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Food and Agriculture Organization of the United Nations

Organisation des Nations Unies pour l'alimentation et l'agriculture

Продовольственная и сельскохозяйственная организация Объединенных Наций

Organización de las Naciones Unidas para la Alimentación y la Agricultura

منظمة الأغذية والزراعة للأمم المتحدة

COMMITTEE ON FISHERIES

SUB-COMMITTEE ON AQUACULTURE

Thirteenth Session

Rome, Italy, 20–23 May 2025

THEMATIC FOCUS 2: AQUACULTURE AND THE CIRCULAR ECONOMY

EXECUTIVE SUMMARY

Aquaculture is emerging as a crucial solution to global food security challenges, especially in the context of the growing population and the increasing demand for nutritious, safe and diverse foods. Integrating circularity principles into aquaculture value chains presents a transformative opportunity to maximize resource efficiency and minimize waste and pollution of aquatic food systems, thus improving overall sector sustainability.

Current circularity concepts, designs, and practices in aquaculture value chains focus on four key areas: (1) optimizing feed inputs by developing and adopting alternative aquafeed ingredients to reduce dependence on conventional feed sources; (2) reusing and recycling resources through integrated aquaculture systems that promote resource efficiency across various production components; (3) valorizing fish by-products and aquaculture waste to support the bioeconomy, with applications in food, feed, agriculture, and energy sectors; and (4) integrating renewable energy into aquaculture operations to reduce reliance on fossil fuels and minimize the industry's carbon footprint.

This working document provides an analysis of current circularity concepts, designs and practices in aquaculture value chains. It examines the key challenges, constraints, and lessons learned from these practices while outlining potential pathways to enhance circularity in the sector. Additionally, it highlights the FAO initiatives and Strategic Plan on sustainable aquaculture development, circularity principles, and bioeconomy.

Suggested action by the Sub-Committee
The Sub-Committee is invited to: ➢ Recognize the importance, significance, and development potential of sustainable aquaculture systems within the circular economy and bioeconomy; ➢ Encourage Members to share experiences, lessons learned, and cases of success in policy development, planning, and applying circularity principles in aquaculture across diverse contexts; and ➢ Recommend specific actions, activities, and provide detailed guidance to FAO to support and expedite the development of sustainable aquaculture systems in the circular economy.

INTRODUCTION

1. Aquaculture plays a pivotal role in addressing global food security by providing nutrient-rich food source of high-quality proteins, omega-3 fatty acids, minerals, and vitamins to meet the growing population's dietary needs. It supports the livelihoods of millions worldwide, particularly in coastal and rural communities, while contributing significantly to the global economy.[1] As an important food production system, aquaculture offers a viable solution to pressing global challenges, such as hunger, poverty, and climate change.[2]

2. However, the rapid growth of aquaculture has garnered criticism for its environmental impacts. A significant portion of this criticism centres around a critical question of whether aquaculture growth is driving a corresponding increase in the demand for fishmeal (FM) and fish oil (FO) as key feed ingredients, thus adding pressure to the associated fisheries.[3] Furthermore, fisheries and aquaculture generate a substantial amount of waste along value chains in the form of product residues and processing by-products, which raise concerns about environmental impacts if not properly managed.

3. A circular economy refers to economic systems based on business models that reuse, recycle and recover (also known as the three Rs of sustainability or the 3R approach) materials in production, distribution and consumption processes for achieving sustainable development. The concept can also be characterized as an approach that can reduce resource consumption by slowing, closing or narrowing natural resource loops.[4] The principles of circularity can be applied to the wider bioeconomy for agrifood systems transformation.[5] An aquaculture system build with circularity principles could minimize waste and maximize resource efficiency by keeping materials, products, and resources in use as long as possible. It is based on three key circular principles: (1) eliminating wastes and pollution; (2) circulating products and materials at their highest value; and (3) regenerating nature, all driven by design.[6]

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[1] FAO. 2024. *The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action*. Rome. https://doi.org/10.4060/cd0683en

[2] Wong, A., Frommel, A.Y., Sumaila, U.R. *et al.* A traits-based approach to assess aquaculture's contributions to food, climate change, and biodiversity goals. *npj Ocean Sustain* 3, 30 (2024). https://doi.org/10.1038/s44183-024-00065-7

[3] FAO. 2025. *Responsible use of fishmeal in aquaculture*. FAO Innovation for Blue Transformation. Rome. https://openknowledge.fao.org/handle/20.500.14283/cd3660en

[4] FAO. 2022. The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. Rome, FAO. https://doi.org/10.4060/cd1211en

[5] FAO. 2024. *Bioeconomy for food and agriculture: A global stocktaking study*. Rome. https://doi.org/10.4060/cd2490en

[6] Ellen MacArthur Foundation. 2013. *Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition*. www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

4. The FAO Strategic Framework 2022−2031,[7] endorsed at the 42nd Session of the FAO Conference, includes the Programme Priority Area 'Bioeconomy for sustainable food and agriculture.' The Communiqué of the Global Bioeconomy Summit 2024 defines the bioeconomy as "the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy." It also notes that the bioeconomy is not a static notion, and its meaning is continually evolving.[8]

5. The notion of bioeconomy was brought to the attention of the Committee on Fisheries at its 36th Session, held in 2024, which acknowledged the great potential for aquatic systems to contribute to the bioeconomy,[9] and Members called on FAO to "integrate sustainable aquatic products into the broader implementation of bioeconomy programmes, especially those related to small-scale fisheries, Indigenous Peoples and local communities."[10]

6. As resource optimization to improve use efficiency, environmental concerns and the need for sustainable practices gain prominence, integrating circularity principles into aquaculture is becoming increasingly vital to transitioning towards a more sustainable and resilient economy.

7. While the concept of circularity has been developed and discussed since the 1970s, only recently has it attracted significant attention from the aquaculture community. Innovations and practices based on circularity principles have been promoted, developed and implemented, aiming at: (1) optimizing aquaculture feed inputs to reduce reliance on finite resources, such as FM and FO from capture fisheries; (2) reusing and recycling resources within aquaculture systems; (3) utilizing fish by-products and aquaculture loss and waste as resources for food, feed, agricultural inputs and energy; and (4) integrating renewable energy into aquaculture operations. All these will need to be systematically integrated with holistic management approaches into sustainable aquaculture value chains and will require enabling policies to accelerate the adoption of viable solutions for positive impact at a larger scale.

OPTIMIZING AQUACULTURE FEED INPUTS TO REDUCE DEPENDENCE ON FINITE RESOURCES

8. As the demand for aquatic food continues to rise, the need for aquafeed to support the growing aquaculture sector will also increase. Currently, the majority of ingredients used in aquafeed manufacture are derived from terrestrial crops, agricultural by-products, FM and FO produced from low-value forage fish and fish by-products. Increasing aquafeed production would intensify the competition for these resources, which serve multiple purposes, including human consumption and livestock feed.[11]

9. The production and utilization of innovative and eco-friendly ingredients derived from food system by-products (secondary products created alongside primary human-consumable products) emerges as a pivotal solution to increase resource use efficiency, reduce food-feed competition and increase food system circularity. Increasing the use of these by-products as feed ingredients has

[7] FAO. 2021. *Strategic Framework 2022−31*. FAO, Rome. https://openknowledge.fao.org/handle/20.500.14283/cb7099en

[8] International Advisory Council on Global Bioeconomy. 2024. *Communiqué of the Global Bioeconomy Summit 2024*. https://gbs2024.org/news/iacgb-communique/

[9] FAO, 2024. *Bioeconomy for Sustainable Food and Agriculture*. COFI/2024/INF/18. Rome. https://openknowledge.fao.org/handle/20.500.14283/np538en

[10] FAO. 2024. *Report of the Thirty-sixth Session of the Committee on Fisheries*, Rome, 8–12 July 2024. FAO Fisheries and Aquaculture Report, No. 1459. Rome. https://doi.org/10.4060/cd2423en

[11] Rana, K.J.; Siriwardena, S.; Hasan, M.R. 2009. *Impact of rising feed ingredient prices on aquafeeds and aquaculture production*. FAO Fisheries and Aquaculture Technical Paper. No. 541. Rome, FAO. 2009. 63 pp. https://openknowledge.fao.org/handle/20.500.14283/i1143e

considerable potential, particularly when combined with other measures, in supporting the much-needed transition towards circular food systems.[12]

Responsible use of fishmeal

10. Substantial progress has been made in the fed-aquaculture sector, including innovations in farming systems, technological advancements, and development and improvements in the variety of ingredients used. These developments have significantly reduced the reliance on aquafeed on FM and FO, and as a result the proportion of FM used in aquafeed has declined from 19 percent in 2000 to 9 percent in 2020.[13]

11. While aquaculture production of aquatic animals has increased dramatically in recent decades, the amount of FM and FO used has not proportionally increased, suggesting that globally aquaculture growth has not driven an increase in capture fisheries used for reduction into FM, although it has changed some regional patterns of reduction fisheries.[14]

Fish by-products for aquafeed

12. Fish by-products (aquatic food residues and aquatic food processing by-products) have emerged as a valuable source for producing FM and FO. The share of FM derived from fish by-products has increased from 25 percent in 2010 to an estimated 34 percent of the global FM production in 2022. This trend is expected to continue in the future.[15] In 2023, approximately 39 percent of the global FM production and 54 percent of the global FO production originated from fish by-products,[16] contributing significantly to principles of circular economy.

13. The quality of FM produced from fish by-products depends on the freshness and nutritional quality of the raw materials. The use of innovative production techniques for fish by-product reduction into FM and FO has resulted in high-quality products with good nutritional and market value.

14. Where setting up an FM plant is not economically viable due to the limited or inconsistent availability of fish by-products, or lack of sufficient logistics and infrastructure for efficient collection, transportation, and processing of fish by-products, the production of fish silage could be an alternative. Fish silage is a liquid product made from whole fish or fish parts, which are liquefied by the action of enzymes in the fish in the presence of an added acid. All fish by-products can then be processed into a hydrolysate with a nutritional composition like what is found in FM when excluding the water. Fish silage can replace some of the FM in feed.

15. Through biorefineries, fish by-products can be processed into ingredients with unique properties needed for specific feed, such as larvae feed. This could also partially replace FM or be supplemented with other plant-, animal-, or microbial-based ingredients.

16. Wastewater derived from fish trimmings contains soluble proteins, fats and other valuable organic compounds. By implementing advanced processing techniques, this nutrient-rich effluent has the potential to be processed into FM and FO and other value-added products.

[12] Sandström, V., Chrysafi, A., Lamminen, M. et al. 2022. *Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply.* Nat Food 3, 729–740 (2022). www.nature.com/articles/s43016-022-00589-6

[13] Glencross, B., Ling, X., Gatlin, D., Kaushik, S., Øverland, M., Newton, R., Valente, L.M. 2024. *A SWOT Analysis of the Use of Marine, Grain, Terrestrial-Animal and Novel Protein Ingredients in Aquaculture Feeds.* Reviews in Fisheries Science & Aquaculture, 1–39. https://doi.org/10.1080/23308249.2024.2315049

[14] FAO. 2024. *The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action*. Rome. https://doi.org/10.4060/cd0683en

[15] FAO. 2025. *Responsible use of fishmeal in aquaculture.* FAO Innovation for Blue Transformation. Rome. https://openknowledge.fao.org/handle/20.500.14283/cd3660en

[16] IFFO, 2024. *The sources of marine ingredients: whole fish & by-products.* www.iffo.com/sources-marine-ingredients-whole-fish-products

17. Aquafeed developed from transformed fish waste offers several advantages. It delivers essential nutrients, such as amino acids, fatty acids, vitamins, macro-minerals, and trace elements, which may be lacking in other (non-FM) alternative formulations. Additionally, these nutrients improve palatability.

18. Depending on the inclusion rates, fish by-product-based ingredients can produce edible food products with compositional characteristics similar to those produced from FM. Incorporating fish by-products and waste into aquafeed would also contribute to sustainable development goals by reducing food loss and promoting circularity in the aquaculture industry.[17]

Agricultural by-products for aquafeed

19. Agriculture by-products include crop residues (the plant material left after harvesting) and processing by-products, such as cereal brans and distiller's grains, sugar by-products, oilseed meals, and fruit by-products. Many of these by-products have been used directly or further processed for use as supplementary feed or as ingredients in formulated aquafeed.

20. Inclusion of fruit by-products and their derivatives from industrial processing of apples, citrus, bananas and grapes into aquafeed as partial alternatives to conventional ingredients has been experimentally explored with several aquatic animals. The aquafeed incorporating fruit by-products sustained the growth performance, productivity and well-being of aquatic animals. The bioactive derivatives of fruit by-products are recognized as immunostimulants, antimicrobials and antioxidative agents. Fruit by-products could become one of the most sustainable plant by-products for the development of the aquafeed production industry.[18]

Terrestrial animal by-products for aquafeed

21. Diverse sources of animal protein are used in compound aquafeed. Rendered animal by-products are the most widely available products.[19] These include meat and bone meal, meat meal, hydrated feather meal, poultry by-product meal, blood meal, and other animal products. The increasing use of appropriately processed animal by-product meals in compound aquafeed provides a way to safely recycle animal by-products into feed for farmed aquatic animals. This has the advantage of converting non-food-grade products with potentially negative environmental impacts accruing to their disposal (through dumping or incineration) into high-quality, nutritious and safe aquatic foods.

22. Early concerns about variable nutrient quality (e.g. high ash contents in meat and bone meals, and amino acid imbalances in feather meal) have been mitigated by modern rendering techniques. Animal by-products, after being properly reprocessed, present great potential to replace FM within aquafeeds when species-specific nutritional requirements are taken into consideration and safety standards are adhered to. As FM and FO substitutes, their use can reduce pressures on marine resources, while lowering feed production costs and improving the profitability of aquaculture ventures.

Insects as an aquafeed ingredient

23. Insects are the most diverse group of animals and a natural food for many fish species. At least sixteen insect species have been tested as an alternative protein source in aquafeeds, and eight insect

[17] Colombo S.M., Roy K., Mraz J., Wan A.H.L., Davies S.J., Tibbetts S.M., Øverland M., Francis D.S., Rocker M.M., Gasco L., Spencer E., Metian M., Trushenski J.T., Turchini G.M. 2022. *Towards achieving circularity and sustainability in feeds for farmed blue foods.* Reviews in Aquaculture 2022, 1–27. doi:10.1111/raq.12766. https://onlinelibrary.wiley.com/doi/epdf/10.1111/raq.12766

[18] Mahmoud A. O. Dawood et al. 2022. *Fruit processing by-products in the aquafeed industry: A feasible strategy for aquaculture sustainability.* Reviews in Aquaculture, Vol. 12, Issue 4, 1945-1965. www.researchgate.net/publication/360314813_Fruit_processing_by-products_in_the_aquafeed_industry_A_feasible_strategy_for_aquaculture_sustainability

[19] Tacon, Albert G.J. 2000. *Rendered animal byproducts: A necessity in aquafeeds for the new millennium*. The Global Aquaculture Advocate, *August 2000.* www.globalseafood.org/advocate/rendered-animal-byproducts-a-necessity-in-aquafeeds-for-the-new-millennium/

species have been used on a trial basis for industrial aquafeed production.[20] Rearing insects on organic waste and agricultural by-products transforms them into valuable resources. This process not only provides a high-quality protein source for aquafeed but also contributes to waste reduction and minimizes waste disposal challenges. Insect meals generally have higher protein contents and superior amino acid profile when compared to plant-based feed ingredients. For instance, in comparison with plant-based protein sources, the black soldier fly meal has a more comparable amino acid profile and elicits a similar protein digestibility to FM.[21] Using insect meal as an alternative to FM in aquafeeds presents a significant opportunity to reduce the current dependence on marine fish resources.

Development of algae-based feeds

24. Microalgae biomass, with its unique composition of bioactive cell metabolites, holds significant potential as a feed ingredient. Rich in essential amino acids, fatty acids, vitamins, and pigments, it provides a balanced and nutrient-dense profile. Beyond serving as a primary component in aquafeeds, microalgae also offer a variety of bioactive compounds that enhance the health and survivability of farmed species while improving the quality of their flesh.[22, 23]

25. Mass production of microalgae offers several advantages over macrophytes. They are photosynthetically more productive, often making their large-scale production both highly efficient and commercially viable. Furthermore, they can be intensively produced with minimal water and arable land requirements, positioning them as an environmentally friendly alternative to the use of traditional FM and FO in aquafeed formulations.[24]

REUSE AND RECYCLE RESOURCES IN AQUACULTURE SYSTEMS

26. Many aquaculture systems are designed with a circular approach, focusing on nutrient reuse, recycling, and recovery. These systems integrate multiple species into a single environment, where waste from one subsystem, whether aquatic or terrestrial, serves as input for another. This concept has led to the development of various integrated systems, which differ based on the species involved, farming technologies, operational intensity, and recycled resources.[25] A key feature of these systems is the synergies and trophic complementarity between species, which enable the upcycling of nutrients from both solid and dissolved waste. Among primary varieties of integrated aquaculture systems are integrated agriculture-aquaculture (IAA), integrated multitrophic aquaculture (IMTA), aquaponics, and polyculture.

Integrated agriculture-aquaculture

27. An IAA system consists of two or more concurrently or sequentially linked farming components, of which at least one is aquaculture. By integrating these components into one system, an

[20] Yuzer Alfiko, Dizhi Xie, Retno Tri Astuti, Joey Wong, Le Wange. 2022. *Insects as a feed ingredient for fish culture: Status and trends.* Aquaculture and Fisheries 7 (2022) 166–178.

[21] Zulkifli NFNM, Seok-Kian AY, Seng LL, Mustafa S, Kim Y-S, Shapawi R, 2022. *Nutritional value of black soldier fly (Hermetia illucens) larvae processed by different methods*. PLoS ONE 17(2): e0263924. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0263924

[22] Kiran BR, Venkata Mohan S. 2021. *Microalgal Cell Biofactory-Therapeutic, Nutraceutical and Functional Food Applications.* Plants (Basel). 2021 Apr 21;10(5):836. https://doi.org/10.3390/plants10050836

[23] Ahmad, A., W. Hassan, S., & Banat, F. 2022. An overview of microalgae biomass as a sustainable aquaculture feed ingredient: food security and circular economy. Bioengineered, 13(4), 9521–9547. https://doi.org/10.1080/21655979.2022.2061148

[24] Nagappana, S., Das, P., AbdulQuadir, M. Thaher, M., Khan, S., Mahat, C., Al-Jabri, H., Vatland, A.K., Kumar, G. 2024. *Potential of microalgae as a sustainable feed ingredient for aquaculture.* Journal of Biotechnology 341 (2021) 1–20. https://doi.org/10.1016/j.jbiotec.2021.09.003

[25] Yuan, D., Edward, P. & Halwart, M. 2019. *Current Practices and Future Prospects for Integrated Agriculture and Aquaculture in Asia – A Regional Review. In* FAO. 2019. Report of the Special Session on Advancing Integrated Agriculture Aquaculture through Agroecology, Montpellier, France, 25 August 2018. FAO Fisheries and Aquaculture Report No. 1286. Rome.
https://openknowledge.fao.org/server/api/core/bitstreams/41eaf371-113f-4024-bf3d-49a49d8256b9/content

output from one component, which otherwise would go to waste, is used as an input for another component. The circular approach enhances land, water and nutrient efficiency compared to standalone agriculture or aquaculture systems with similar resource inputs and operational intensity. IAA systems are typically semi-intensive, exhibiting greater stability and resilience and less negative environmental impacts due to their diverse production functions and ability to reuse waste nutrients within the system.

28. A typical example of IAA is rice-fish culture that integrates rice farming with fish cultivation, creating a mutually beneficial system. Fish control pests, weeds, and algae while fertilizing the soil, improving rice yields. In return, rice plants provide shade and protection for fish. This method boosts food production, increases farmers' income, and optimizes land and water use. It also reduces reliance on chemical fertilizers and pesticides, promoting biodiversity and ecosystem health. Similar systems have been developed to co-culture other aquatic animals of higher market value with rice, such as crayfish, mitten crabs, and rice-field eels. Some systems, e.g. the crayfish-rice integrated culture in China, are highly productive and economically efficient.[26] These systems have the potential to support the intensive production of aquatic animals while simultaneously enhancing water, space, and nutrient use efficiency.

Integrated multitrophic aquaculture

29. In an IMTA system, fed aquaculture species (e.g. shrimp or finfish) are cultured alongside inorganic extractive species (e.g. seaweeds, microalgae or other vegetation), organic extractive species (e.g. shellfish, which are suspension and/or deposit feeders) and benthic detritivores (e.g. sea cucumbers).[27] When cultured in the right proportions, these extractive species recycle nutrients excreted by the fed species that would otherwise be lost in the system. By mimicking natural ecosystems, IMTA promotes nutrient cycling, enhances biodiversity and optimizes resource utilization in aquatic environments.

Aquaponics

30. Aquaponics, an IAA system, combines aquaculture and hydroponics to create a mutually beneficial system. In this setup, fish waste acts as a natural fertilizer for the plants, while the plants help filter and purify the water for the fish. This closed-loop system minimizes water usage, eliminates the need for chemical fertilizers, and optimizes land use, resulting in a highly efficient and sustainable method of food production. It offers a promising solution for growing both fish and crops in a resource-efficient manner.

Polyculture

31. Polyculture involves cultivating two or more species within the same culture system, where they occupy different trophic levels and spatial niches. A key advantage of polyculture is the reduction of feed waste and the more efficient use of nutrient and water resources. Additionally, polyculture promotes biodiversity, which enhances resilience against diseases, pests, and environmental fluctuations, making the system more stable and sustainable.

32. A typical example is the Chinese carp polyculture system where grass carp, silver carp, bighead carp, common carp, mud carp and black carp are cultured together in the same pond. Grass carp, as herbivores, consume green forages and other artificial inputs, while silver carp and bighead carp, as filter feeders occupying the water column, feed on phytoplankton and zooplankton respectively. Common carp, mud carp and black carp are bottom feeders, scavenging on detritus, benthos and molluscs. Uneaten feed and fish wastes fertilize the pond, supporting phytoplankton growth and sustaining the ecosystem.

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[26] Jiang, Y., Cao, C. 2021. *Crayfish–rice integrated system of production: an agriculture success story in China.* A review. *Agron. Sustain. Dev.* 41, 68 (2021). https://doi.org/10.1007/s13593-021-00724-w

[27] Chopin, T. 2013. Integrated multitrophic aquaculture (IMTA). In R. A. Meyers (Ed.), *Encyclopedia of sustainability science and technology*. Springer. https://doi.org/10.1007/978-1-4419-0851-3_173

Recirculating aquaculture systems

33. Recirculating aquaculture systems (RAS) provide an innovative solution for sustainable aquaculture by minimizing water usage and environmental impacts. This technology achieves water efficiency and nutrient recycling through the following five mechanisms:

(i) **Filtration and reuse:** RAS provides a closed-loop water system where water is continuously filtered, allowing it to be reused multiple times. This reduces the overall water intake needed for fish farming and lowers the potential for pollutants to reach external water bodies. The filtration process also captures valuable nutrients, such as nitrogen and phosphorus, which can be repurposed as fertilizers or used in integrated farming systems, promoting a closed-loop approach.

(ii) **Reduction of discharge:** By recycling water, RAS limits waste discharge, thus minimizing impact on local ecosystems and reducing the risk of nutrient pollution common in traditional aquaculture methods. This is crucial for preserving water quality and protecting aquatic biodiversity.

(iii) **Conservation of resources:** RAS uses much less freshwater drawn from natural sources compared to other conventional aquaculture systems, contributing to the conservation of freshwater resources amid increasing global water scarcity.

(iv) **Scalability of urban aquaculture:** RAS technology is particularly well-suited for urban environments where space and water resources may be limited. By promoting vertical integration and production efficiency, RAS supports local food security initiatives in densely populated areas. This is especially meaningful for cities far from traditional farming areas, as it reduces reliance on long supply chains and ensures a steady supply of fresh produce. The controlled environment of RAS allows for continuous production, regardless of external weather conditions, which is particularly beneficial for maintaining a steady supply of fish throughout the year.

(v) **Enhanced biosecurity:** The controlled environment of RAS allows for better management of pathogens and diseases, reducing the need for antibiotics and chemicals. This aligns with circularity principles by emphasizing health and reducing chemicals and waste.

VALORIZING FISH BY-PRODUCTS AND AQUACULTURE LOSS AND WASTE

34. The traditional linear economy model, characterized by a "take-make-dispose" approach, significantly contributes to environmental degradation and resource depletion. In contrast, a circular model emphasizes sustainability by pursuing the minimization of raw material inputs, valorization of wastes or side streams, preservation of the resource value of a product as long as possible during its life cycle, process redesign and reintegration of used products at their end-of-life. Investments in bioeconomy industries, such as biorefineries that transform the waste using biotechnology, should be promoted as part of agrifood systems transformation and the development of coastal areas.[28]

35. Fish by-products, including heads, skin, fin, scale, viscera, account for approximately 30 to 70 percent of total aquatic production,[29] and hold immense potential for reuse. They can be converted into food, feed, functional bioproducts, and agricultural inputs. Aquaculture waste, such as effluent and sludge, traditionally considered a problem, can also be processed into biofertilizers or used for the production of biogas. These applications not only add value to fish by-products and aquaculture wastes but also contribute to sustainability by reducing waste and promoting circularity.

[28] Gomez San Juan, M. 2024. *The bioeconomy toolbox – A guide to support the development of sustainable bioeconomy strategies and policies*. Environment and Natural Resources Management Working Paper, No. 99. Rome, FAO. https://doi.org/10.4060/cc8856en

[29] Naghdi, S., Rezaei, M., Heidari, M.G., Tahergorabi, R., Lorenzo, J.M. & Mirzaei, F. 2024. *Insights into fishery by-product application in aquatic feed and food: a review.* Aquacult Int 32, 5851–5910 (2024). https://doi.org/10.1007/s10499-024-01447-x

Fish by-products for food

36. The most nutrient-dense parts of fish, such as heads, bones and skin, are often discarded during processing. However, simple technologies like drying, canning, and mincing can be used to create tasty and nutritious products for human consumption from these overlooked parts. By designing processing methods, these by-products can be reintroduced and upcycled into the food system, transforming them into valuable human food. This can significantly reduce food loss and waste, conserve nutrients, and lessen the ecological footprint of food production.

Fish by-products for nutraceuticals, pharmaceuticals, cosmetic products and the textile industry

37. Fish by-products contain various bioactive compounds and natural pigments, such as carotenoids, collagen and protein hydrolysates, which can be extracted and isolated for use in functional food, nutraceuticals, pharmaceuticals, and cosmetic products due to their antihypertensive, antioxidative, anticoagulant and antimicrobial properties.[30,31] Currently, these high-value components are recovered in small amounts through cost-effective resource-recycling processes. However, more efficient extraction methods could significantly increase their yield.

38. By-products from crustacean processing industries (mainly heads and shells) account for approximately 75 percent of the total weight of crustaceans (shrimp, crabs, prawns, lobster and krill). Chitin comprises 20-58 percent of the dry weight of these by-products..[32] Chitin extraction from crustacean shells offers a potential solution to minimize waste and produce valuable compounds. Chitin and its derivatives are renewable, biocompatible, biodegradable, and non-toxic. They are used as biomaterials in a wide range of applications, including biomedical purposes (e.g. artificial skin, bones and cartilage regeneration), food preservation (e.g. edible films), pharmaceutical purposes (e.g. drug delivery),[33] and agriculture (e.g. biopesticides, biofertilizers, and agricultural films for seed and fruit coatings).[34]

39. Fish scales and skin are also being explored for use in the textile industry.[35] Innovations in sustainable fashion have led to the development of fish leather, which is durable and has a unique texture. This leather is used in making accessories like bags, shoes, and belts,[36] and is also used in jewellery and other accessories in the fashion industry.

Fish by-products and aquaculture waste for biofertilizers

40. As the global demand for organic farming increases, there is a growing need for efficient and environmentally friendly fertilizer solutions. Fish by-products and aquaculture waste, such as effluent

[30] Gomez San Juan, M., Bogdanski, A. & Dubois, O. 2019. *Towards sustainable bioeconomy - Lessons learned from case studies.* Rome, FAO. 132 pp. License: CC BY-NC-SA 3.0 IGO. https://openknowledge.fao.org/server/api/core/bitstreams/5509d9e4-34f9-47ea-b312-7b40029fd66c/content

[31] Responsible Seafood Advocate. 2024. *Circular economy: New tech turns fish waste into valuable pharma and cosmetic ingredients*. www.globalseafood.org/advocate/circular-economy-new-tech-turns-fish-waste-into-valuable-pharma-and-cosmetic-ingredients/

[32] S.M. Kuddus, R.I.Z. Ahmad. 2013. *Isolation of novel chitinolytic bacteria and production optimization of extracellular chitinase.* Journal of Genetic Engineering and Biotechnology, 11 (2013), pp. 39-46. https://doi.org/10.1016/j.jgeb.2013.03.001

[33] Imen Hamed, Fatih Özogul, Joe M. Regenstein, 2016. *Industrial applications of crustacean by-products (chitin, chitosan, and chitooligosaccharides): A review.* Trends in Food Science & Technology, Vol. 48, 40-50. www.sciencedirect.com/science/article/pii/S0924224415002721

[34] Malerba M, Cerana R. 2019. *Recent Applications of Chitin- and Chitosan-Based Polymers in Plants.* Polymers (Basel). 2019 May 8;11(5):839. www.researchgate.net/publication/332993030_Recent_Applications_of_Chitin-_and_Chitosan-Based_Polymers_in_Plants

[35] Erh-Jen Hou, Chi-Shih Huang, Ying-Chou Lee, Hsueh-Ting Chu. 2022. *Upcycled aquaculture waste as textile ingredient for promoting circular economy,* Sustainable Materials and Technologies, Volume 31.

[36] The Sustainable Living Guide. 2024. *The Rise of Fish Leather in the Fashion Industry.* https://thesustainablelivingguide.com/fish-leather/

and sludge, are rich in nutrients like nitrogen and phosphorus as well as trace elements, such as potassium, calcium, magnesium, iron, copper and manganese. These waste materials can be recovered and processed into biofertilizers for agricultural use while ensuring contamination risks are addressed. The repurposing enables these waste nutrients to be recycled from aquatic food production systems back into agriculture, simultaneously addressing the issue of waste management in aquatic food systems and reducing the environmental impacts caused by mining and artificial fertilizers.

Fish by-products and aquaculture waste for renewable energy

41. Fish by-products, wastewater from fish trimmings, and aquaculture effluent are rich in nutrients and organic matter. They have the potential to be repurposed for biofuel production as a renewable energy source.

42. For instance, oil extracted from tilapia by-products has been demonstrated as a promising source for producing biofuel. With the addition of chemical catalysts and short-chain alcohols, the oil can be transesterified and converted into biodiesel.[37] Additionally, fish by-products can be used as substrates to produce biogas through anaerobic biodigestion.[38]

43. Seaweeds represent a promising and sustainable feedstock for biofuel production. Their high availability, easy fermentable composition, and good degradation potential make them a suitable candidate for alternating fossil fuels as an advantageous energy resource.[39,40]

44. Intensive aquaculture, e.g. intensive shrimp culture, often produces large amounts of solid waste in the form of semi-flowing sludge, which contains biomass of high energy and nutrient contents. It can be treated in anaerobic biodigesters to produce biogas.[41]

RENEWABLE ENERGY INTEGRATION IN AQUACULTURE

45. With the growing demand for environmentally friendly practices to reduce greenhouse gas emissions and carbon footprint, the growing importance of optimizing aquaculture systems powered by renewable energies is increasingly gaining recognition in the global food production sector.

46. Intensifying competition for land resources, as the world's population surges, leads to the use of land for two distinct production purposes, such as aquaculture-photovoltaic integration, which provides an approach to increase land use efficiency.

47. Aquavoltaics, where solar panels are constructed over aquaculture water surfaces, allow for the simultaneous production of aquatic animals and solar electricity. The use of land for two production purposes increases land use efficiency, easing the ever-intensifying competition for land resources by different sectors.

[37] Lee, T. C. et al. 2022. Tilapia wastes to valuable materials: A brief review of biomedical, wastewater treatment, and biofuel applications. Mat. Today Proc. 57, 1389–1395. https://doi.org/10.1016/j.matpr.2022.03.174

[38] Bücker, F., Marder, M., Peiter, M.R., Neutzling Lehn, D., Mendonça Esquerdo, V., de Almeida Pinto, L.A., & Konrad, O. 2020. *Fish waste: An efficient alternative to biogas and methane production in an anaerobic mono-digestion system*. Renewable Energy, Volume 147, Part 1, Pages 798-805. https://doi.org/10.1016/j.renene.2019.08.140

[39] Zhao, Y., Bourgougnon, N., Lanoisellé, J-L., and Lendormi, T. 2022. *Biofuel Production from Seaweeds: A Comprehensive Review*. Energies. 2022; 15(24):9395. https://doi.org/10.3390/en15249395

[40] Alvarado-Ramírez, L., Santiesteban-Romero, B., Poss, G., Sosa-Hernández, J.E., Iqbal, H.M.N., Parra-Saldívar, R., Bonaccorso, A.D. & Melchor-Martínez, E.M . 2023. *Sustainable production of biofuels and bioderivatives from aquaculture and marine waste* Frontiers in Chemical Engineering, vol. 4, 1072761. https://doi.org/10.3389/fceng.2022.1072761

[41] Rittiron, T. and Wannakomol, A. 2015. *The biogas production from shrimp farming waste*. Suranaree J. Sci. Technol. 23(2):85-90. www.thaiscience.info/Journals/Article/SJST/10984547.pdf

48. Integrating solar energy into aquaculture farms provides an alternative off-grid and power backup solution. This is particularly crucial for aquaculture operations in remote areas or places where power grids are inaccessible, or electricity supply is unreliable.

49. Recent advancements in integrating solar energy in aquaculture have led to the invention of solar pond aerators, which provide an eco-friendly and potential cost-effective way for pond aeration.

50. The integration of renewable energy sources into aquaculture practices reduces the dependence of aquaculture on energy supply from fossil fuels, decreases greenhouse gas emissions, leads to significantly lower carbon footprints, saves aquaculture operational costs, and therefore plays a critical role in enhancing aquaculture efficiency and circularity.

ISSUES, CONSTRAINTS AND CHALLENGES

51. Integrating circularity principles into aquaculture presents a promising opportunity to improve resource efficiency, reduce environmental impacts and enhance both sustainability and profitability. However, the transition to circular practices in aquaculture value chains comes with a range of challenges, constraints, and issues that must be overcome to achieve success.

Policy and regulatory barriers

52. The existing policies and regulations are often overly broad and not well-suited to support or encourage circular aquaculture economy initiatives effectively. Policies specifically supporting circular aquaculture may be developed based on the current policy and legislation framework.

53. Some policies and regulations are outdated, hindering the implementation of sustainable practices and causing stakeholders to be hesitant to adopt circular models. It is crucial to review and update these regulations, especially considering the latest technological advancements and their impact on utilizing and valorizing food system by-products and waste.

54. Clear definitions specifically for circular strategies and approaches in aquaculture have yet to be established, nor has a framework for a circular aquaculture economy. This lack of clarity leads to confusion and challenges in monitoring, evaluating, and regulating the practices and their impacts.

Technology complexity

55. Developing circular aquaculture involves redesigning production systems based on ecological principles, with the focus first on rethinking the way we produce and use, then on preventing and reducing waste, and finally on resource reuse and upcycling. Aquaculture includes a wide variety of species, culture systems, and resources, creating a challenge in the development of technologies and innovations to address this complexity.

56. Integrated aquaculture, which involves the production of multiple species, necessitates a diverse set of knowledge and skills to manage various farming components effectively. This poses significant challenges, especially for small-scale farmers.

57. Biological values and the quality of fish by-products and aquaculture waste vary significantly. Valorizing these resources requires the development and utilization of specialized technologies and facilities and adapting them to the local context.

Inadequate infrastructure

58. Inadequate infrastructure for systematic collection, transportation, storage, waste treatment, and by-product processing poses significant barriers to establishing circular systems in aquaculture value chains. Often, facilities for waste treatment and valorization are lacking at the aquaculture farm level.

Financial constraints

59. Transitioning to a circular model in aquaculture entails upfront investments in technology and infrastructure, which may not guarantee immediate financial returns. This economic uncertainty can deter producers from adopting sustainable practices despite their long-term benefits.

60. Products from circular aquaculture models often command a premium because of the high cost of reprocessing and limited supply, or the additional cost associated with waste reuse, recycling, and reduction.

Awareness gaps

61. The concept of circular economy was developed as early as the 1970s. However, the purposeful link and conceptual association between CE and aquaculture are relatively recent developments. Knowledge gaps among aquaculture stakeholders regarding circularity principles can obstruct implementation. Educational initiatives are essential to encourage sustainable practices and emphasize the benefits of circular systems.

Insufficient stakeholder collaboration

62. Successful implementation of circular practices requires cooperation among various stakeholders, including farmers, processors, policymakers, and researchers. Building a collaborative environment can be challenging due to differing priorities and interests across the sector and with other sectors within a holistic bioeconomy.

LESSONS LEARNED AND WAY FORWARD

Policy development

63. Conducive policies and regulatory frameworks are crucial for providing an enabling policy environment for the development of a circular aquaculture economy. Policymakers should be well informed of the latest technology developments and innovations to ensure that any policy reforms are based on scientific evidence.

64. Policy development is encouraged to review and enhance the current policies and regulations to: (1) incentivize circular technology development, and the use of products derived from circular practices; and (2) promote cooperation and collaboration among stakeholders, such as farmers, processors, policymakers, industry leaders and researchers.

65. Aquaculture is an integral part of bioeconomy strategies. Having a holistic framework of bioeconomy supports creating the enabling environment for investments in cross-sectoral innovations that valorize waste and by-products.

66. At the international level, countries should pursue harmonization and mutual recognition of policies and regulations regarding the biosecurity and food safety concerns associated with the use of products derived from circular practices.

67. Policy coherence between different national sectors as well as with international commitments can be achieved through the development of holistic bioeconomy strategies.

68. The application of circular economy principles in aquaculture should be approached in a differentiated manner, tailored to the specific context of regions, types of aquaculture (freshwater vs marine aquaculture), and scales of aquaculture operations.

Technology and innovation

69. Historically, aquaculture has aligned well with the core principles of the circular approaches through diverse integrated systems. However, further enhancing its circularity requires even greater technological advancements and innovation to improve or develop new resource-efficient aquaculture systems, experiment with new or improved products, and reintegrate side streams into production schemes. Bioeconomy business models can help identify cross-sectoral opportunities and facilitate the integration of circularity principles in the design of production and processing activities.

70. Knowledge of the composition (nutrients and contaminants) of raw materials, such as fish by-products or residues from aquaculture, is crucial for optimizing the utilization of these raw materials in a safe way in terms of human, animal and environmental health, as well as being economically viable, supporting all the pillars of a sustainable bioeconomy.[42]

71. Simple and low-cost technologies that can be used with minimal investment and at a small scale (such as fish silage production) should be developed and promoted.

72. Recent innovations, such as the production of insect meals, microalgae production for food and feed, fish by-product utilization in aquafeeds and valorization, and the development of innovative integrated farming systems, have been the primary driving forces and enablers of the transition of aquaculture from conventional linear models, such as ‘production and consumption,’ to a more circular one.

73. A conducive policy environment should be created to encourage technological development and stimulate, nurture, and scale up innovation for enhancing circularity in aquaculture value chains.

Monitoring and evaluation

74. Effective monitoring is crucial to ensure that new systems, technologies, and products meet the biosecurity, food safety, and environmental requirements while simultaneously maximizing resource use efficiency, reuse, recycling, and waste reduction.

75. Proper evaluation mechanisms should be developed in addition to some existing tools, such as Life Cycle Assessment, to develop quantitative indicators of circularity and their contribution to the bioeconomy. These indicators can be used to encourage investment and incentivize circular practices and derived products.

Public awareness

76. The use of fish by-products and alternative feed ingredients, along with waste recycling and valorization in aquaculture, is often associated with biosecurity, food safety concerns, and social acceptance issues. To address these challenges, it is crucial to ensure the public is well-informed and educated about the benefits of circularity and the products derived from circular production processes. Additionally, raising awareness and engaging the public on sustainability can stimulate consumer demand for responsibly sourced aquaculture products. This can, in turn, strengthen market incentives for producers to transition toward more circular production processes, fostering a more sustainable and resilient aquaculture industry.

FAO’s roles in circular aquaculture

77. FAO serves as an intergovernmental platform for information sharing, policy dialogue, and knowledge brokering. It actively supports and facilitates the development of policies, regulations, and guidelines that integrate circular principles into aquaculture value chains. To promote aquaculture circularity, FAO is ready to provide technical assistance to governments in implementing policy reforms, such as targeted subsidies, tax incentives, safety standards, and certification. These reforms

[42] FAO. 2021. *Aspirational Principles and Criteria for a Sustainable Bioeconomy*. Rome, FAO. 16 pp. https://openknowledge.fao.org/handle/20.500.14283/cb3706en

should be complemented by increased investments, effective project implementation, and the production and dissemination of knowledge products. Furthermore, FAO prioritizes the multistakeholder partnerships at global, regional, national, and subnational levels. These partnerships aim to foster a more sustainable and resilient aquaculture sector.

78. **Bioeconomy for sustainable food and agriculture** is a Programme Priority Area in FAO's Strategic Framework 2022‒2031, which steers its efforts to transform agrifood systems and promote a food secure world for all.

79. FAO's **Blue Transformation Roadmap**[43] outlines a comprehensive strategy for reshaping aquatic food systems, focusing on sustainable aquaculture intensification, improved fisheries management, updating the value chains of aquatic products (including reducing food loss and waste), all of these in the context of needed climate change adaptation and mitigation measures. It also emphasizes the need for stronger governance and increased investment in the sector. The roadmap's recommended actions for aquaculture operations and aquatic food value chains align closely with CE principles and contribute to a sustainable bioeconomy. To enhance the effectiveness of circular approaches, the roadmap calls for further development of metrics and criteria across key areas, scaling-up investment in by-product valorization practices, the expansion of integrated aquaculture systems, the adoption of innovative technologies, and the use of renewable energy. These efforts will help optimize resource use, minimize waste, and foster a more sustainable and resilient aquaculture sector.

80. The **Guidelines for Sustainable Aquaculture** (GSA) (COFI:AQ/XIII/2025/INF.11) provide a comprehensive framework for managing and developing sustainable aquaculture practices. The GSA emphasize the integration of circularity principles, which align with the goals of achieving sustainable use, responsible management, conservation, and restoration of aquatic ecosystems and biodiversity, as well as mitigating the impacts of climate change.

[43] FAO. 2022. *Blue Transformation – Roadmap 2022–2030: A vision for FAO's work on aquatic food systems*. Rome. https://doi.org/10.4060/cc0459en