

Governing Precision Aquaculture for Equitable and Responsible Automation: Implication for Developmental Programme Extension

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Abstract

Precision aquaculture uses artificial intelligence (AI), Internet of Things (IoT) sensors, computer vision, digital twins, and automated systems to improve aquatic animal production, feed efficiency, disease control, and environmental performance. However, its rapid growth raises concerns about data ownership, algorithmic accountability, animal welfare, employment, and the inclusion of small-scale farmers. This review examines how precision aquaculture can be governed to promote fairness, responsibility, and sustainability, with particular attention to agricultural extension and development programmes in the Global South. Drawing on research on precision fish farming, responsible innovation, digital agriculture, food governance, and ICT adoption in Nigeria, the paper examines five key areas: data ownership and control, algorithmic accountability and auditing, animal welfare, inclusive innovation and labour transitions, and adaptive governance across different levels. It proposes a Responsible Precision Aquaculture (RPA) framework based on anticipation, reflection, inclusion, and responsiveness. It also introduces a draft Responsible Precision Aquaculture Index (RPAI), comprising five pillars and twenty-five proposed indicators for assessing farms, programmes, and jurisdictions. Furthermore, the paper outlines region-specific governance pathways for the Nordic region, Southeast Asia, Latin America, and Sub-Saharan Africa. The review argues that responsible automation depends not only on technological accuracy but also on fair data ownership, transparent decision-making, animal welfare, livelihood protection, and inclusive governance. Agricultural extension systems are identified as a vital link between precision technologies and their fair and responsible adoption.

Review / Conceptual Framework

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Introduction

Aquaculture is entering a period in which sensing, prediction, and automated control can increasingly be embedded in routine production. Internet of Things sensors can continuously observe water quality; computer vision can estimate biomass and behaviour; predictive models can anticipate disease or oxygen depletion; and automated systems can adjust feeding or environmental controls. (Cortes, 2026; Awolumate, 2018a; Mundi et al., 2024) These

capabilities promise lower input use, faster responses, and greater resilience. They also change where decisions are made and who can make them.

This matters because food-system technologies do not operate outside institutions. The data that feed an algorithm are generated by farms, workers, animals, and environments; the models are selected and trained through technical and commercial infrastructures; and their recommendations can

influence production, labor, and environmental outcomes. Recent work in Nature Food frames AI as an emerging infrastructure for food innovation and emphasizes data quality, transparency, inclusive data ecosystems, and the augmentation of human expertise. A recent aquaculture-specific review similarly identifies human-centered AI, ethics, governance, data foundations, and digital literacy as critical to sustainable deployment. The opportunity, therefore, is not simply to make aquaculture more automated, but to design institutions capable of governing automation responsibly. (Cortes, 2026; Awolunate, 2018a; Mundi et al., 2024; Awolunate, 2026)

Here we argue that precision aquaculture should be treated as socio-technical infrastructure through which data, decision-making authority and value are redistributed. This reframing connects technological governance with the established sustainability objectives of aquaculture. It also complements the Food and Agriculture Organization's 2025 Guidelines for Sustainable Aquaculture, which emphasize equity, participation, transparency, accountability, environmental stewardship and adaptable governance across local to global levels. We propose five governance pillars (Fig. 1) and a conceptual Responsible Precision Aquaculture Index (RPAI; Fig. 2) to provide a basis for assessment. Evidence from Nigeria illustrates why this governance questions are practical rather than abstract. Awolunate's work on ICT adaptability among Lagos fish farmers, together with research on digital platforms and mobile communication among Nigerian fish farmers, points to the importance of technological accessibility and communication capacity in determining whether digital tools can be used effectively. Related work on digital market information, cooperative support, and aquaculture productivity further suggests that information and institutional arrangements can shape economic performance. Studies of climate-information sourcing, digital learning resilience, and community-based adaptive education likewise indicate that digital capability is intertwined with extension systems, financial access, and adaptive capacity. These findings do not establish a universal model for precision aquaculture, but they provide an empirical rationale for treating inclusion, information access and institutional capability as governance variables rather than peripheral adoption issues. (Inyang et al., 2017; Awolunate, 2018b; Mundi et al., 2024; Awolunate, 2026; Awolunate and Ashiedu, 2026; Awolunate et al., 2025; Awolunate et al., 2026)

Data sovereignty and ownership

Precision aquaculture converts everyday production into data: stocking, feeding, growth, water quality, disease signals, energy use, mortality, market transactions and environmental conditions. The strategic question is therefore not only whether data are available, but who can access, combine, interpret, reuse and monetize them. Data governance in agriculture is increasingly recognized as a question of ownership, control and bargaining power rather

than a purely technical matter. For aquaculture, the risk is especially acute where farmers depend on proprietary platforms or cloud services. (Berisha et al., 2026; Datta et al, 2026; Awolunate, 2018b; Mundi et al., 2024) A producer may generate valuable longitudinal data while having limited control over its secondary uses, model training or portability. This can create an asymmetry between data generation and data governance. It may also make switching suppliers difficult if historical data are locked into incompatible systems.

Governance should therefore move upstream: data rights, portability, consent, purpose limitation and interoperability should be addressed before digital markets become entrenched. Farmer organizations and regulators should have a role in defining collective data rights, while contracts should specify access, retention, secondary use and deletion. Open standards can reduce technological lock-in without requiring all commercially sensitive information to become public. The objective is data stewardship that protects legitimate commercial interests while preserving producer agency.

Governance responses emerging in the literature include: data trusts and cooperative data-governance models (as in the PescaData cooperative platform in Latin America, where fishers retain ownership, transparency, co-design and security rights; Platform Cooperativism Consortium, 2025); federated learning, which allows models to be trained across farms without centralising raw data; open sensor-data standards promoted by industry initiatives; and embedding data standards within farm certification. For extension programming, the implication is direct: extension agents must become data-governance intermediaries, negotiating data-sharing agreements, informing farmers of their rights, and building the digital literacy that underpins meaningful consent. Prior evidence that ICT utilisation by extension officers is itself constrained by infrastructure and capacity deficits (Akpabio and Inyang., 2007; Fregene, Inyang and Awolunate, 2011; Inyang et al., 2015) means that data-sovereignty capacity must be built into extension organisations, not only on farms.

Algorithmic Accountability and Auditability

As precision aquaculture moves from computer-based advice to fully automated activities such as feeding, grading, crowding and harvesting, it becomes important to ask not only whether the algorithms work but also who is responsible when they fail. The European Parliament's framework for algorithmic accountability and transparency provides a useful guide (European Parliament, 2019). It recommends matching the level of supervision to the possible risks of automated decisions. These risks include the impact of a decision, its scale, whether its effects can be reversed, and whether the decision can be checked and explained. The framework also supports impact assessments that involve the public, cooperation among regulators and standards organisations, and certification systems similar to product-safety

certification. In aquaculture, four main measures can help ensure accountability.

First, supervision should match the level of risk. Low-risk advisory tools, such as fish growth forecasts, may need basic monitoring and user training. However, automated systems that control feeding, oxygen supply or harvesting need stronger checks and risk assessments. Independent certification may also be necessary when system failure could cause serious harm to fish welfare or food safety.

Second, automated systems must be easy to check. Their records should explain how the models were developed, where the training data came from and how well the systems perform after installation. Regular checks should identify changes in model performance. Comparing results across farms using open datasets can also help identify weaknesses.

Third, responsibility must be clearly defined. If an algorithm contributes to mass fish deaths or poor animal welfare, it should be possible to identify the responsibilities of the technology provider, system integrator and farmer. Responsibility should cover the entire system, including the people and organisations involved, rather than focusing only on the software.

Fourth, farmers should understand and question automated decisions. Human-centred artificial intelligence (AI) research stresses that farmers need clear explanations of automated recommendations. They should understand why a recommendation was made, when it may be unreliable and how to challenge or override it. Transparency and meaningful human supervision can help build trust in these systems (Frontiers in Aquaculture, 2026).

These requirements also have important implications for agricultural extension. Extension officers and farmer organisations need to develop *algorithmic literacy*, which means understanding how automated systems work, interpreting their recommendations and recognising their possible limitations. This is important because studies have identified technology-related fears and limited capacity among extension personnel (Akpabio et al., 2018). Training and capacity-building are also important for effective technology transfer (Inyang et al., 2018; Solomon et al., 2006). An automated recommendation is not always correct or fair simply because a computer produces it. Its performance depends on the data used to train the model, the factors selected, the assumptions built into it and the conditions in which it operates. A model trained for a particular fish species, temperature, stocking density or farming system may produce different results when used under other conditions. For this reason, accountability should extend beyond software developers. Farm operators, technology providers, system integrators, certification bodies and regulators may all have responsibilities. The greater the possible harm from an automated decision, the stronger the need for human supervision, proper record-keeping, traceability, testing and ways to challenge the system.

UNESCO's *Recommendation on the Ethics of AI* and the OECD AI Principles provide useful guidance on human supervision, transparency, accountability, system reliability and risk management (UNESCO, 2021). The main principle is that the level of accountability should match the level of risk. Low-risk advisory tools may require clear information, regular performance checks and user training. However, systems that automatically control feeding, water quality, medication-related decisions or other high-risk activities need stronger testing, safety measures, audit records and clearly assigned responsibilities. Farmers should receive enough information to understand why a system makes a recommendation, recognize when it may be unreliable and know how to override it.

Animal-Welfare Assurance in Automated Aquaculture Systems

Automation can improve fish welfare monitoring because it allows farmers to observe fish more often and reduces dependence on occasional human checks. Computer vision, behaviour recognition and environmental sensors can help detect unusual swimming, overcrowding, low oxygen levels and changes in feeding behaviour earlier than traditional methods. However, these measurements do not fully represent the welfare of fish. When automated systems focus only on what they can easily measure, they may overlook other important aspects of fish welfare. For example, an algorithm designed to improve feed efficiency may ignore fish behaviour, environmental conditions or handling practices. Automation can also increase the effects of poorly planned production practices by carrying them out faster and on a larger scale.

Fish welfare should therefore be considered from the beginning of system design, rather than checked only after the system has been introduced. Automated models should be assessed based on their effects on fish welfare, not only their prediction accuracy or production performance. Human inspection should remain available, especially when sensor readings conflict or the system is uncertain. Research on aquaculture welfare also shows that fish welfare is an evolving scientific and governance concern, not just a technical measurement. The main question is not simply whether artificial intelligence (AI) can monitor fish, but whether it helps farmers protect them more effectively. Automation presents both benefits and risks for fish welfare. On the positive side, continuous and non-invasive monitoring of fish behaviour, feeding, swimming and other health indicators can help identify stress, low oxygen levels, disease and injury earlier than manual observation alone. Vision systems can also help identify dead or injured fish, while unusual behaviour can trigger welfare alerts (Norwegian Veterinary Institute, 2026; IntechOpen, 2026). However, the same technology can encourage farmers to increase stocking density, reduce safety margins or pursue faster growth at the expense of fish welfare. To prevent these risks, welfare objectives must be clearly included in the design of

automated systems rather than treated as an afterthought (IntechOpen, 2026).

Several measures can support responsible fish welfare management. These include welfare considerations in feeding and stocking decisions; using clear and verifiable welfare indicators, such as mortality, injuries and behaviour, in certification schemes such as the Aquaculture Stewardship Council (ASC) and the Global Seafood Alliance (GSA); and using sensor-based monitoring to support certification. For important decisions that may affect fish welfare, human approval should be required before automated systems act. A major challenge is that welfare models developed for salmon in clear Nordic waters may not work well in small-scale farms with muddy or cloudy water and limited data. Extension programmes should therefore help farmers and other stakeholders develop practical welfare-monitoring methods, agree on suitable local welfare standards and test affordable sensors under local conditions. This approach builds on community-based monitoring and evaluation practices in agricultural extension (Inyang & Daniel, 2018; Daniel & Inyang, 2019).

Inclusive Innovation and Labour Transition

The benefits of precision aquaculture may not reach all farmers equally. Systems that require large investments may favour large farms and companies with reliable electricity, internet access, technical support and finance. Small-scale farmers may struggle with high costs, poor infrastructure and limited digital skills. Automation may also reduce some routine jobs while increasing the need for workers who can monitor systems, analyse data and maintain equipment.

Inclusion should be measured by actual results, not just expressed as a goal. Responsible precision aquaculture should consider who can afford the technology, understand its results, question its decisions and benefit financially from its use. Digital skills training, local-language interfaces, shared services, cooperative purchasing, affordable sensors and agricultural extension support can help reduce these barriers (Awolunate, 2018b; Mundi et al., 2024; Awolunate et al., 2025; Awolunate et al., 2026). The effects of automation on workers also require attention (Awolunate, 2026; Awolunate et al., 2025). Rather than replacing human knowledge and skills, automation should support farmers and workers to make better decisions. They should be able to understand, monitor and supervise digital systems. This approach agrees with wider arguments that artificial intelligence (AI) should strengthen human expertise rather than replace it. Therefore, success should not be measured only by how many farmers adopt the technology, but also by whether it improves their skills, decision-making power and ability to cope with challenges.

Responsible innovation provides a useful guide for achieving these goals. Stilgoe, Owen and Macnaghten (2013) identify four key principles: anticipation, reflexivity, inclusion and responsiveness. These principles can also guide precision

aquaculture. Anticipation means assessing who may benefit or lose before introducing automation. Automation can shift work from routine activities, such as feeding fish, testing water and cleaning equipment, to system monitoring, data analysis and maintenance. Although these changes may improve safety and working conditions for some workers, they may also lead to job losses, especially among workers with limited digital skills. Inclusion means ensuring that small-scale farmers and women are not left behind because of high technology costs, limited digital access or unfair platform arrangements. Women play important roles in labour-intensive activities, including fish processing and marketing, in many regions. Studies of aquaculture marketing in Nigeria show that access to information, finance and organisational support is important for maintaining marketing activities and improving performance (Inyang et al., 2022a, 2022b, 2022c). If automation excludes these groups, it may increase existing inequalities in gender and livelihoods (Inyang & Udong, 2013; Etuk et al., 2011).

Responsiveness means that technology and related policies should be adjusted when problems arise or when users' needs change. Policy sandboxes, participatory design with farmer organisations and digital platforms developed jointly with producers can help make technology more inclusive. However, these approaches work best when producer organisations have a real say in decisions. For agricultural extension and development programmes, this requires a combined approach. Technology transfer should go hand in hand with workers' skills development, cooperative business models for sharing precision equipment, gender-sensitive technology design and entrepreneurship support for young people in agriculture (Inyang et al., 2018; Udofot & Inyang, 2017).

Adaptive multilevel governance

Precision aquaculture is developing faster than many regulations can keep up. Sensors, computer models and automated devices may be used in different places, even when rules for testing, data management and accountability are not the same. As a result, existing regulations may become outdated or create difficulties for those who must follow them. A better approach is adaptive multilevel governance, which allows rules to change as technology and evidence develop (FAO, 2025; Pacheco et al, 2025; de Boon et al., 2022; Awolunate and Fregene, 2026; Awolunate et al., 2026). International principles can set minimum standards for transparency, safety, accountability, animal welfare and fairness. National and regional institutions can then adapt these standards to local species, ecosystems, production systems and institutional capacity. The FAO Guidelines for Sustainable Aquaculture provide a useful foundation because they support policies and actions at local, national, regional and global levels, (FAO, 2025).

Adaptive governance also requires continuous learning. Regulators need information about system failures and near misses. They should review standards as new evidence

becomes available and involve affected farmers and workers when revising rules. Regulatory sandboxes, gradual approval processes and regular independent audits can help institutions learn while allowing useful innovations to continue. The main goal is to move from approving a technology once to monitoring and managing its performance over time. Governance must operate at different but connected levels, including farms, value chains, national regulatory bodies and international platforms. Research on digital fisheries shows that digitalisation can change how decisions are made and how information is controlled. Its success depends on institutional capacity, participation, trust and the fair distribution of information. Without proper safeguards, digital systems may increase surveillance and dependence, even when they improve transparency (Frontiers in Marine Science, 2026).

A practical governance system should include clear data-management rules and policies for using algorithms at farm level; shared data standards and systems for comparing performance at industry level; and national capacity to assess algorithmic risks, protect data and enforce animal-welfare standards. Policy sandboxes can support controlled testing of new technologies. At the international level, governance should align with the FAO Blue Transformation agenda, OECD AI principles and relevant certification standards (FAO, 2022; OECD, 2019; OECD, 2024). However, coordination remains a major challenge. Responsibilities may be divided among institutions, and data standards may differ, even in well-resourced monitoring systems. Agricultural extension organisations can help bridge these gaps by connecting farmers with regulators, representing farmers' views when standards are developed, and sharing lessons from field experience to improve policies. This role is consistent with evidence on partnerships between businesses and extension services and the conditions needed for effective extension programming (Ekanem and Inyang, 2016; Inyang et al., 2012).

A framework for responsible precision aquaculture

As shown on Figure 1, the five pillars work together to provide a framework for responsible governance. Precision aquaculture uses sensors, internet connections, computer models and automated systems to manage fish production. However, the effects of these technologies depend on the rules, institutions and skills available to guide their use. The framework therefore focuses on five key questions: Who controls the data? Who can check the algorithms? Is fish welfare protected? Who can participate and benefit? Can institutions adjust to changing needs? Responsible automation depends on the relationship between technology, governance and local conditions. These conditions include infrastructure, farm size, fish species, labour arrangements, market structure, regulatory capacity and the environment (Awolumate and Ashiedu, 2026; Awolumate and Fregene, 2026; Awolumate and Williams, 2021; Awolumate and Inyang, 2019a). A technology that works well on a large,

well-connected farm may not be suitable or fair for small-scale farmers unless it is adapted to their needs. The framework also supports continuous learning and improvement. When a technology is introduced, information about its performance is collected, monitored and checked. The lessons learned are then used to improve the technology, policies and governance arrangements. These improvements guide future use. This approach makes governance an ongoing process rather than a one-time exercise to meet requirements. It also helps connect governance principles with measurable results.

Responsible Precision Aquaculture Framework

This review proposes a Responsible Precision Aquaculture (RPA) framework that brings together the five governance areas in a continuous cycle. The cycle has four stages, based on the responsible innovation framework developed by Stilgoe et al. (2013). Each stage connects the five governance areas with the roles of agricultural extension services.

ANTICIPATE: Before introducing a technology, identify how data will be collected and used, where algorithms will make decisions, and the possible effects on fish welfare and workers. Consider how the technology may affect small-scale farmers and women, including who may benefit and who may face disadvantages.

Role of extension services: Help assess new technologies and prepare guidance to support farmer organisations and policymakers in making informed decisions.

REFLECT: Examine who owns the data, how algorithms make decisions and whether the system gives enough attention to fish welfare. Consider how the meaning of efficiency is defined and whether farmers' practical knowledge is valued alongside information provided by technology companies.

Role of extension services: Organise discussions with farmers and support joint assessments that allow farmers to share their experiences and views.

INCLUDE: Ensure that farmers, workers, consumers and local communities have opportunities to participate in decisions about digital platforms, standards and certification. Farmers should also understand and agree to how their data will be used.

Role of extension services: Encourage farmer participation, support cooperative data-sharing arrangements and ensure that women and other underrepresented groups are included.

RESPOND: Use the lessons learned to improve regulations, protect fish welfare, provide workers with new skills and adjust incentives where necessary. Institutions should continue learning from experience and use the findings to improve future decisions.

Role of extension services: Provide training and retraining, monitor the results of technology use and share evidence with relevant institutions to support better policies and decisions.

The main message of this framework is that all five governance areas are necessary and must work together. Protecting farmers' data is not enough if they cannot check or question algorithmic decisions. Similarly, protecting fish welfare will not ensure fair outcomes if small-scale farmers cannot access or benefit from the technology. The four stages also depend on institutions that can learn and adapt as conditions change. The framework builds on the growing discussion of artificial intelligence, sustainability and governance in aquaculture (Frontiers in Aquaculture, 2026). It also gives agricultural extension a clear role in helping developing countries introduce and manage precision aquaculture in ways that are fair, responsible and suitable for local conditions.

Towards a Responsible Precision Aquaculture Index

The proposed RPAI provides a conceptual structure for assessing whether a precision-aquaculture deployment is responsible (Fig. 2 and Table 2). It comprises seven dimensions: Data Governance (DG), Algorithmic Accountability (AA), Animal Welfare (AW), Social Inclusion (SI), Labour Transition (LT), Environmental Performance (EP) and Regulatory Compliance (RC).

$$\text{RPAI} = f(\text{DG}, \text{AA}, \text{AW}, \text{SI}, \text{LT}, \text{EP}, \text{RC}).$$

The equation is deliberately presented as a functional form rather than a validated scoring equation. No weights or thresholds are imposed at this stage because these should be determined empirically and transparently. Future validation should combine expert elicitation, stakeholder consultation, reliability testing, sensitivity analysis and cross-context validation. Indicators could include data portability and consent mechanisms; documented model validation and auditability; welfare outcomes and human override capacity; affordability and accessibility; worker training and job transition; resource-use and environmental outcomes; and compliance with applicable laws and standards. (Awolumate, 2018b; Mundi et al., 2024; Awolumate, 2026; Inyang et al., 2017; Awolumate and Inyang, 2019b). The index is intended as a governance instrument, not a ranking of farms or countries. It could support procurement, certification, investment due diligence, regulatory review and technology assessment. Most importantly, it would make responsible deployment assessable alongside productivity.

To make the framework measurable, we propose a draft Responsible Precision Aquaculture Index (RPAI) with five pillars and five candidate indicators each, scored 0–2 per indicator (0 = absent, 1 = partial, 2 = institutionalised), giving a maximum of 50 points.

Pillar 1 — Data sovereignty and ownership: (1) farm data ownership and access rights are contractually defined; (2) data-sharing consent procedures exist and are understood by producers; (3) cooperative or trust-based data-governance arrangements cover collective data; (4) interoperability and data-portability standards are adopted; (5) benefit-sharing from data commercialisation is established.

Pillar 2 — Algorithmic accountability and auditability: (1) an inventory of algorithmic decision systems is maintained; (2) algorithmic impact assessments are conducted for actuating systems; (3) model documentation, validation and drift monitoring are in place; (4) third-party audit or certification pathways exist; (5) explainability and human-override provisions are available to users.

Pillar 3 — Animal-welfare assurance: (1) continuous welfare monitoring covers key behavioural and health indicators; (2) welfare constraints are embedded in automated control objectives; (3) welfare metrics are standardised and auditable; (4) welfare incidents trigger review and accountability procedures; (5) welfare outcomes are integrated into certification.

Pillar 4 — Inclusive innovation and labour transition: (1) distributional impact assessment includes smallholders and women; (2) reskilling and transition programmes exist for affected workers; (3) shared-access or cooperative models lower entry barriers; (4) participatory design processes involve producer organisations; (5) affordability and digital-literacy support are provided.

Pillar 5 — Adaptive multilevel governance: (1) national regulatory capacity for precision aquaculture exists; (2) policy sandboxes support supervised innovation; (3) industry–regulator–research coordination platforms function; (4) alignment with international standards (FAO, OECD, certification schemes) is maintained; (5) feedback loops connect field evidence to policy revision.

The RPAI is intended for use by farms, value-chain programmes and jurisdictions, and as an extension diagnostic: low pillar scores identify precisely where development programming should intervene. Its design follows index-building practice in sustainability governance and would require pilot validation, weighting and sensitivity analysis before formal adoption.

Regional pathways for responsible precision aquaculture

Responsible governance does not mean that every region must follow the same approach. Instead, all regions should follow common basic principles, while adapting their strategies to local needs and conditions (Table 3).

Africa: Key priorities include affordable digital infrastructure, farmers' control over their data, systems that can work together, local-language interfaces, digital extension services, and greater involvement of African researchers and institutions in developing models (Awolumate, 2018a; Mundi et al., 2024; Awolumate et al., 2025; Awolumate et al., 2026). These efforts should reduce dependence on external technologies and strengthen local skills and capacity (Awolumate, 2018b; Mundi et al., 2024; Awolumate et al., 2025).

Southeast Asia: Aquaculture in this region is diverse and rapidly developing. Key priorities include ensuring that digital systems work together, checking the reliability of

algorithms, improving traceability, protecting fish welfare, and supporting small-scale farmers. Regional standards can improve coordination while allowing adjustments for different fish species and production systems.

Latin America: Precision aquaculture is closely linked to environmental protection, social justice and local livelihoods. Technology assessment should therefore consider not only farm performance but also its effects on watersheds, coastal areas, landscapes, local communities and sensitive ecosystems.

Across these regions, the main goal is to apply shared minimum standards while adapting implementation to local conditions. These standards should promote transparency, accountability, animal welfare, inclusion, environmental protection and meaningful human oversight.

Nordic and North Atlantic pathway (salmon and recirculating aquaculture systems—RAS): These regions have advanced levels of automation. Key priorities include checking automated feeding and fish-crowding systems, developing common data standards across farms, and ensuring that automated systems protect fish welfare. However, obtaining suitable data and ensuring that models work well across different farms remain important challenges (Norwegian Veterinary Institute, 2026).

Southeast Asian pathway (shrimp, tilapia and small-scale pond farming): As aquaculture expands rapidly in this region, priorities include affordable sensors, federated learning that allows models to learn from data held by different small-scale farms, responsible management of disease-surveillance data through public–private partnerships, and digital skills training delivered through extension services.

Latin American pathway (cooperatives and links with small-scale fisheries): Priorities include cooperative systems that allow producers to control their data, as demonstrated by PescaData; traceability systems that provide direct benefits to producers; and stronger links between small-scale fisheries and aquaculture value chains. These efforts should follow principles of fairness and justice in the use of aquatic resources (Platform Cooperativism Consortium, 2025).

Sub-Saharan African pathway (Nigeria, Ghana and Kenya—catfish and tilapia): Aquaculture in these countries is largely driven by small and medium-sized businesses that face challenges with feed markets, marketing, finance and access to information (Inyang et al., 2022a, 2022b; Awolunate & Inyang, 2019, 2020a, 2020b). Key priorities include using agricultural extension services to support the adoption of precision aquaculture, providing shared sensor facilities through cooperatives, developing mobile-based advisory services, and supporting youth entrepreneurship in agriculture (Inyang et al., 2018). Digital platforms developed or funded by external organisations and technology providers should also be governed in ways that protect African farmers' control over their data. Research in Nigeria on extension

programming, the use of ICT-based climate information and credit models for capacity development provides a useful foundation for designing these approaches (Inyang et al., 2015, 2018; Ekanem & Inyang, 2016; Okon & Inyang, 2016).

Governance priorities for the next decade

Five main priorities emerge from the framework. First, farmers' data rights should be clearly established before digital markets become difficult to regulate. Contracts and standards should explain who can access, transfer, reuse and take responsibility for the data. Second, accountability should match the level of risk involved in automation. Systems that can cause serious harm should undergo stronger testing and regular audits. Third, animal welfare and environmental protection should be included in system design rather than left mainly to later inspections or certification. Fourth, inclusion should be measured by examining access to technology, affordability, skills, participation and the sharing of benefits. Fifth, institutions should be able to update their rules as technology advances and new evidence becomes available.

These priorities call for a shift from focusing mainly on technology to building good governance into technology from the beginning. The aim is not to slow innovation but to ensure that it serves the public interest. Recent research on food systems warns that artificial intelligence (AI) is becoming part of the infrastructure that shapes decision-making power and professional skills. Precision aquaculture shows how this can affect everyday farm operations. Governance arrangements should therefore develop before automated systems become so established that changing them becomes difficult (FAO, 2025; de Boon et al., 2022; Awolunate & Fregene, 2026; Awolunate et al., 2026).

Overall, the evidence points to ten priorities for responsible precision aquaculture: (1) establish legal rights that protect farmers' ownership of and access to their data, including the right to transfer them; (2) require assessments of the possible effects of automated systems, with stricter checks for systems that pose greater risks; (3) make animal welfare a basic requirement of automated control systems, not simply an optional goal; (4) provide resources to strengthen agricultural extension services so that extension officers can support data governance, explain how algorithms work and promote animal-welfare monitoring; (5) develop cooperative and trust-based data systems that include small-scale and artisanal producers; (6) invest in open standards, systems that can work together and shared datasets for comparing performance; (7) establish controlled testing environments, known as policy sandboxes, where regulators, researchers and producers can test new technologies together; (8) provide fair training and support for aquaculture workers whose jobs are affected by automation; (9) test and validate the Responsible Precision Aquaculture Index (RPAI) as a common tool for assessing responsible governance; and (10) align national strategies with the FAO Blue Transformation agenda and OECD AI principles while allowing developing countries to address their own needs and priorities.

The main message of this review is that the future of precision aquaculture should not be judged only by how accurately it estimates fish biomass or improves production. It should also be judged by how fairly farm data are managed, how well automated decisions can be checked, how effectively fish welfare is protected, how widely the benefits of innovation are shared, and how well governance systems respond to new challenges.

Conclusion

Precision aquaculture should not be judged only by how well it estimates fish weight, improves feeding, or detects diseases. It should also be judged by who controls the data, who benefits from automation, whose knowledge is considered, whether fish welfare and the environment are protected, and who takes responsibility when systems fail. The proposed governance framework and Responsible Precision Aquaculture Index (RPAI) provide a starting point for assessing these issues. The main message is simple: technological progress must be supported by strong

institutions. Responsible precision aquaculture depends not only on automation but also on human involvement, effective governance, and public accountability.

Precision aquaculture can improve sustainability, but its future depends on the decisions made today. Decisions about data ownership, algorithm accountability, fish welfare, inclusive innovation, and cooperation among different levels of government will determine whether automation creates wider benefits or concentrates power in the hands of a few. Agricultural extension services can play an important role in connecting technology with farmers and guiding its fair and responsible use. However, they need adequate resources, training, and digital skills to perform this role effectively. The proposed framework and RPAI provide a foundation for this work. The regional pathways also show that responsible precision aquaculture must respond to local needs and conditions, even though its basic principles can be applied across different regions and technologies.

Table 1 | Governance challenges and priority responses

Governance challenge	Emerging risk	Governance question	Priority response
Data sovereignty	Producer data controlled or reused without meaningful agency	Who controls access, portability and secondary use?	Data rights, consent, portability, interoperability and collective stewardship
Algorithmic accountability	Opaque or poorly validated recommendations	Who can inspect, challenge and take responsibility?	Risk-based validation, audit trails, human oversight and override
Animal welfare	Optimization of measurable outputs at the expense of broader welfare	Does automation protect welfare or only proxy variables?	Welfare-by-design, outcome validation and human inspection
Inclusion & labour	Technology benefits concentrated among well-capitalized users; work is displaced or transformed	Who can access, understand and benefit?	Affordable systems, digital literacy, extension and worker transition
Adaptive governance	Rules lag behind rapidly changing technologies	How can institutions learn and revise?	Adaptive standards, regulatory sandboxes and periodic review

Figure 1 | Governance architecture for responsible precision aquaculture

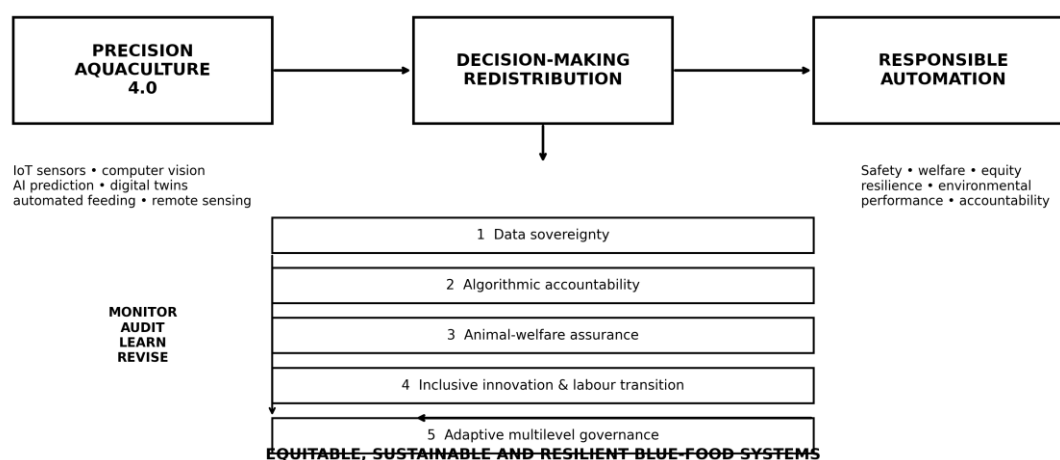
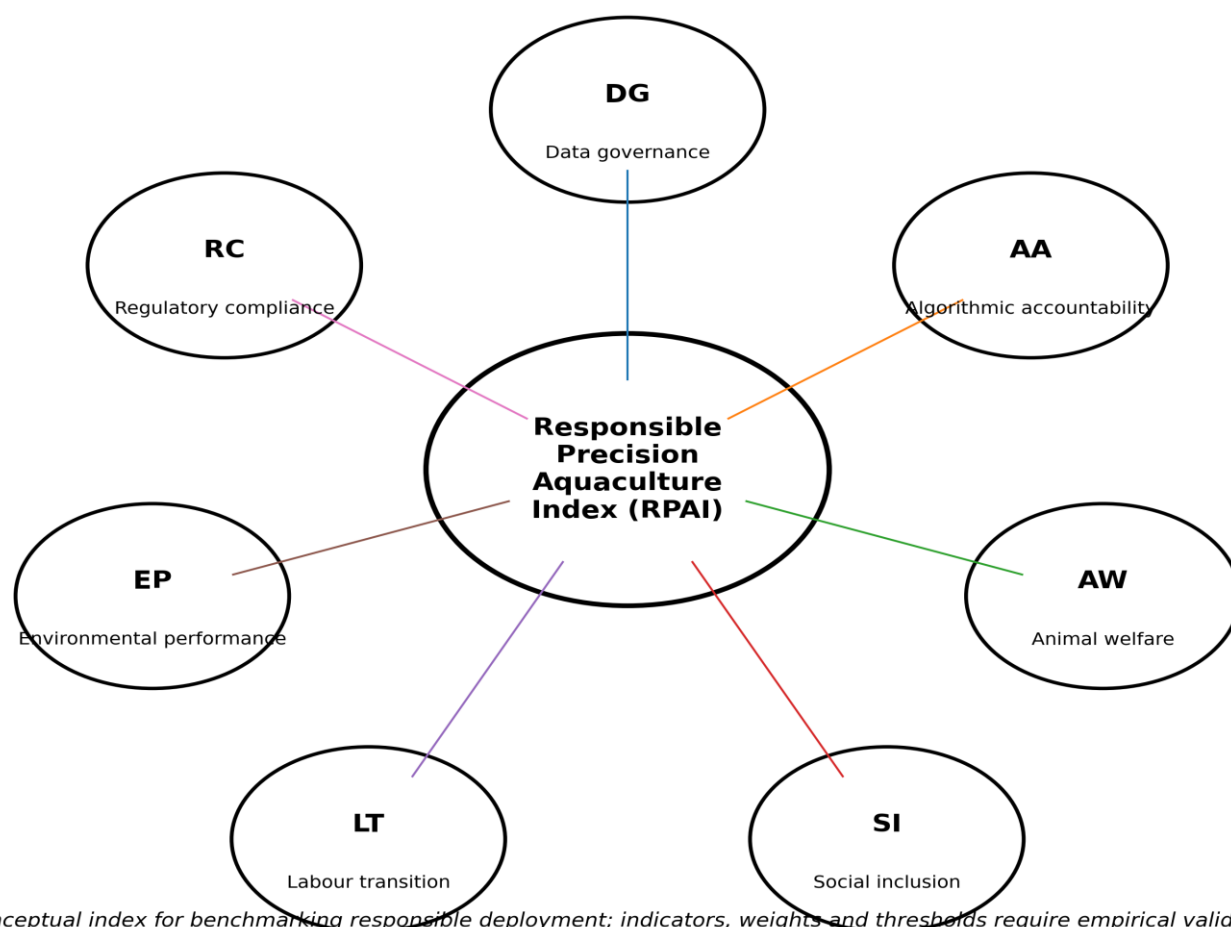


Figure 1. Governance architecture linking precision technologies to decision-making redistribution, five governance pillars, responsible automation and blue-food outcomes. The feedback loop emphasizes continuous monitoring, audit, learning and policy revision.

Table 2 | Proposed RPAI dimensions and illustrative indicators

RPAI dimension	Core question	Illustrative indicators
DG — Data governance	Who controls the data?	Consent; portability; access rights; purpose limitation; interoperability
AA — Algorithmic accountability	Who can audit or challenge the system?	Validation; model documentation; audit logs; uncertainty disclosure; override
AW — Animal welfare	Does automation protect welfare?	Behavioural indicators; mortality; stress proxies; welfare outcomes; human inspection
SI — Social inclusion	Who can access and benefit?	Affordability; connectivity; digital literacy; local-language access; participation
LT — Labour transition	Who gains or loses from automation?	Training; task changes; job quality; reskilling; worker participation
EP — Environmental performance	Does automation reduce harm?	Water/energy efficiency; emissions; nutrient losses; ecosystem indicators
RC — Regulatory compliance	Who is legally accountable?	Licensing; standards compliance; incident reporting; traceability; enforcement

Figure 2 | Proposed Responsible Precision Aquaculture Index (RPAI)



Conceptual index for benchmarking responsible deployment; indicators, weights and thresholds require empirical validation.

Figure 2. Proposed Responsible Precision Aquaculture Index (RPAI). The seven dimensions are conceptual at this stage; empirical work is required to determine indicators, weights and thresholds.

Table 3 | Regional pathways for responsible precision aquaculture

Region	Contextual priority	Governance pathway
Africa	Infrastructure constraints, diverse smallholder systems, digital-capacity gaps	Affordable and interoperable technologies; producer data rights; local-language interfaces; digital extension; regional research capacity
Southeast Asia	Rapid commercialization and technologically diverse aquaculture	Algorithmic auditing; interoperability; traceability; welfare assurance; smallholder inclusion
Latin America	Strong interaction between aquaculture, ecosystems and livelihoods	Ecosystem-level safeguards; social participation; environmental monitoring; responsible data use
Cross-regional minimum floor	Shared risks across technology contexts	Transparency; accountability; welfare; inclusion; environmental responsibility; human oversight

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