), 31–37. https://doi.org/10.1002/jctb.6563

Yang, X., Cao, D., Chen, J., Xiao, Z., & Daowd, A. (2020). AI and IoT-based collaborative business ecosystem: a case in Chinese fish farming industry. *International Journal of Technology Management*, *82*(2), 151. https://doi.org/10.1504/IJTM.2020.107856