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SCIENCE POLICY REPORT • JUNE 2025

Advancing sustainability and circularity in aquaculture to build a resilient global food system

The authors and their affiliations are listed in the appendix. The report reflects solely their views and vision on advancing sustainability and circularity in aquaculture to build a resilient global food system.

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Advancing sustainability and circularity in aquaculture to build a resilient global food system

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Foreword

The world is facing accelerating climate change and an alarming decline in biodiversity. These challenges are closely linked to human activities, in particular economic expansion and, especially critical, the way we produce and consume food. Transforming the food system is a crucial step to mitigating these challenges. Aquaculture has the potential to drive this transformation, o ering diverse production methods – whether marine or freshwater, pond-based or integrated multitrophic systems – that can enhance a sustainable food supply, and reduce pressure on wild ecosystems. Freshwater aquaculture o ers signi cant opportunities for growth in countries such as Brazil and Germany. This report highlights the role of freshwater aquaculture in both countries in advancing a low-carbon and biodiversity-friendly food system.

This report is the result of the workshop “Sustainable Aquaculture – Environmental Impacts and Food Security”, held in Berlin, Germany, in October 2023. An interdisciplinary group of emerging scientists from Brazil and Europe assessed the environmental impacts and the potential of freshwater aquaculture as a key component of the global food production system. It was jointly organised by the Brazilian Academy of Sciences (ABC), the German National Academy of Sciences Leopoldina, and the Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB). The workshop is the fourth event of the series “Water and Regional Development”, initiated by the Leopoldina and the ABC in São Carlos, Brazil, in 2014.

This report presents the outcomes of the workshop, re ecting the views of the participating emerging scientists, and not necessarily the views of the organising institutions.

The organisers are grateful to the IGB for their generous support and for hosting the event, especially Werner Kloas and Silvia Kanzler for facilitating the organisation of the workshop.

The organisers extend their gratitude to Professor Klement Tockner (member of the Leopoldina), Professor Adalberto Val (member of the ABC), Professor Maria Célia Portella (São Paulo State University), Professor Evoy Zaniboni Filho (Federal University of Santa Catarina) and Professor Werner Kloas (Emeritus Leibniz Institute of Freshwater Ecology and Inland Fisheries) for their coordination and support. The organisers also wish to thank the Embassy of Brazil in Berlin for hosting the public part of the event.

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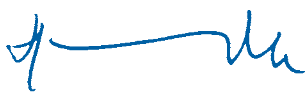

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Executive summary

Humanity faces existential risks due to rapid climate change and an unprecedented loss of biodiversity. These risks are interlinked, driven by human population and economic growth, and require a fundamental transformation of the economy but also, in particular, of the food system. To make our food production and consumption more efficient and resilient, sustainable and increasingly circular systems are seen as a necessary path forward.

While acknowledging its many challenges, the aquaculture sector is growing rapidly and offers enormous potential to shift the global food system towards greater efficiency and sustainability. The various techniques of fish production in aquaculture, whether marine or freshwater, pond-based or integrated multitrophic systems, have the potential to provide a sustainable global food source high in both quality and quantity.

This report aims to outline a path for making aquaculture, especially freshwater aquaculture, a resilient, future-proof and increasingly circular mode of production. As a group of emerging scientists, we focus on the available freshwater aquaculture technologies and offer a comparative perspective on the fish farming sectors in Brazil and Germany.

Despite many differences, Brazil and Germany share great potential for growth in the freshwater aquaculture sector. Fish production and consumption in both countries fall below the global average, with freshwater finfish aquaculture the primary production method. However, Germany produces only 2% of its consumed fish domestically. Both nations face similar challenges regarding impacts of climate change, high production costs, negative public perception, labour shortages, and regulatory barriers. Expanding sustainable aquaculture requires strong political support, strategic measures, and efforts to enhance public awareness of its benefits compared to other animal production sectors.

This report envisions a sustainable freshwater aquaculture that minimises environmental impacts while ensuring economic and social viability. We therefore emphasise that both research and technological advancements, as well as economic feasibility, are crucial in enhancing productivity, resource efficiency, and environmental sustainability. Each production mode has different requirements which need to be fulfilled to become sustainable. Accordingly, we present research and technological innovations for the entire spectrum of freshwater aquaculture. Topics related to international trade have been excluded from this report, as addressing them, though important, would require a different approach and analysis.

The report recommends that policymakers, public institutions, non-governmental organisations (NGOs), and the aquaculture industry in Brazil and Germany take the following actions:

1) **Streamline bureaucracy:** Limit the number of regulatory bodies responsible for licensing and controlling freshwater aquaculture facilities.
2) **Introduce aquaculture officers:** These officers, located within regulating bodies, would guide prospective aquaculture entrepreneurs through the entire licensing and monitoring process, from initial concept to full implementation.
3) **Offer meals based on sustainable aquaculture products:** Integrate domestically produced sustainable (freshwater) aquaculture products into public canteens, schools, and universities.

Resumo executivo

A humanidade enfrenta riscos existenciais devido às rápidas mudanças climáticas e à perda sem precedentes de biodiversidade. Esses riscos estão interligados, são impulsionados pelo crescimento populacional e econômico, e exigem uma transformação profunda da economia e, também, em particular, do sistema de produção de alimentos. Para tornar a produção e o consumo de alimentos mais eficientes e resilientes, sistemas sustentáveis e cada vez mais circulares são considerados caminhos essenciais.

Apesar de seus muitos desafios, a aquicultura é um setor em rápido crescimento e com grande potencial para tornar o sistema alimentar global mais eficiente e sustentável. As diversas técnicas de produção de peixes na aquicultura – seja em ambientes marinhos ou de água doce, em viveiros ou sistemas integrados como a aquaponia – têm potencial para fornecer globalmente alimentos de alta qualidade e em grande escala, de forma ambientalmente sustentável.

Este relatório propõe caminhos para tornar a aquicultura, especialmente a de água doce, num modelo de produção resiliente, preparado para o futuro e cada vez mais circular. Como um grupo de jovens cientistas, focamos nas tecnologias disponíveis de aquicultura em água doce e adotamos uma perspectiva comparativa entre os setores de produção de peixes no Brasil e na Alemanha.

Embora bastante diferentes, Brasil e Alemanha compartilham um grande potencial de crescimento na aquicultura de água doce. A produção e o consumo de pescado em ambos os países estão abaixo da média global, sendo a aquicultura de peixes de água doce o principal método de produção. No entanto, a Alemanha produz apenas 2% do peixe que consome. Ambos os países enfrentam desafios semelhantes: impactos das mudanças climáticas, altos custos de produção, percepção pública negativa, escassez de mão de obra e barreiras regulatórias. A expansão da aquicultura sustentável exige forte apoio político, medidas estratégicas e esforços para maior conscientização pública sobre seus benefícios em relação a outros setores de produção animal.

Este relatório vislumbra uma aquicultura sustentável em água doce que minimize os impactos ambientais, assegurando viabilidade econômica e social. Portanto, enfatizamos que avanços científicos e tecnológicos, aliados à viabilidade econômica, são essenciais para melhorar a produtividade, a eficiência no uso de recursos e a sustentabilidade ambiental. Cada modo de produção possui requisitos próprios que precisam ser atendidos para se tornar sustentável. Por isso, apresentamos inovações científicas e tecnológicas aplicáveis a todo o espectro da aquicultura de água doce. Questões ligadas ao comércio internacional foram deliberadamente excluídas, pois demandariam outra abordagem analítica.

O relatório recomenda que formuladores de políticas públicas, instituições governamentais, organizações não governamentais (ONGs) e a indústria da aquicultura no Brasil e na Alemanha adotem as seguintes medidas:

1) **Otimizar a burocracia:** Limitar o número de órgãos reguladores responsáveis pelo licenciamento e fiscalização da aquicultura em água doce.
2) **Introduzir agentes de aquicultura:** Técnicos vinculados aos órgãos reguladores que acompanhem empreendedores da aquicultura ao longo de todo o processo de licenciamento e monitoramento.
3) **Oferecer refeições com produtos sustentáveis de aquicultura:** Integrar produtos de aquicultura (de água doce) sustentáveis e de produção nacional nas cantinas públicas, escolas e universidades.

Zusammenfassung

Der Klimawandel und der beispiellose Biodiversitätsverlust bedrohen die Menschheit mit existenziellen Risiken. Bevölkerungswachstum und wirtschaftliche Entwicklung beschleunigen diese eng miteinander verknüpften Herausforderungen und erfordern einen grundlegenden Wandel – nicht nur in unserer Wirtschaft, sondern auch im Ernährungssystem. Nachhaltige und zunehmend zirkuläre Systeme sind daher unabdingbar, um die Lebensmittelproduktion und den -konsum effizienter und widerstandsfähiger zu gestalten.

Trotz zahlreicher Herausforderungen wächst die Aquakultur rasant und bietet enormes Potenzial, das globale Ernährungssystem effizienter und nachhaltiger zu gestalten. Ob marine oder süßwasserbasierte Fischproduktion in Teichanlagen oder integrierte multitrophische Systeme – weltweit liefern diese Techniken hochwertige und nachhaltige Nahrungsmittel.

Dieser Report zeigt, wie die Süßwasseraquakultur als widerstandsfähiges, zukunftssicheres und zunehmend zirkuläres Produktions- und Konsummodell weiterentwickelt werden kann. Die Autorengruppe analysiert dabei alle verfügbaren Aquakulturtechnologien und nimmt eine vergleichende Perspektive auf die Aquakultursektoren in Brasilien und Deutschland ein.

So unterschiedlich Brasilien und Deutschland auch sind, beide Länder verfügen über ein großes Wachstumspotenzial im Bereich der Süßwasseraquakultur. In beiden Ländern liegen Fischproduktion und -konsum unter dem globalen Durchschnitt, wobei die Süßwasserfischzucht dominiert. Deutschland deckt nur 2% des von ihm konsumierten Fisches durch eigene Fischzucht. Darüber hinaus stehen beide Länder vor ähnlichen Herausforderungen, wie Klimawandel, hohe Kosten, negative öffentliche Wahrnehmung, Fachkräftemangel und bürokratische Hürden. Eine nachhaltige Aquakultur erfordert daher politische Unterstützung, strategische Maßnahmen und eine verstärkte öffentliche Sensibilisierung.

Dieser Report diskutiert Vorschläge einer nachhaltigen Süßwasseraquakultur, die Umweltbelastungen minimiert und wirtschaftliche sowie soziale Tragfähigkeit gewährleistet. Aus unserer Sicht sind sowohl Forschung und technologische Fortschritte als auch wirtschaftliche Machbarkeit entscheidend, um Produktivität, Ressourceneffizienz und ökologische Nachhaltigkeit zu steigern. Die unterschiedlichen Produktionsmethoden erfordern jeweils spezifische Lösungen für langfristige Nachhaltigkeit. Daher präsentieren wir Forschungsergebnisse und technologische Innovationen für das gesamte Spektrum der Süßwasseraquakultur. Themen des internationalen Handels wurden ausgeschlossen, da sie eine separate Analyse erfordern.

Dieses Dokument empfiehlt, dass politische Entscheidungsträger, öffentliche Institutionen, Nichtregierungsorganisationen (NGOs) und die Aquakulturbranche in Brasilien und Deutschland folgende Maßnahmen ergreifen:

1) **Reduktion bürokratischer Hürden** durch eine Begrenzung der zuständigen Genehmigungs- und Kontrollbehörden für Süßwasseraquakultur.
2) **Etablierung von Aquakulturbeauftragten** auf Seiten der Behörden, die Antragstellende über den gesamten Genehmigungs- und Monitoringsprozess hinweg begleiten.
3) **Mahlzeiten auf Basis nachhaltiger Aquakultur anbieten:** Integration nachhaltig erzeugter, heimischer (Süßwasser-)Aquakulturprodukte in die Gemeinschaftsverpflegung öffentlicher Einrichtungen wie Schulen, Universitäten und Kantinen.

Resumen ejecutivo

La humanidad enfrenta riesgos existenciales debido al cambio climático y a la pérdida de biodiversidad. El crecimiento de la población y el desarrollo económico impulsan estos riesgos interconectados y requieren no solo un cambio fundamental de nuestra economía, sino también del sistema alimentario. Sistemas sostenibles y cada vez más circulares son indispensables para diseñar la producción y el consumo de alimentos más eficientes y resilientes.

A pesar de sus desafíos, la acuicultura crece rápidamente con un potencial enorme para ser el sistema alimentario global más eficiente y sostenible. Ya sea en la producción de peces en agua marina o dulce, en estanques o en sistemas multitróficos integrados, estas técnicas ofrecen alimentos de alta calidad y sostenibles a nivel mundial.

Este informe muestra cómo la acuicultura de agua dulce puede desarrollarse como un modelo de producción y consumo resiliente y cada vez más circular. El grupo de autores analiza todas las tecnologías acuícolas disponibles y adopta una perspectiva comparativa sobre los sectores acuícolas en Brasil y Alemania.

Aunque son muy diferentes, Brasil y Alemania comparten un alto potencial de crecimiento en el sector de la acuicultura en aguas continentales. En ambos casos, la producción y el consumo de pescado están por debajo del promedio mundial, predominando la acuicultura de agua dulce. Alemania solo cubre el 2% de su consumo de pescado con su propia producción acuícola. Además, ambos países enfrentan desafíos similares, como el cambio climático, altos costos, percepción pública negativa, escasez de profesionales especializados y obstáculos burocráticos. Por ello, una acuicultura sostenible requiere apoyo político, medidas estratégicas y una mayor sensibilización pública.

Este informe aborda propuestas para una acuicultura de agua dulce sostenible que minimiza el impacto ambiental y garantiza la viabilidad económica y social. Consideramos esenciales la investigación, los avances tecnológicos y la factibilidad económica para mejorar la productividad, la eficiencia en el uso de recursos y la sostenibilidad ecológica. Cada método de producción demanda soluciones específicas para lograr una sostenibilidad a largo plazo. Por ello, se presentan resultados de investigación e innovaciones tecnológicas para todo el espectro acuícola, excluyendo los temas de comercio internacional al requerir un análisis aparte.

Este documento recomienda que los responsables políticos, las instituciones públicas, las organizaciones no gubernamentales (ONG) y el sector de la acuicultura en Brasil y Alemania adopten las siguientes medidas:

1) **Simplificar burocrática:** Limitar el número de organismos reguladores responsables de la concesión de licencias y del control de las instalaciones de acuicultura en aguas continentales.
2) **Introducir de agentes de acuicultura:** Estos agentes, integrados en los organismos reguladores, guiarían a los futuros emprendedores del sector a lo largo de todo el proceso de concesión de licencias y monitoreo, desde la idea inicial hasta la implementación completa.
3) **Ofrecer comidas basadas en productos de acuicultura sostenible:** Integrar productos de acuicultura sostenible (de aguas continentales) de producción nacional en comedores públicos, escuelas y universidades.

1. Sustainable Aquaculture

In 2022, approximately 185 million tonnes of aquatic animals (including fish, crustaceans, molluscs and other aquatic animals, but excluding aquatic mammals and reptiles) were produced worldwide, with an estimated total first sale value of USD 472 billion (FAO, 2024). At 91 million tonnes, capture fisheries remain a main source of fish; however no further increase in catch yields is expected in the future. At 94.4 million tonnes, aquaculture production of aquatic animals (both freshwater and marine) surpassed capture fisheries for the first time **(Figure 1).** By 2030, the annual global fish consumption and production are expected to rise, driven primarily by the intensification and expansion of aquaculture production (FAO, 2024).

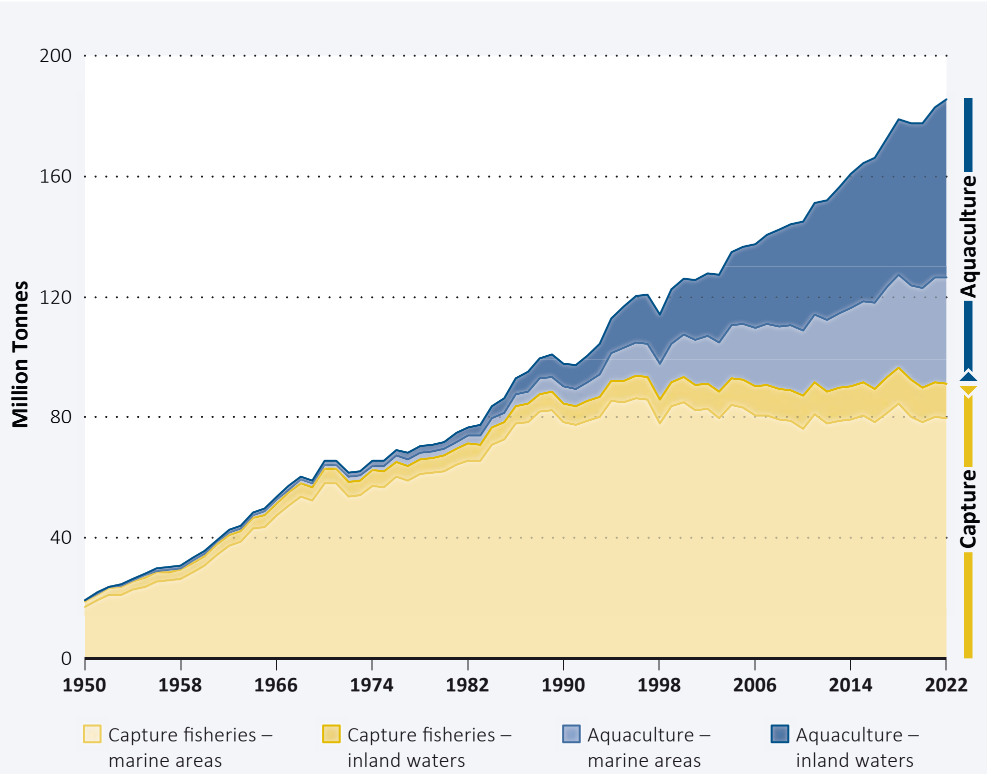

Figure 1.*Development ofglobalfishproduction (aquacultureandcapture fisheries)intheperiod 1950–2022(FAO2024).*

Aquaculture, broadly defined as the farming of aquatic organisms including fish, molluscs, crustaceans, and aquatic plants, has become increasingly important to meet the global demand for animal protein and micronutrients. Well over 300 taxonomically recognised finfish species are farmed in aquaculture worldwide. This industry exhibits great diversity and has the potential to become an ever more significant source of food, employment, and income globally.

In 2022, fish accounted for the largest proportion of global aquaculture production at 65.2% (61.6 million tonnes), followed by mussels (20%), crustaceans (13.5%), and other aquatic animals (1.3%). Most fish (89.7%) were produced in inland aquaculture. According to the FAO, when practised sustainably, freshwater aquaculture is considered a cornerstone of a resilient food system, offering high efficiency and lower environmental impact compared to other animal production forms, such as cattle.

Sustainable fish production in freshwater aquaculture involves the efficient use of feed, water, and energy, while reusing by-products and waste streams. In this way, aquaculture can increasingly align with the Sustainable Development Goals (SDGs)/Agenda 2030, such as SDG 2 ("zero hunger") or SDG 12 ("responsible consumption and production") (Troell et al., 2023). Aquaculture production has promoted social, economic, and environmental resilience, supporting people in low- and middle-income countries with high-quality food (Belton et al. 2018).

The history and development of aquaculture reflect a journey marked by innovation and technological advancements in various production systems. From traditional pond culture to modern, high-tech, fully controllable systems that recirculate water, aquaculture has reduced the environmental impact of production and demonstrated adaptability and potential for further expansion (Ahmed & Turchini, 2021, Valenti et al., 2021).

Aquaculture has the potential to play an important role in the nutritional landscape by contributing to per capita protein intake, combating micronutrient deficiency, and offering a sustainable energy source within the food system (Gephart et al., 2021a). As summarised by the FAO (2022) and UN Nutrition (2021), aquatic foods are a fundamental part of sustainable, healthy diets, and aquaculture production can certainly be a major source of more sustainable and healthy diets worldwide. Studies by Naylor et al. (2021) and the FAO (2024) found that consuming aquatic foods from sustainable fisheries and aquaculture is more effective in reducing potential environmental impacts than consuming terrestrial animal-based foods.

The challenges inherent in aquaculture production offer fertile ground for innovative solutions that protect the environment, foster economic growth, and promote social equity, thereby integrating the three pillars of sustainability (social, economic, and environmental), as outlined by Purvis et al. (2019), and paving the way for positive change. Sustainable aquaculture practices strive to minimise environmental impacts by addressing concerns such as habitat degradation, threats to biodiversity, pollution, and the overuse of finite resources. These practices also tackle issues of economic feasibility, such as creating favourable conditions for production, competition, and demand for fish. Successful aquaculture practices should further involve raising awareness about the benefits of aquaculture-produced fish, ensuring products are accessible to many (ideally to all), and developing strategies to attract and recruit talent.

This report aims to take a closer look at the aquaculture sectors in Brazil and Germany to highlight both the opportunities and challenges the industry faces in both countries. Brazil and Germany differ in terms of context, economic scale, economic structure, and the importance of their aquaculture sectors. However, opportunities for aquacultural development remain largely untapped.

In both countries, fish production and consumption are lower than the global average. Farmed fish production mainly originates from freshwater finfish aquaculture in both countries. Brazil (with a production of 887,000 tonnes, PeixeBR, 2024) is far from being one of the largest fish producers globally, despite its vastness and climate variation (Reis et al., 2016). As a result, the country is highly dependent on imported fish products. While aquaculture is widespread, it is practised using different technologies, ranging from simple inland ponds in the north to high-tech net cages in large rivers and reservoirs in the south-east (Valenti et al., 2021). This diversity presents a challenge when it comes to the sustainable development of this sector in Brazil.

While global aquaculture is growing, the aquaculture sector in Germany is shrinking. According to the German Federal Statistical Office, 35,184 tonnes of aquaculture products were produced across Germany in 2023, of which 16,849 tonnes (47.9%) were fish and 18,029 tonnes (51.24%) were molluscs. Crustaceans (34 tonnes) and algae (and other aquatic organisms) played only a minor role. Germany is heavily dependent on fish imports, with only 2% of all finfish consumed in the country originating from domestic aquaculture production. Per capita fish consumption is approximately 10 kg in Brazil and 14 kg in Germany (2022), which is significantly lower than the global average of 20.5 kg per year (FAO FishStatJ, 2023).

Additionally, the aquaculture sectors in both countries face similar challenges: 1) multifaceted consequences of rapid climate change, 2) high production costs, 3) poor public perception and prejudices, 4) scarcity of skilled labour, and 5) excessive bureaucracy and lack of consistent regulation. The authors of this paper regard robust political support, appropriate measures, and coordinated efforts to raise awareness of the benefits of aquaculture over other sectors of animal production as crucial to the expansion of sustainable aquaculture.

The authors present research and technological innovations across the entire spectrum of freshwater aquaculture. The wide variety of production modes in aquaculture have different requirements and achieve different levels of circularity, each with its respective benefits. The objective is not to reach perfect circularity but rather to make progress towards it through the various options outlined in the paper, whether via more traditional, low-tech production modes or modern, high-tech solutions. Nonetheless, the highlighted research and technological advancements are key to enhancing economic feasibility, productivity, resource efficiency, and mitigating environmental risks in aquaculture.

Furthermore, efforts related to education and capacity building are addressed, targeting consumer awareness and attitudes, identifying behaviours driving demand for sustainable seafood, and fostering a market conducive to responsible practices (B lan, 2020). This document emphasises the urgency to promote dynamic policies that facilitate regulations and foster an appropriate regulatory environment that supports the development of aquaculture. Sustainability is achievable with competent, well designed and dynamic governance through which the industry embraces the basic principles of equity, accountability, efficiency, and predictability (Jolly et al., 2023). Given the above, this report excludes any discussion of bilateral and international trade.

2. The potential of freshwater fish aquaculture as part of a sustainable and resilient food system

Fish is an essential part of global human nutrition and represents one of the most widely consumed sources of animal protein worldwide (Statista, 2023). It is not only a valuable source of protein and essential nutrients for a healthy diet, but also an integral part of the culture and traditions of many societies, especially in regions with strong fishing and aquaculture practices. Exemplified by the Mediterranean diet, considered one of the healthiest in the world (Román et al., 2019; Trichopoulou & Vasilopoulou, 2000), fish is widely regarded as an easily digestible protein that supplies a broad range of macro- and micro-minerals, vitamins, and essential fatty acids, and is associated with various effects beneficial to health and longevity (Hibbeln et al., 2019; Biomar, 2023).

The rapid growth of aquaculture has helped satisfy the nutritional needs of a growing population, reduce poverty (by creating new jobs for local communities) and combat malnutrition, while also providing economic stability and growth in many regions worldwide. However, despite being one of the world's fastest-growing food-producing sectors, the aquaculture industry still has significant opportunities to improve its environmental, social, and economic sustainability. It also has the potential to expand into regions with low aquatic food self-sufficiency, high import dependence, and low consumption.

In fact, a significant expansion of the aquaculture sector – particularly freshwater aquaculture – could not only increase the consumption of diverse aquatic animal protein at reduced prices, but also improve public health by alleviating nutrient deficiencies, providing essential nutrients such as omega-3 fatty acids, and reducing reliance on red and processed meats (Golden et al., 2021). Therefore, the responsible growth of the aquaculture sector is essential for fulfilling both healthy and environmentally sustainable diets (Willett et al., 2019).

The food production system is responsible for one third of global greenhouse gas (GHG) emissions (Crippa et al., 2021). Evidence shows that, when framed sustainably within the context of circular bioeconomy, aquaculture has the potential to be more environmentally friendly than terrestrial animal production (Gephart et al., 2021b). Traditional farming with low environmental impact (e.g. trout in flow-through systems) and farming of lower trophic level freshwater fish in sustainable production systems – such as those focusing on water reuse, waste reduction, and upcycling, while using sustainable resource inputs, particularly energy and feed – can substantially increase aquaculture's contribution to protein in the global food system. This approach also minimises impacts on valuable water resources, particularly in the face of climate change (NOAA Fisheries, 2020).

Despite producing, on average, lower GHG emissions than terrestrial animal production (**Figure 2**), the carbon footprint (CO_2 equivalent) per kg of protein varies widely, ranging from 4 to 75 kg (vs. 4 to 540 kg for wild-caught seafood) (The Fish Site, 2021). This variability underscores the importance of focusing on highly efficient, low-impact species and increasingly circular production systems, taking into account region-specific conditions when expanding aquaculture as an integral and sustainable part of a resilient global food system.

When controlled environment aquaculture systems, such as recirculating aquaculture systems (RAS), are integrated with renewable energy production they can increase the industry's resilience towards climate change-induced impacts, such as high water temperature and low wa-

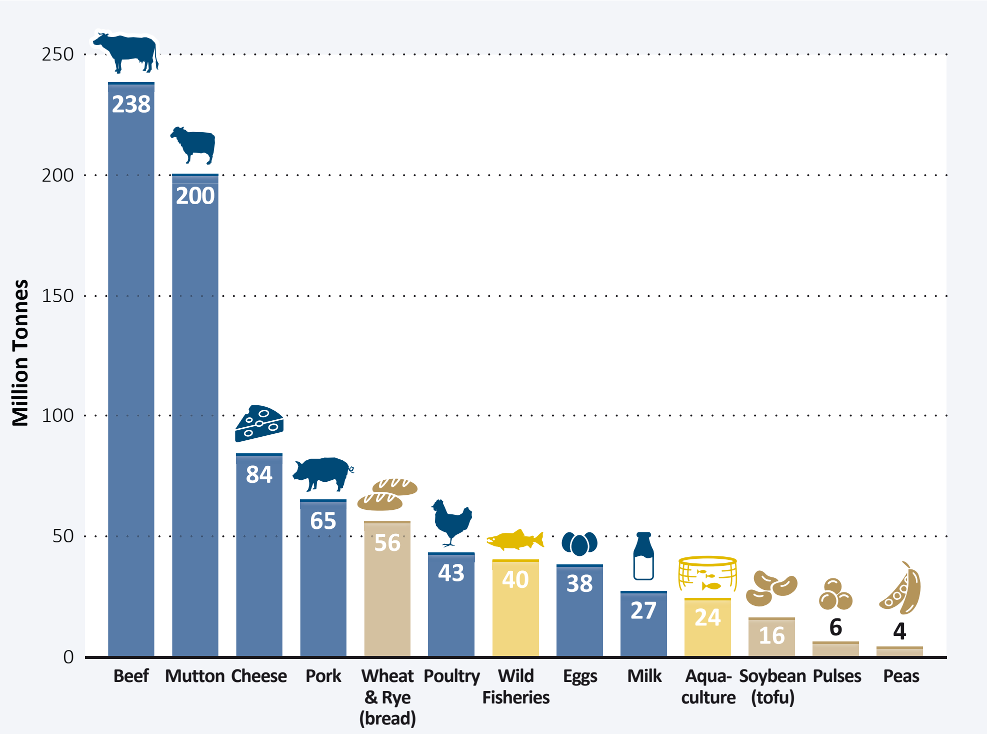

Figure 2. *CO_2-eqemissions ofproteinsources(basedon Gephartetal.,2021a; Poore&Nemecek,2018, accordingtoOceana2021). Wheatandryewereadded despitebeingaminor proteinsource(anaverage proteincontentof9%was usedforcalculations).*

ter availability (Ahmed & Turchini, 2021). These higher-tech, more intensive systems are characterised by greatly reduced water consumption due to water reuse, improved management of solid and dissolved waste, and reduced GHG emissions. This is particularly true when extended to multitrophic systems that focus on productive use of water and nutritious effluents (e.g., polyculture, aquaponics, integrated multitrophic aquaculture, biofloc systems, rice-fish systems, fertigation) (see **Section 3**). Moreover, these systems offer the advantage of being highly space-efficient per unit of production and flexible in terms of location, especially when compared to livestock farming, which requires vast expanses of land. This flexibility opens up the potential for closer proximity to urban centres (e.g. logistics hubs close to cities), reduced transportation-related emissions, and reduced space requirements in a world with increasingly scarce arable land.

While high-tech indoor controlled environment aquaculture systems require substantial capital investment and specialised knowledge, and represent only part of the solution, the principles of water reuse and efficient effluent treatment can be extended to less capital-intensive outdoor systems. These include raceway recirculating aquaculture systems following the Danish model (Jokumsen and Svendsen, 2010) or pond recirculation systems, as seen in some tilapia farms in Brazil (Zimmermann et al., 2023). More extensive forms of aquaculture, such as traditional pond farming of carp or flow-through aquaculture of salmonids, are and will continue to be crucial in many regions as sustainable forms of protein production, providing vital social, environmental, and biodiversity benefits (see **Section 3**).

Compared to terrestrial livestock production, commercial-scale fish aquaculture is a substantially younger industry with a less concentrated species portfolio. This portfolio ranges from marine to freshwater species, and from carnivorous to omnivorous and herbivorous species, offering opportunities for optimisation. Despite the comparable lack of professional long-term domestication in the majority of these species, the potential of fish as highly efficient feed converters is clear. Being poikilothermic and requiring less energy to resist gravity, most major aquaculture species are more efficient in converting feed protein into human-edible protein than cattle and pigs. For example, Atlantic salmon, arguably the most domesticated aquaculture species, achieves similar protein and calorie retention efficiencies to chicken (Fry et al., 2018). Therefore, focusing on species diversification – concentrating on the naturally most efficient species – and strategically domesticating these species (for more efficient protein utilisation, higher edible yield, faster growth, higher disease resistance, etc.) could propel aquaculture towards becoming the most efficient animal protein-producing industry worldwide. Given their often lower protein requirements, exceptional growth and feed conversion performance (e.g., the air-breathing African catfish or Arapaima), and general suitability for intensive cultivation, omnivorous, warm-water-adapted freshwater fish species offer particularly great potential for the development of an efficient, resilient, and sustainable global aquaculture industry.

In this context, a resilient food system is a complex structure built on the three pillars of sustainability: financial equity, societal support, and minimal environmental impact, all while exhibiting resilience, particularly towards pressures induced by climate change. Although aquaculture is on track to become such a resilient food system, some challenges remain. These will be explored in the following paragraphs.

2.1 Focused diversification strategies across the whole value chain

Aquaculture is already the most diverse farming system globally (Metian et al., 2020). According to FAO (2024), well over 300 finfish species are currently farmed worldwide. This diversity extends to production systems and aquatic ecosystems, reflecting local bio-geographical adaptations in aquaculture. It will thus be crucial to follow a strategy of focused diversification, concentrating on and improving upon the substantial yet underexplored potential of highly efficient, low-impact species, as well as modern and improved farming methods. At the same time, it is important to continue supporting established aquaculture enterprises to provide affordable, eco-friendly, and healthy food products for both current and future generations. Additionally, there is strong consumer demand for convenient, easy-to-prepare, and healthy food products, which aquaculture can supply through such a focused and streamlined strategy.

2.2 Reduction and reuse of waste

Along with convenient aquaculture products and co-product variants (e.g. fillets, with a 30–70% yield, meat trimmings, and mechanically deboned meat (MDM)), aquaculture generates tremendous amounts of potentially reusable by-products. These by-products offer an opportunity to increase circularity by minimising food loss and waste during post-production processing, maximising human edible yield from the by-products, and using them in animal feed (Malcorps et al., 2021) or for other side products, such as fish skins, leather and scales. Aquaculture also generates side streams, such as solid and dissolved effluents, which are often seen as trade-offs (environmental performance vs. food security) in sustainable and healthy food production (Blanchard et al., 2017; Troell et al., 2023). These aquaculture-specific side streams have massive potential to be upcycled, as they contain valuable sources of phosphorus, nitrogen, and other nutrients with broad applications, even beyond aquaculture. However, as long as primary nutrients remain inexpensive, these side streams will remain underutilised until effluents control is enforced. Therefore, strategies to properly manage the nutrient flows in aquaculture and beyond are urgently needed in the European Union (EU) and Brazil to explore further interlinkages, trade-offs, and synergies in food systems (see **Section 3**).

2.3 Biodiversity protection and climate change resilience

Biodiversity conservation is a key objective in both the EU and in Brazil. In the EU, semi-intensive pond aquaculture facilities, which culture fish species in monoculture or polyculture (e.g., carp, tench, pike-perch), are recognised as biodiversity hotspots for surrounding flora and fauna.

Additionally, such ponds provide unique ecosystem services not seen in other food production systems (Fehlinger et al., 2023). Not only ponds, but also state-of-the-art systems such as recirculating aquaculture systems or partially recirculating flow-through systems can have an (at least indirect) impact on local ecosystem biodiversity due to effluent treatment measures and minimal risk of escapees, while also enabling intensive and efficient production. These systems show great potential for sustainable aquaculture expansion (see **Section 3**). In Brazil, however, major biodiversity losses are associated with soybean production, a key land-based ingredient in animal feed production, including for aquaculture. Over the last decade, soybean production has greatly increased in Brazil, intensifying the demand for freshwater and land resources (Taherzadeh & Caro 2019). Deforestation for crop farming is not only responsible for biodiversity loss but also accelerates regional climate changes, which again contribute to shortfalls in soybean and maize production (Leite-Filho et al., 2024). Furthermore, aquaculture itself can increase the risk to local biodiversity when non-native fish species are used. Effective measures must therefore be taken to prevent non-native species from escaping the fish farm and becoming invasive in the environment.

This underlines that sustainable practices for aquaculture and related value chains (e.g., feed production and processing) are essential for nature conservation and building resilience to climate change.

2.4 Greater self-sufficiency and streamlined regulations

In light of the climate change crisis, achieving greater self-sufficiency should be a priority for both Germany and Brazil. The current over-reliance on imported fish and seafood – often produced in jurisdictions with less stringent environmental regulations – needs to be addressed by supporting sustainable domestic aquaculture production growth. This growth should be accompanied by a focus on local market needs, including the production of species with sufficient demand at affordable prices, as well as raising consumer awareness about responsible aquaculture products and practices (see **Section 4**). However, the transition towards aquaculture growth will inevitably require the development of a skilled workforce. Moreover, both Brazil and Germany face excessive bureaucratic regulations that hinder the expansion of sustainable aquaculture production (see **Section 5**).

2.5 Community involvement

Technology-intensive production methods offer promising opportunities for the future of freshwater aquaculture. At the same time, it is essential to support and enhance traditional practices through technological advancements, as the sector thrives on methodological diversity and strong local community involvement. Local community involvement in aquaculture should be protected and nurtured. Both Germany and Brazil have long histories of fish farming passed down through generations. For example, in Europe, common carp has been farmed using the traditional Dubisch method (a three-year cycle) in small farms since the early 1800s, though the first historical reports of domesticated carp rearing date back to the 13th century AD (Billard, 1999). In Brazil, fish farming dates back to the 17th century, but professional aquaculture began only in the 1970s. Despite this, Brazil's aquaculture sector remains primarily characterised by small artisanal pond farms, typically less than two hectares in size (Valenti et al., 2021). These farms have kept the tradition of pond farming alive by passing down knowledge, techniques, and facilities within families. However, in order for these businesses to remain profitable, economic transformation, such as diversifying into processing, will be necessary.

3. Science and innovation

Science and innovation (S&I) play a key role in advancing sustainable aquaculture by addressing challenges such as environmental pollution and waste management, fish welfare, disease prevention, climate change, and water scarcity. By leveraging best practices and emerging technologies, S&I can significantly enhance the aquaculture sector's sustainability, resilience, and contribution to global food security. This section explores how advancements in production systems, aquafeed, water treatment, and fish health, aligned with the One Health framework and the UN Sustainable Development Goals, can create a resource-efficient, scalable, and ethical aquaculture industry that benefit both low- and high-tech farming systems.

To move towards more sustainable aquaculture practices, it is essential to take into account local expertise and limitations. Among the numerous possibilities, reducing linear and promoting circular practices is crucial, especially given the world's finite resource base. In this regard, making smart choices regarding aquafeed, water and waste management, as well as addressing fish welfare and health issues, will be vital topics in future policies.

3.1 Sustainable and circular aquaculture systems

In order to steer the global food production system towards more efficient resource use with lower emissions, aquaculture must be more closely integrated into the broader food production framework **(Figure 3)**. Food production should be considered holistically, rather than separating land-based and water-based farming practices. In a globalised world, these two approaches are interconnected: for example, land-based raw materials (such as black soldier fly larvae) are used in aquaculture feeds, and aquaculture waste can contribute to land-based farming practices (Stetkiewicz et al., 2022). As such, food systems should be increasingly interlinked, and sustainability can be improved by understanding and optimising these interrelations through coherent management of water, food, waste and other resources.

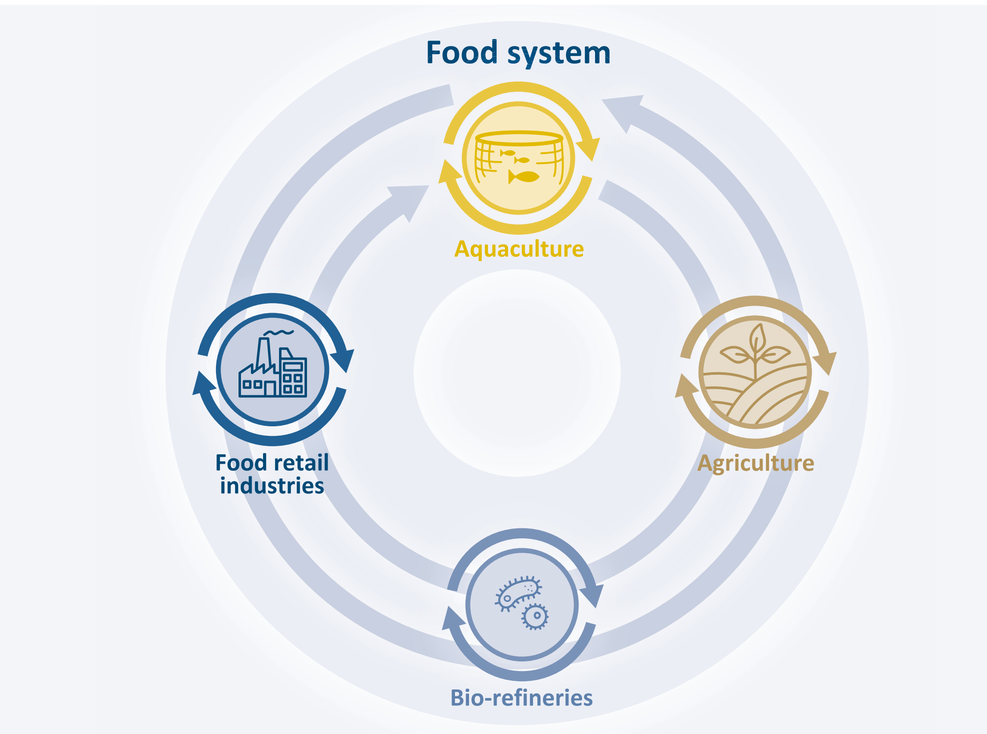

Figure 3. *Circularflowin anintegratedfoodsystem model,withequitable rolesforaquaculture andotherfoodindustry sectors.*

While pond-based aquaculture is widely used in Latin America, flow-through systems are more prevalent in European aquaculture, both of which have long supported high-quality food production. These systems can facilitate large-scale production while promoting ecosystem services, such as self-purification capacity and the creation of natural food webs that enhance ecological cycles, depending on the location and regional characteristics. However, the adoption of these production systems, along with their nutrient dynamics, must be carefully managed to comply with water quality regulations, such as the EU Water Framework Directive and Brazilian National Water and Sanitation Agency.

Other production systems, including recirculating aquaculture systems (RAS) and integrated multitrophic aquaculture (IMTA), have the potential to offer sustainability benefits when fully validated and adapted to be both technically and economically viable. In this context, it is essential to balance the three pillars of sustainability – economic, environmental and social – especially considering the different realities across countries and even within regions of the same country. Valenti et al. (2021) highlight the highly diverse aquaculture landscape in Brazil as an example of such variation.

Sustainability can be achieved through various paths, not necessarily requiring large investments or the adoption of high-tech approaches. A practical approach is to preserve and enhance existing aquaculture knowledge, integrating the best available scientific knowledge. In the following sections, we will outline several examples of how this can be accomplished.

3.2 Aquafeed

Aquafeed is typically the primary cost in farming fish (Cooney et al., 2021). Technologies based on artificial intelligence (AI) could help fish farmers increase productivity and profitability by improving decision-making, optimising fish growth, monitoring feeding behaviour of fish, and controlling environmental conditions. AI-based technologies offer tremendous potential for sustainable aquaculture, enabling farmers to reduce waste generation by optimising feeding and water management efficiency (Mandal and Ghosh, 2024).

The aquafeed industry is reconsidering alternative feed formulations that embrace more circular and ecological approaches (Colombo et al., 2022). Thanks to advancements in ingredient processing and biorefining technologies, a wider range of ingredients and additives is now available (e.g., enzymes, nucleotides, probiotics, and growth promoters), which are increasingly used in aquafeeds. Additionally, innovative systems are emerging, with farms using low-cost, local by-products to create their own feed, such as circular farms with high waste turnover. Furthermore, efforts are being made to better utilise organic waste from retail food production and fish processing, making the entire process more circular.

The optimisation of diets and feed management on farms (e.g., using automatic feeders) has contributed to improved digestibility, nutrient absorption, immunity, growth rate (shortening production cycles and increasing productivity per area), survival, and water quality (reducing nutrient load in effluent). In Germany, high-tech aquaculture farms have adopted automatic feeding systems and precision feeding technologies. However, one of the greatest challenges to developing sustainable aquaculture is the rising cost of diets (Dawood & Koshio, 2020). In Brazil, diverse production systems exist, and premium diets may be unaffordable for many fish farmers. These farmers are experimenting with alternative feed raw materials such as insects and agricultural waste. Nevertheless, low-cost automatic feeding systems have been adopted in some regions, and their use should be more widely promoted.

The scientific community has made significant progress in understanding the basic behavioural and physiological processes in fish, such as breathing and food intake/digestion. In Germany, this knowledge has driven the use of bioenergetics-based solutions in aquaculture, particularly in optimising feeding practices and reducing nutrient waste, as seen in trout and common carp aquaculture (Prabhu et al., 2019). These bioenergetics-based solutions aim to match the fish's nutritional needs with highly digestible feed ingredients to improve growth efficiency and minimise environmental impact. Through this approach, valuable nutrients from aquaculture effluents can be reused to cultivate secondary crops or enhance the growth of natural food sources for fish, such as in periphyton-based systems, enabling fish to utilise naturally occurring food growing on underwater structures, such as algae, tiny animals or other microorganisms (David et al., 2022). These models could also support aquaponic systems, in which fish effluents are directly utilised for plant cultivation (Shaw et al., 2023), reducing the need for chemical, less sustainable fertilisers, and making double use of input water. In Brazil, there is also growing interest in cost-effective feeding optimisation practices, focusing on approaches such as periphyton-based systems (Negri et al., 2023) and aquaponics (Pinho et al., 2021), which can enhance fish growth while minimising environmental impacts.

3.3 Advancing circularity through integrated production, water and effluent treatment technologies

Aquaculture relies on high-quality water and stocking material, appropriate raw materials for feed, and best management practices. Some systems, such as RAS (Recirculating Aquaculture Systems), IMTA (Integrated Multi-Trophic Aquaculture), and aquaponics are inherently designed to achieve a higher level of circularity. However, even in more linear systems commonly employed in aquaculture, many improvements can be made to increase their level of circularity. Water recirculation, reuse and *in situ* recycling of waste biomass streams (e.g., processing by-products, feed wastes, sludge), within aquaculture, as well as other food production practices such as agriculture, could represent major steps towards circularity (Chary et al., 2024). However, any measures aimed at advancing circularity and sustainability must be implemented in an economically viable manner.

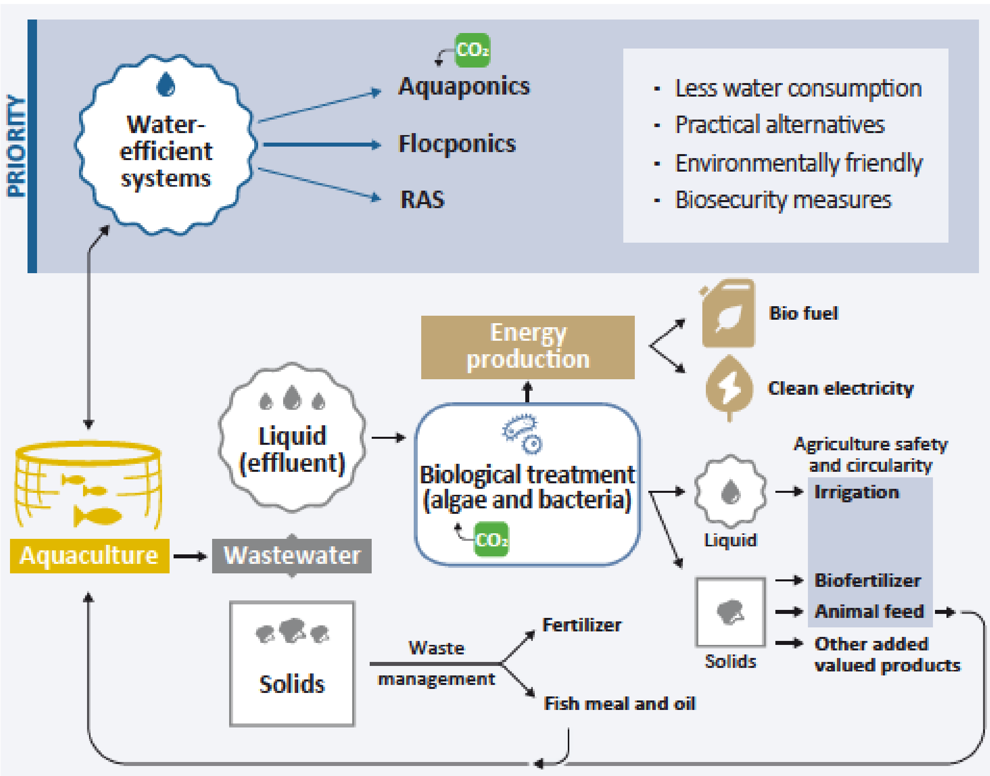

Figure 4. *Circular management of wastewater and organic waste streams from aquaculture production (Source: Koushik Roy, based on Capson-Tojo et al., 2020).*

Effluents and solid waste streams from fish farming have proven to be valuable resources in sustainable practices, ranging from small-scale to large scale, low-tech to high-tech production systems. Essential nutrients, such as nitrogen and phosphorus, can be recirculated back into food production processes through various existing technologies, including use in the production of algae, bacteria, insect biomass, plants or simple composting, thereby closing gaps within the food system **(Figure 4)**. Through waste recycling, it is possible to produce biogas (fermentation), energy (e.g. hydropower or microbial fuel cell), fish feed, fertilisers, clean water for reuse, or even apply pond water as fertigation. These practices not only promote environmental sustainability but also support economic sustainability in aquaculture. However, these technologies must be made attractive and feasible within aquaculture settings, especially for small and middle-sized producers, with a focus on low-cost and accessible technologies. (Ahmad et al., 2022; Lopes et al., 2020).

Fish farming can become more sustainable and circular when food production is integrated with waste management, both within farms and related industries. In the EU and Latin America, a few obstacles prevent effective waste re- and upcycling, meaning that fish farming and other animal production sectors continue to rely heavily on unsustainable ingredients like soybean and fish meal. These ingredients are known to exert major negative impacts, particularly in terms of their carbon footprint. However, a wide variety of existing and recently developed technologies can safely and sustainably recycle waste streams, not only from aquaculture but also from households, municipalities, and other industries, enabling the acquisition of circular raw materials to be used in food-producing industries as a whole.

3.4 Fish health and welfare

Even when cultured fish are provided with high-quality water and adequate nutrition, disease outbreaks can still occur. In the past, disease-related mortality of aquatic animals has led to significant economic losses and reduced food security worldwide (Golden et al., 2021). To avoid these issues, it is crucial to follow best practices for disease prevention, monitoring, and reporting. In this regard, good management practices must be prioritised, along with the creation of disease-free, safe zones, the use of disease-resistant breeds, in compliance with biosafety protocols, and the use of vaccines and immunity boosters to improve animal health and welfare (Boudry et al., 2021; Naylor et al., 2021).

One of the pivotal roles of S&I is the development of artificial intelligence (AI) technologies. AI has emerged as a transformative tool with significant potential to revolutionise aquaculture practices. It enables fish farmers to detect and predict anomalies, diseases, and stress indicators, allowing for proactive interventions to mitigate health issues and reduce losses (Mandal & Ghosh, 2024). Connecting new technologies with aquaculture to achieve greater sustainability, as outlined in the SDGs, will require the effective translation of scientific knowledge to both farmers and policymakers **(Table 1)**. This could be strongly supported by local and governmental interest, creating opportunities for farmers to access credit lines or other approaches that would stimulate the adoption of more sustainable practices (Gjedrem, 2012).

SDG	Role of science and innovation and recommendations regarding fish health and welfare to achieve sustainable aquaculture
1 NO POVERTY	Science and innovation contribute to poverty alleviation and equitable income distribution through capacity building, access to affordable technologies, and strategies for disease prevention. Sustainable practices improve productivity and resilience of small-scale fish farmers, and science-driven approaches favour economic growth and food security, especially in vulnerable communities
2 ZERO HUNGER	Science and innovation play a crucial role in achieving higher productivity and incomes for small-scale food producers, including fish farmers. The recommendations on capacity building, access to information, disease prevention, and improved farming techniques aim to provide a source of safe and nutritious food, promoting sustainable practices and income for communities
3 GOOD HEALTH AND WELL-BEING	Sustainable aquaculture practices that prioritise fish health and welfare can help reduce the risks of diseases and contaminants in fish products, ultimately improving human health through safe consumption. To achieve SDG 3, it is necessary to accelerate the implementation of disease prevention practices and management, reduce the use of antibiotics, enable traceability and quality assurance, and foster education and the adoption of new technologies
6 CLEAN WATER AND SANITATION	Aquaculture must prioritise water quality management to ensure the health and welfare of farmed fish. Sustainable practices such as Good Management Practices, proper sanitation facilities and strategic measures to prevent diseases are highly recommended to help maintain clean water and minimise pollution, which is in line with this goal
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Science and innovation in aquaculture technologies and infrastructure are focused on achieving sustainable and efficient practices that benefit both fish health and the environment. It is extremely important to develop a planned and resilient infrastructure and align technological innovation with applied and low-cost solutions
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Sustainable aquaculture practices align with this goal by promoting responsible and efficient production methods that minimise waste, resource consumption, and environmental impact. It is highly recommended to establish production patterns and educate consumers and fish farmers to encourage responsible use of resources, medicines, waste reduction, and sustainable production methods
17 PARTNERSHIPS FOR THE GOALS	Global partnership cooperation, financial support and collaboration among universities, companies and governments are essential to achieve the other SDGs. Strengthening the means to implement strategic measures to achieve fish health and welfare is vital to achieve sustainable aquaculture

Table 1. *Links between the SDGs and the adoption of actions related to fish health and welfare, moving towards sustainable aquaculture productions.*

4. Consumer awareness and capacity building for the sector's future workforce

Aquaculture, which now produces a record 94.4 million tonnes of aquatic animals (FAO, 2024), is fundamentally driven by consumer demand and consumer perception. However, as the sector expands, its reliance on coastal and freshwater ecosystems, many of which are already under significant environmental pressure, has raised concerns about its sustainability. Issues such as effluent discharge, biodiversity loss, interactions with wild populations, overexploitation of fishery resources, and animal welfare challenges have negatively influenced public perception (Bacher, 2015). This tension between growing market demand and environmental concerns underscores the need for greater consumer awareness and a skilled workforce capable of implementing sustainable practices.

A well-trained workforce is a key asset in any animal production system, and in aquaculture this is particularly crucial given the prevalence of small-scale producers. Providing technical and professional training is essential not only to support local enterprises but also to preserve and enhance the knowledge accumulated over generations of fish farmers. By strengthening expertise at all levels of the sector, it becomes possible to align consumer expectations with responsible production, ultimately improving the industry's reputation and securing its long-term sustainability.

4.1 Consumer perceptions and awareness

In both the Brazilian and German context, the demand for fish, particularly from aquaculture, is currently low. As outlined in **Section 1**, the average annual per capita fish consumption in Brazil and Germany is 10 kg and 14 kg respectively. While the below-average per capita fish consumption in both countries is influenced by cultural factors, the higher prices of fish products compared to other protein sources can further reduce consumption. The higher prices for aquaculture products often reflect the high operational costs and the logistics involved in distributing perishable products.

Another issue is the misconception that aquaculture products have lower nutritional value, especially when compared to fish from capture fisheries. This view often leads consumers to prefer wild fish over fish from aquaculture. A recent study conducted by Cantillo et al. (2023) found that surveyed groups expressed a preference for wild over farmed fish. Ruiz-Chico et al. (2020) showed that consumers perceive aquaculture products as less natural due to the use of chemicals and feeds, which they believe affects the quality and flavour of the products. Other studies have also found that consumers believe aquaculture practices score poorly with respect to sustainability, particularly in terms of environmental friendliness, when compared to traditional capture fisheries (Ruiz-Chico et al. 2020). Changing these cultural perceptions could help increase motivation to consume fish in both countries.

In contrast to this view, aquaculture products are in fact a valuable source of essential nutrients in the human diet, including omega-3 fatty acids, vitamins (e.g., A, D, and B12), minerals (e.g., iodine and selenium), and proteins with high biological value (FAO, 2020). Additionally, compared to fish from wild capture fisheries, the production process and origin of aquaculture fish can be made more transparent and traceable. As a result, the quality of aquaculture products can be more easily assessed and should be communicated accordingly to consumers (Subasinghe et al., 2023). This landscape is gradually changing. According to data from the FAO (2024), in 2022, for the first time in history, the consumption of aquaculture products surpassed that of capture fisheries. This growth in aquaculture consumption indicates its potential to further contribute to meeting the rising global demand for aquatic foods. In their study, Cantillo et al.

(2023) concluded that promoting aquaculture products requires positively framed messaging and creating positive images of aquaculture to increase fish consumption, particularly focusing on product quality, safety, and environmental responsibility. This promotion could involve the creation of specific labels for aquaculture products, along with diverse advertising strategies. To support high-quality food security sustainably, fish consumption (especially from aquaculture) should be promoted in countries with currently low consumption, such as Brazil and Germany (Flores et al., 2022; Pedroza Filho et al., 2020).

To promote fish consumption in Brazil, the Ministry of Fisheries and Aquaculture launched the *Semana do Peixe* (Fish Week) campaign in 2010, aiming to encourage the consumption of fish and fish products. The campaign highlights the health benefits of a fish-based diet and educates consumers on the quality, variety, and preparation of fish. In 2023, Fish Week was adopted by all Brazilian states and the Federal District, resulting in a 35% increase in fish sales nationwide during the campaign week (Gandra 2024). A comparable initiative in the EU is the #TasteTheOcean campaign, organised by the Directorate-General for Maritime Affairs and Fisheries (DG MARE). This campaign works with European celebrity chefs to create exclusive recipes featuring local, seasonal fish products from either wild fisheries or aquaculture. The goal is to encourage consumers to buy and enjoy sustainable fish and seafood, making better and more informed choices. In the 4th edition (2024), the content produced by DG MARE was distributed in all EU Member States in 22 different languages, reaching approximately 1 million people with 1.7 million impressions and 65,000 interactions. However, such campaigns have mainly promoted the consumption of marine fish, meaning there is still significant potential to boost the consumption of fish from freshwater aquaculture.

While the increased distribution of this information is a positive step toward fish consumption, introducing fish into children's diets and encouraging its routine inclusion in everyday meals from an early age could further promote its consumption. A recent project in the Czech Republic involved supplying catfish products to many schools and preschool canteens (Mraz & Roy, 2022). This study showed that using fish in school canteens was an effective strategy for promoting fish consumption by developing an affective memory of eating fish and introducing aquaculture products into students' eating habits.

Expanding the current distribution of information to reach a larger population is essential. This expansion can be achieved through digital influencers and social media platforms that inform society about the nutritional value and sustainability of aquaculture products, broadening the audience for such campaigns.

In addition to promoting consumer awareness and ensuring competitive prices for aquaculture products, it is crucial to adopt sustainable labels and certifications for aquaculture products in countries where they do not yet exist. These quality control certifications will reinforce the quality of aquaculture products and encourage their consumption.

4.2 Capacity building for future generations

Aquaculture is an ancient form of farming, with the evolution of knowledge historically rooted in traditional observations of species. Over time, it has advanced to include mastery of reproduction, nutrition, health, genetics, and other essential skills. This expertise has been cultivated not only through academic courses but also through day-to-day practice. However, the aquaculture field faces challenges that threaten this wealth of knowledge. The current decline in interest and participation in aquaculture risks the loss of valuable techniques and practices developed over generations. This erosion undermines opportunities to integrate these insights into the development of innovative technologies and practices within this sector.

One of the main challenges facing the future of aquaculture in Brazil and in Germany is the lack of interest from younger generations due to factors such as hard work, unfavourable work-life balance, and unpredictable, low income (EP, 2021). In Brazil, this is reflected in a recent survey showing that, from 2012 to 2023, the largest reduction in the workforce within the primary sector took place (3%, IBGE, 2023), which includes both aquaculture and agriculture. Specifically, there are about 230,000 fish farms in Brazil (IBGE, 2023), but there is a lack of up-to-date statistics on the total number of workers in the sector, despite a global reduction in the workforce in fish farms (FAO, 2024). While Brazil's aquaculture production is growing, the aquaculture workforce represents only approximately 0.04% of the entire country's workforce[1]. In Germany, the aquaculture sector is stagnating, and the number of aquaculture farms decreased from over 3,300 in 2015 to fewer than 2,000 farms in 2023 (Lasner & Gimpel, 2024).

In addition, the low gender inclusivity in this field remains an issue (Adam & Njogu, 2023). While women's participation in aquaculture research (academia) and in the fish processing industry is common, women still face considerable challenges in other areas of aquaculture. For example, the production of fingerlings and fish is largely dominated by men, with women often lacking access to resources, control over assets, and decision-making power. This gender disparity must be addressed directly and thoughtfully by acknowledging the challenges for women and developing technologies that help overcome these.

A communication platform connecting aquaculture practitioners, research institutions, related industries, decision-makers and civil society could serve as an effective tool to facilitate innovations, promote integration, and encourage the sustainable growth of the sector. In this context, local communities and associations can play a vital role in communication among different actors, ensuring the co-development of local best management practices that are aligned with cultural and gender diversity. Knowledge transfer to fish farmers must be a public policy, conducted as a continuous, gender-balanced, and participative process led primarily by extension services, research, and education institutions, rather than by private entities. This approach will ensure equitable access to resources and information, thereby safeguarding existing aquaculture-based livelihoods. Additionally, such initiatives will support effective regional cooperation, planning, and governance, ultimately enhancing aquaculture practices.

Particularly for small and medium-scale fish farmers, knowledge transfer is key to developing profitable aquaculture enterprises that maximise social and economic benefits while minimising environmental impacts. A clear example of successful collaboration can be seen in the tilapia (*Oreochromis niloticus*) production across Brazilian states (see **Figure 5**). The production is unevenly distributed across the country, with some regions standing out in terms of production volume. Notably, the state of Paraná leads Brazil in production **(Figure 5)**, despite having less favourable climate conditions compared to other regions. This success can be attributed to the structured technical knowledge and resource and data transfer among various actors, particularly through community cooperatives of local fish farmers.

In Paraná, local cooperative systems consolidate and coordinate small-scale farms to improve efficiency on the tilapia value chain, while minimising negative impacts on rural employment. These cooperatives provide feed, fish, technical assistance, and oversee the slaughter process. They also play a critical role in transferring knowledge on management, business, and technical practices through both formal and informal education. This system of collaboration and knowledge transfer is highly beneficial for tilapia production in Paraná, especially considering that cooperatives and farmer associations are not traditionally common in Brazil (Valenti et al., 2021). Therefore, the exchange of technical, scientific, business and management knowledge related

1 Total number of employees in the Brazilian aquaculture sector accounts for 20,996 out of a total national workforce of 52,790,864. Figures are taken from https://datampe.sebrae.com.br/profile/industry/pesca-e-aquicultura and https://datampe.sebrae.com.br/profile/geo/brasil (SEPRAE, 2022).

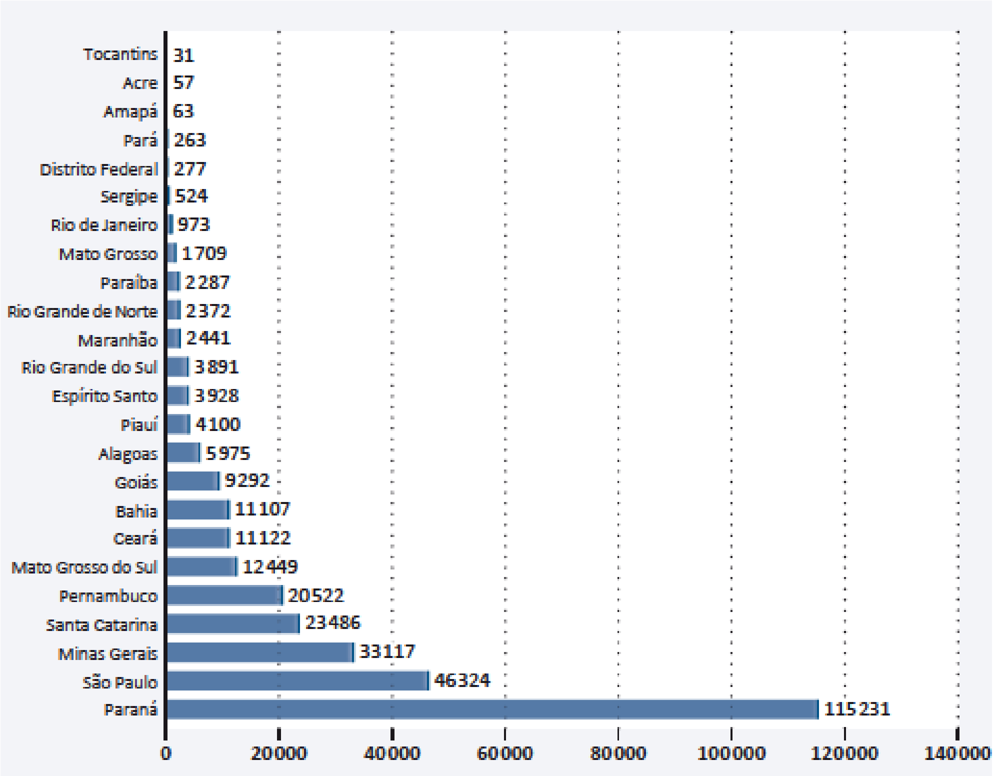

Figure 5. *Brazilian production (tonnes per year) of tilapia (Oreochromis niloticus) per state in 2018. Adapted from Pedrosa Filho et al. (2020)*

to aquaculture and environmental sustainability is crucial for the sector's growth. It leads to improvements in production management, fish health, nutrition and environmental monitoring, all of which are key to long-term success.

Capacity building, especially for future generations, is also a key topic in Europe, as highlighted by the European Parliament resolution of 16 September 2021 regarding the workforce in the fisheries industry (EP, 2021). This resolution states that efforts to address capacity building should focus on making the sector more accessible, sustainable, and appealing to younger generations. Achieving this requires the creation of adaptable working environments that reintegrate individuals with disabilities, foster social inclusion, and generate stable incomes. Ensuring mutual recognition of qualifications without imposing excessive financial or bureaucratic burdens can enhance staff mobility and attract new talent. The establishment of an association for young aquaculture professionals and the allocation of budgetary resources to support generational renewal will further energise the sector. Additionally, promoting high environmental and social sustainability standards will strengthen the sector's long-term economic stability and attractiveness. The digitisation of aquaculture activities will also empower younger generations to leverage intuitive software and innovative technologies, improving safety, working conditions, and operational efficiency in aquaculture. Furthermore, technological innovation can help promote gender equality. Advancing knowledge transfer and capacity building in aquaculture requires a multifaceted approach that strengthens the production chain while fostering innovation and professional development. Promoting the dissemination of local, traditional and indigenous knowledge, along with adopting new technologies, can enhance efficiency and sustainability in fish farming. Targeted efforts to raise public appreciation of aquaculture professionals will attract and retain talent. Facilitating knowledge transfer between universities and fish farmers will bridge critical expertise gaps and support local food security. Educational trips to fish farms can introduce children to the aquaculture business, inspiring early interest in and awareness of the sector. Expanding technical courses and professional programmes, such as technical education and postgraduate residencies in aquaculture in Brazil, will ensure a steady supply of skilled professionals prepared to meet the challenges of the industry.

5. Policy and regulation

Aquaculture is a global industry in a changing world. The legal and regulatory framework governing this food-supplying sector operates on multiple levels. The EU defines rules and regulations that are directly or indirectly relevant to aquaculture (e.g., Water Framework Directive, Animal Health Law, regulation on the use of foreign and locally absent species in aquaculture, Habitats Directive). These rules and regulations are then incorporated into German national legislation. Based on this national legislation, the federal states are ultimately responsible for specific aquaculture regulations. However, administrative procedures, spatial planning, and licensing (e.g., water permission) are complex, and the clear determination of responsibilities is often challenging. A similar regulatory and administrative ambiguity exists in Brazil. Economic-environmental zoning specific to aquaculture is entirely absent, and there is a lack of clear characterisation of the diverse micro-regions of Brazil in this regard. Considering this diversity and the great natural potential for aquaculture in Brazil, there is a definite need for legislation adapted to regional characteristics, such as climate, species, economic goals and water scarcity. Thus, the lack of legislation that is compatible with and applicable to the different aquaculture activities in both Brazil and Germany creates major obstacles, making it difficult to attract investment and grow the sector.

Expanding the aquaculture sector and its related activities requires a clear vision. National strategy plans (e.g., NASTAQ, 2014; NASTAQ, 2020 in Germany) have been developed to describe the current state, bottlenecks, and goals for how the aquaculture sector should be developed and guided towards sustainably increasing aquatic food production. Similarly, Brazil developed the National Aquaculture Development Plan (PNDA, 2022), addressing challenges to be overcome, the main technical and economic bottlenecks, and strategies for the increased productivity and competitiveness of Brazilian aquaculture.

However, comparing the objectives of past strategic plans with current achievements illustrates the inadequacies of the current regulatory environment in accomplishing self-determined goals. To realise the ambitious targets formulated in strategic planning and achieve greater self-sufficiency through sustainable domestic aquaculture production, it is of utmost importance to firstly unify, and secondly reduce and streamline regulations.

Excessive bureaucracy and delays caused by government bodies in licensing projects thwart progress in the aquaculture sector and disincentivise newcomers. Only reliable legislation will provide planning security and, in turn, maintain or increase aquaculture production. In a constantly changing environment with ongoing technical development, legislation should create a future-proof framework that makes the sector more attractive for investments from both current and new businesses.

5.1 Regulatory obstacles in Germany

The expansion of sustainable aquaculture practices requires a streamlined and unambiguous regulatory framework that is accessible to all stakeholders, from policymakers to practitioners. A major obstacle is the involvement of a wide variety of authorities in the approval process for aquaculture facilities in Germany **(Figure 6).**

When establishing a new aquaculture facility (construction) or making structural changes to an existing farm (modernisation) in Germany, an official "building permit application" is usually required. This application must be submitted to the Lower Building Authority (at the district/municipal level within a federal state). Depending on the scope of the project and the Lower

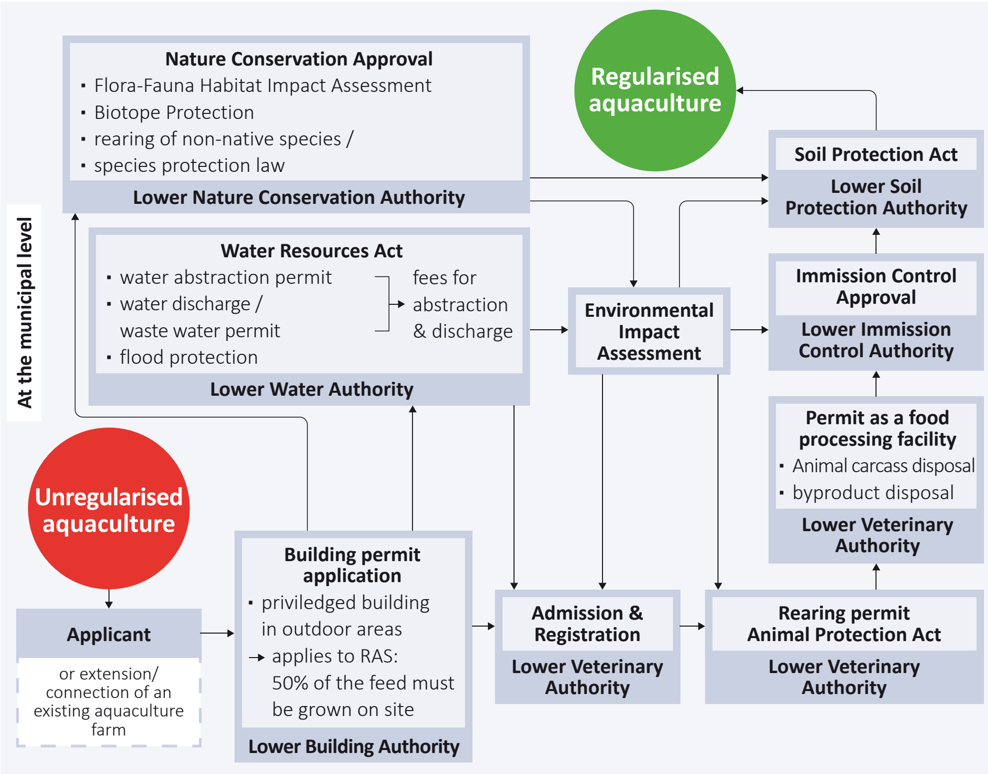

Figure 6. *Authorities involvedinfilingabuilding permitapplicationto establishanaquacul-turebusiness(whether flow-throughorRAS)ina federalstateinGermany.*

Building Authority, numerous other authorities may be involved or consulted.

As a mandatory part of the process, the Lower Water Authority, the Lower Nature Conservation Authority and the Lower Veterinary Authority must participate. Depending on the federal state, municipality, and project scope, additional authorities may be consulted, including the Lower Soil Protection Authority and the Immission Control Authority. These authorities assess the application for the aquaculture facility and may request further statements or documentation if necessary.

Each authority checks the "building permit application" for compliance with the legal framework in its area of responsibility and ensures conformity with relevant regulations and laws. For example, the Lower Water Authority reviews the application under the Water Resources Act, the State Water Act, Surface Water Regulation, the Waste Water Levy Act, the Wastewater Regulation, and other applicable laws.

The "building permit application" will only be approved after all official requirements have been met and the applicant has addressed all necessary points. In practice, multiple rounds of hearings are often necessary before a final decision is issued, and applicants are frequently confronted with additional requirements and requests for changes. Due to the involvement of numerous authorities and the highly individualised requirements, the application process can be extremely complex, time-consuming, and unpredictable. The processing time of a "building permit application" for an aquaculture facility can take several years.

5.2 Regulatory obstacles in Brazil

Brazil is globally recognised for its vast hydrographic capacity, which includes an extensive network of rivers, lakes, and aquifers. However, this abundance of water resources also presents challenges, particularly due to disparities among Brazilian states in terms of legislation,

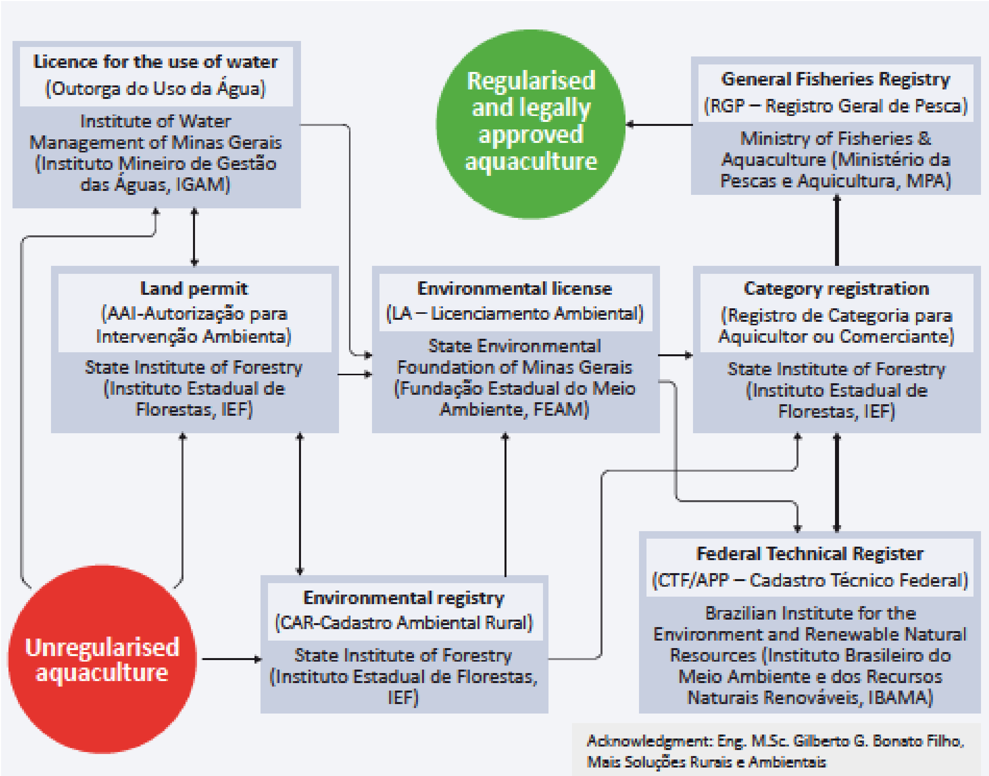

Figure 7. *Example of the bureaucracy involved in the regulation and legal approval of an aquaculture project in Brazil can be seen in the challenges faced during the regularisation of aquaculture in the Zona da Mata region (Minas Gerais, Brazil).*

infrastructure, and environmental conditions. To understand the complexity of regulating aquaculture activities in Brazil, one needs only to consider the country's division into 26 states and one federal district. Each of these entities has its own set of laws and regulations governing aquaculture, along with distinct infrastructure and environmental conditions.

Overall, the licensing and regulatory procedures for aquaculture across various states are notably bureaucratic and time-consuming, potentially deterring producers and impeding the development of Brazil's aquaculture sector. **Figure 7** above illustrates the complex licensing dynamics via mixed pathways that represent the general bureaucratic steps required to obtain a permit for an aquaculture facility in the Zona da Mata region (State of Minas Gerais, Brazil). The process involves at least five distinct public bodies. In Minas Gerais, applicants must first secure a licence for the use of water (*Outorga do Uso da Água)* from the Institute of Water Management of Minas Gerais (*Instituto Mineiro de Gestão das Águas, IGAM*) if the water catchment volume is above 1 l/s or if the dam contains more than 5,000m³ of water; otherwise, a certificate of negligible use suffices. Due to local topography and water availability, many properties are situated in a Permanent Preservation Area (APP), thereby necessitating a permit for environmental intervention (*AAI – Autorização para Intervenção Ambiental*) from the State Institute of Forestry (*Instituto Estadual de Florestas, IEF*). Moreover, as aquaculture facilities are predominately located in rural areas, applicants are required to register with the rural environmental registry (*CAR – Cadastro Ambiental Rural*) of the IEF. When the water surface of the planned aquaculture facility exceeds 2ha, an environmental licence (*LA – Licenciamento Ambiental*) must be obtained from the State Environmental Foundation of Minas Gerais (*Fundação Estadual do Meio Ambiente, FEAM*). For activities with potential pollutant effects and for the utilisation of environmental resources, a federal technical register (*CTF/APP – Cadastro Técnico Federal*) is necessary, which is issued by the Brazilian Institute for the Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, IBAMA*). Additionally, applicants must register their economic status as either producer or retailer (*Registro de Categoria para Aquicul-*

torouComerciante) with IEF. Finally, prospective aquaculture producers are required to secure an official entry in the General Fisheries Registry (*RGP – Registro Geral de Pesca*), which is managed by the Ministry of Fisheries and Aquaculture (*MinistériodaPescaeAquicultura,MPA*).

The main challenges faced during the approval stages, as reported by the locals, are: 1) lack of required documents, such as undocumented land ownership; 2) the financial cost of the process; 3) lack of knowledge about the process; 4) the fines applied. Environmental licensing is highlighted as the most challenging stage, as the lack of documents and knowledge primarily become apparent during this phase. Similar to the German case, the whole approval process takes more than two years to be concluded.

5.3 Streamlining regulations

Since aquaculture is embedded in the natural environment and relies on its resources for production, competing legislations come into play. If aquaculture is to take on a greater role in domestic food production, there is a need to carefully re-examine how existing legal frameworks balance multiple environmental and food security priorities. For instance, regulations related to nature protection, such as those concerning fish-predatory species, water use, and effluent discharge, can present challenges for aquaculture development in regions like Europe, Germany, and Brazil.

One potential solution to the regulatory complexity could be the appointment of "aquaculture officers". These officers would serve as dedicated contact points at the federal state level, helping facilitate the licensing and monitoring process for aquaculture projects from concept to realisation. The introduction of such a role could reduce barriers to entry (such as time and resources) and uncertainty for prospective aquaculture entrepreneurs, increasing the likelihood of project success and attracting more new industry participants to the sector. Furthermore, simplification could also be achieved through integrated procedures managed by a single lead authority.

Brazil has already made initial attempts to simplify administrative and licensing procedures. First, a ministry was created to address matters related to fishing and aquaculture (Ministry of Fishing and Aquaculture, MPA; https://www.gov.br/mpa/pt-br). Second, professional aquaculture licensing has been made mandatory for any entity aiming to engage in aquaculture production, as stated in Ordinance No. 174 of 26 December 2023. Third, quarterly meetings of the National Council of Aquaculture and Fisheries (CONAP) have been introduced. These meetings aim to propose public policies for managing aquaculture and fishing activities across the country and to promote dialogue between different levels of the government and the public.

To date, Germany has not implemented any legislative or regulatory measures aimed at simplifying and streamlining its aquaculture policy and regulations.

6. Recommendations

Aquaculture has great potential to contribute to a sustainable, circular, and resilient global food system. To unlock its ability to support healthy human diets, especially in regions with low self-sufficiency, three main objectives must be met.

1) Simplify regulatory procedures to support the sustainability of existing aquaculture enterprises and facilitate the creation of new ones.
2) Implement effective education and workforce development, while fostering consumer awareness about the sustainability and health benefits of modern aquaculture.
3) Translate scientific knowledge and innovations into practical, sustainable solutions.

To achieve these objectives, we recommend the following actions.

Policy and regulation

To fully unlock the potential of sustainable aquaculture, national legislation and regulations should facilitate, not hinder, the implementation of innovative approaches in aquaculture. We recommend that policymakers in Brazil and Germany take the following actions.

- **Introduce aquaculture officers:** These officers, based at regulatory bodies, would guide prospective aquaculture entrepreneurs through the entire licensing and monitoring process from initial concept to full implementation. This dedicated role would reduce entry barriers, increase efficiency, and minimise resources and uncertainty, thus enhancing project success and attracting new participants to the sector.
- **Streamline bureaucracy:** Limit the number of regulatory bodies responsible for licensing and controlling freshwater aquaculture facilities. Producers in both countries face excessive bureaucracy. Initial efforts to simplify administrative and licensing procedures should include the establishment of a dedicated government department for this industry. In addition, regular intergovernmental meetings should be held to develop public policies and foster dialogue between government bodies and the public.

Consumer awareness and education for a future workforce

Raising public awareness about the benefits of aquaculture products is vital to increasing consumer demand. At the same time, educating and building capacity for a skilled workforce is crucial for aquaculture's growth. We recommend that public institutions, non-governmental organisations (NGOs), and the aquaculture industry (in both countries) take the following steps:

- **Offer meals based on sustainable aquaculture products:** Integrate domestically produced sustainable (freshwater) aquaculture products into public canteens, schools, and universities. This initiative can help support public health and promote the role of aquaculture in transforming the food production sector.
- **Launch a mainstreaming programme:** Raise societal awareness about the nutritional benefits of fish and the sustainable, secure, and transparent practices behind domestic freshwater aquaculture. Collaboration between governmental bodies, NGOs and the sector can help improve public perception and address prevailing biases against farmed fish.
- **Intensify training programmes:** Promote fish farming as a promising career path for young professionals. A skilled workforce is needed to scale up sustainable freshwater aquaculture, including:
  · Technical training for practitioners.
  · Academic training for research, education, and governance roles.

Science and innovation for practice

The bi-directional and transdisciplinary transfer of knowledge between science and the aquaculture industry is crucial for adapting to an ever-changing environment. We recommend that scientific institutions, in collaboration with government bodies and private sector stakeholders, take the following steps:

- **Develop technological packages:** These should be tailored to local needs and opportunities, focusing on sustainable technologies that offer economically viable solutions. These packages should include the selection of appropriate species, the re-use of by-products, and the implementation of effective waste management strategies to improve circularity.
- **Co-develop local best management practices (BMPs):** In collaboration with industry and government agencies, develop BMPs, guidance, and tools that encompass skills, knowledge, technology, services, infrastructure and governance. In this process, social and gender equity should also be considered.

Final thoughts

By implementing these recommendations, we can advance aquaculture towards a more sustainable, efficient, and circular future, with broad benefits for public health, food security, and environmental sustainability. Proper science, education, and policy are essential to realise aquaculture's full potential in building resilient and sustainable food systems.

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