Multispecies Nutrient Optimization: A Transdisciplinary Approach to Sustainable Livestock and Aquatic Feed Design

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Abstract
This review explores the emerging field of multispecies nutrient optimization in livestock and aquaculture feed systems through a transdisciplinary lens. Conventional single-species feed models, while efficient in isolated contexts, often fail to address the interconnected sustainability challenges of climate change, biodiversity loss, and nutrient inefficiency. By contrast, multispecies systems leverage biological synergies, circular resource flows, and localized feed inputs to enhance ecological resilience and production efficiency.
Drawing on global case studies—from integrated poultry–fish systems in Southeast Asia to AI-driven aquaculture in Norway, insect-based protein supply chains in Africa, and seaweed-algae feed integration in Chile and Indonesia—the review identifies key strategies such as nutrient recycling, feed circularity, and cross-species nutrient targeting. A cross-case synthesis reveals both shared approaches and region-specific challenges, shaped by policy environments, infrastructure, and knowledge systems.
The review also addresses the ethical, environmental, and equity dimensions of feed innovation, emphasizing the need for inclusive governance, animal welfare considerations, and global feed justice. Looking forward, scaling these models will require coordinated innovation ecosystems, strategic financing, and policy frameworks that embed feed systems into broader climate and agri-food agendas.
Multispecies feed design emerges not only as a technical advancement but as a critical lever for transforming global food systems toward greater sustainability, equity, and resilience.

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1. Introduction

1.1. From Single-Species Formulation to Multispecies Synergy

Historically, animal feed design has been grounded in a single-species formulation paradigm, where rations are optimized for maximum performance of individual species in isolation. This reductionist approach, while effective in controlled environments, increasingly reveals limitations in the face of global challenges such as climate change, resource constraints, and biodiversity loss. In response, a multispecies approach to feed formulation has emerged—one that prioritizes ecological efficiency, nutrient cycling, and interspecies complementarities across integrated farming systems.
Multispecies feed strategies leverage the synergistic effects of co-rearing diverse species, such as poultry and fish, or ruminants and monogastrics, to enhance productivity while minimizing environmental impact. For instance, integrated systems like poultry-fish farming benefit from the nutrient recycling capacities of both animals—poultry droppings serve as pond fertilizer, promoting plankton growth that fish consume. This synergy reduces external feed inputs and promotes circularity (Thomas *et al.*, 2021). In terrestrial systems, multispecies grazing—such as co-grazing cattle, sheep, and goats—enhances pasture utilization

and supports a more balanced ecological footprint. Different species select distinct plant types, thereby reducing selective overgrazing and improving pasture resilience. As Walker (1997) emphasizes, this strategy not only boosts biomass yield but also supports biodiversity by mimicking natural herbivore assemblages (Walker, 1997).

The shift toward multispecies feed design also aligns with system-level sustainability goals. For example, Meeh *et al.*(2014) explored how smaller-scale multispecies pasture systems could support food production for large populations with reduced ecological disruption, highlighting their potential in climate-resilient agriculture (Meeh *et al.*, 2014).

Moreover, the benefits of multispecies systems extend to plant-based feed production. Moloney *et al.* (2020) compared monoculture swards with binary and multispecies combinations in intensive silage systems. Their findings revealed that diverse plant communities not only yielded more biomass but also supported greater forage quality—providing a broader nutritional base for different animal species (Moloney *et al.*, 2020).

In aquaculture, the movement from monoculture toward polyculture and integrated multitrophic aquaculture (IMTA) systems is gaining traction. These systems co-cultivate species from different trophic levels—such as fish, bivalves, and algae—allowing waste from one species to serve as input for another. Fulton and Sainsbury (2022) argue that ecosystem-scale thinking in fisheries management, including feed design, is essential to achieve multispecies maximum sustainable yield (MSY) in the face of uncertain ecological interactions (Fulton & Sainsbury, 2022).

The microbiological dimension of feed systems is also relevant. Mhuireach*et al.* (2022) demonstrated that multispecies livestock grazing influences the soil microbiome, enhancing its complexity and resilience. These microbial communities in turn affect forage quality and nutrient cycling, closing feedback loops between feed composition, animal health, and environmental sustainability (Mhuireach*et al.*, 2022).

Transitioning from single-species feed formulation to a multispecies framework entails reimagining feed not merely as a nutritional input, but as an ecological mediator. This shift supports sustainable intensification, enhances circular resource use, and paves the way for resilient food systems. Cross-species nutritional insights, combined with systemic thinking and integrated design, are foundational to this transformation

1.2. Why Feed Design Matters for Sustainability, Food Security, and Climate Goals

The design of animal feed occupies a critical intersection in the pursuit of sustainable food systems, climate action, and global food security. With animal production systems accounting for a significant share of global land use, greenhouse gas (GHG) emissions, and freshwater withdrawal, rethinking feed formulation presents a unique opportunity to simultaneously address ecological footprints, circular economy principles, and nutritional resilience across both terrestrial and aquatic food chains.

A primary concern in the sustainability of animal feed is its contribution to GHG emissions. Livestock production, especially ruminants, is a major emitter of methane, nitrous oxide, and carbon dioxide. However, feed sourcing and formulation greatly influence emission intensity. For example, incorporating agro-industrial by-products or food waste into feed can reduce reliance on carbon-intensive crops like soy or maize, thereby mitigating emissions while contributing to waste valorization. Makkar (2018) highlights how food-not-feed strategies—using human food leftovers for animal nutrition—reduce pressure on land and lower emissions, a concept exemplified by swill-fed pork systems in Japan (Makkar, 2018).

Feed systems are also central to nutrient cycling, especially nitrogen and phosphorus. Poorly optimized feed leads to nutrient excretion, polluting soil and water systems. Conversely, precision feeding and integrated nutrient management can close nutrient loops. Tully and Ryals (2017) underscore that aligning feed inputs with agroecosystem nutrient flows—particularly through manure recycling—can simultaneously boost productivity and reduce environmental externalities (Tully & Ryals, 2017).

Biodiversity is another critical lens through which feed design must be viewed. The global expansion of feed monocultures such as soy contributes to deforestation, land degradation, and species extinction. In contrast, diversified feed ingredients—including underutilized crops, seaweeds, insects, and agroforestry products—can reduce ecological harm and foster resilience. Toledo and Burlingame (2006) argue that biodiversity in both cultivated and wild feed resources supports ecosystem services, nutritional diversity, and long-term food security (Toledo & Burlingame, 2006).

Circular food systems—which aim to minimize waste, close material loops, and optimize biomass use—place feed design at their core. Oosting *et al.* (2022) describe how animal production in tropical regions can enhance circularity by feeding on by-products, facilitating nutrient return to soils, and reducing competition between feed and food uses (Oosting *et al.*, 2022). Such systems also promote integrated land use strategies, for instance, combining aquaculture effluent treatment with fodder crop irrigation.

Feed decisions have far-reaching implications for food security. Globally, around one-third of cereal production is diverted to animal feed, even as hundreds of millions face undernutrition. Optimizing feed to reduce reliance on human-edible crops frees up agricultural resources for direct human consumption. Moreover, feed efficiency—measured by feed conversion ratios (FCR)—plays a key role in determining how much food can be produced with limited inputs. As Godfray and Garnett (2014) explain, sustainable intensification—where more output is achieved with fewer resources—hinges on the intelligent design of inputs like feed, alongside genetic and management improvements (Godfray & Garnett, 2014).

Food waste offers another underutilized resource stream for livestock feeding. Rather than being landfilled or incinerated, food waste—properly sanitized and reformulated—can meet a significant portion of nutritional needs for pigs, poultry, and fish. Dou *et al.* (2018) emphasize that such approaches not only reduce environmental burdens but also contribute to more resilient and circular supply chains (Dou *et al.*, 2018).

Furthermore, feed systems influence water sustainability. Growing feed crops is a major consumer of freshwater, particularly in arid regions. Vågsholm*et al.* (2020) stress that designing circular food systems—where animal excreta, crop residues, and wastewater are reintegrated—can reduce water demand while maintaining productivity and food safety standards (Vågsholm*et al.*, 2020).

Lastly, feed design is deeply intertwined with climate adaptation strategies. As weather patterns shift, feed crops become more vulnerable, while livestock nutritional needs evolve. Mottet *et al.* (2018) highlight the importance of locally adapted herbivores and feed systems that can buffer against climate shocks, minimize import dependencies, and maintain food production stability under stress conditions (Mottet *et al.*, 2018).

In conclusion, animal feed design is not merely a nutritional challenge but a systems-level sustainability imperative. It shapes how we manage resources, structure food systems, and meet climate and biodiversity goals. A transdisciplinary feed strategy—linking agronomy, ecology, economics, and nutrition—is essential for ensuring that animal agriculture evolves in harmony with planetary boundaries and human development priorities.

1.3. Purpose, Scope, and Research Questions of This Review

This review aims to critically assess the evolution and potential of multispecies nutrient optimization in feed design for both livestock and aquatic systems. In an era marked by escalating environmental constraints, shifting dietary demands, and urgent climate goals, traditional single-species feed strategies fall short of delivering holistic sustainability. Instead, this paper explores how integrating nutritional requirements across species can create synergies that reduce resource use, enhance ecological resilience, and align feed systems with circular economy principles.

The scope of this review spans terrestrial and aquatic domains, emphasizing case studies where multispecies feed strategies have been implemented or proposed. Drawing from nutritional ecology, systems thinking, and emerging data technologies, the review integrates knowledge from animal science, agronomy, and sustainability research.

The central research questions guiding this review are:

- How does multispecies feed design differ from conventional approaches in terms of sustainability outcomes?
- What biological, technological, and economic principles underpin effective multispecies nutrient optimization?
- What are the cross-sectoral innovations and governance mechanisms necessary to scale multispecies feed design in diverse global contexts?

2. Key Concepts in Nutritional Ecology and Feed Science

Nutritional ecology and feed science form the foundation for understanding how animals acquire, process, and utilize nutrients in both natural and managed environments. In multispecies feed systems, the complexity is heightened by interactions between species, their divergent physiological requirements, and environmental contexts. This section explores key concepts such as nutrient partitioning, ecological stoichiometry, feeding behavior, gut microbiota, and trade-offs in mixed-species feeding systems—all of which are crucial for designing ecologically sound and nutritionally efficient feed strategies.

A central tenet of nutritional ecology is nutrient partitioning—the allocation of nutrients to different biological functions such as growth, reproduction, or maintenance. In multispecies systems, partitioning is influenced not only by species-specific metabolic demands but also by resource competition and environmental constraints. For instance, in mixed herbivore communities, coexisting generalist species occupy distinct nutritional niches, thereby reducing overlap and enhancing community-level nutrient utilization (Behmer & Joern, 2008). These niche differences are often subtle, depending on both macronutrient preferences and micronutrient acquisition strategies.

Ecological stoichiometry—the study of the balance of energy and multiple chemical elements in ecological interactions—plays a crucial role in feed formulation. The ratio of carbon, nitrogen, and phosphorus in feed not only determines growth rates but also shapes excretion profiles and nutrient cycling dynamics. Sperfeld*et al.* (2017) emphasize that stoichiometric mismatches between feed composition and animal requirements can lead to inefficiencies and increased waste, with broader implications for sustainability (Sperfeld*et al.*, 2017).

Another valuable conceptual framework is nutritional geometry, which models nutrient intake and regulation across multidimensional nutritional space. This approach reveals how animals adjust their feeding behavior to achieve an optimal balance of nutrients when offered complex or imbalanced diets. Simpson and Raubenheimer (2012) suggest that animals exhibit nutrient-specific foraging decisions, which are critical when designing mixed-species diets to avoid over- or under-supplying particular nutrients (Simpson &Raubenheimer, 2012).

In mixed-species systems, feeding behavior becomes both a physiological and ecological variable. Social interactions, dominance hierarchies, and species-specific foraging strategies influence feed intake and efficiency. Lihoreau*et al.* (2015) propose a model of social nutritional ecology, emphasizing that group-level dynamics affect individual nutrient regulation, especially in settings where species or individuals share feeding zones (Lihoreau*et al.*, 2015).

One of the most transformative areas of nutritional ecology is the study of the gut microbiota and its role in nutrient efficiency and health. The gastrointestinal tract hosts a diverse microbial community that modulates digestion, immunity, and even behavior. In multispecies systems, differences in microbial assemblages can shape how efficiently nutrients are extracted from similar diets. Li *et al.*(2021) found that dietary species richness in herbivores altered gut microbial composition and improved post-weaning performance, demonstrating how microbial ecology intersects with dietary complexity (Li *et al.*, 2021).

Moreover, feedback loops between diet, host physiology, and microbial communities have been shown to cause regime shifts in microbiota composition. Guittar *et al.* (2021) argue that such shifts may lead to alternative stable states with differing capacities for nutrient processing, implying that feed interventions can have long-lasting microbial consequences (Guittar *et al.*, 2021).

Integrating gut microbiome dynamics into feed science also allows for community metabolic modeling, which predicts how microbial populations process different substrates and interact with the host. Mendes-Soares and Chia (2017) describe how these models bridge biochemistry and ecology, providing a systems-level understanding of nutrient transformation within the gut (Mendes-Soares & Chia, 2017).

Despite the promise of multispecies feed systems, they also entail ecological and nutritional trade-offs. Balancing the needs of species with different digestive physiologies—such as ruminants, monogastrics, or fish—requires careful calibration of feed composition. Misalignment in nutrient targeting may result in suboptimal growth for some species, increased competition, or waste production. Lambert (2024) illustrates how metabolic modeling can identify such trade-offs and guide adaptive feed formulations that minimize inefficiencies while maximizing overall system output (Lambert, 2024).

The science of feed design in multispecies systems is deeply embedded in ecological theory and biological complexity. It demands an interdisciplinary approach that integrates nutritional ecology, microbial systems, feeding behavior, and ecological feedbacks. As feed science evolves toward sustainability, these core concepts will remain essential for navigating the trade-offs and opportunities inherent in designing nutritionally and ecologically optimized diets for diverse animal communities.

2.1. Comparative Physiology Across Livestock and Aquatic Species

Understanding the comparative physiology of livestock and aquatic species is essential for effective multispecies feed formulation. Differences in digestive anatomy, enzymatic capabilities, nutrient absorption, and metabolic demands significantly influence how species utilize feed ingredients. These physiological traits impose constraints and opportunities when designing integrated or shared feed systems across species.

Ruminants, such as cattle and sheep, have evolved a complex, multi-chambered stomach that enables microbial fermentation of fibrous plant materials. The rumen hosts a diverse microbiota capable of breaking down cellulose and hemicellulose, allowing ruminants to thrive on low-quality forages. Protein and energy metabolism in ruminants relies heavily on microbial protein synthesis and volatile fatty acids derived from fermentation. This contrasts sharply with monogastrics like pigs and poultry, whose simpler digestive systems prioritize enzymatic digestion in the stomach and small intestine, requiring diets rich in readily digestible carbohydrates and high-quality protein (Furness *et al.*, 2015).

Fish, meanwhile, present diverse digestive strategies depending on their habitat and trophic level. Carnivorous species such as salmon possess short digestive tracts and high protease activity, enabling efficient protein digestion, while herbivorous or omnivorous fish like tilapia have longer intestines and a broader enzymatic toolkit suited to plant-based diets. Karasov and Douglas (2013) emphasize that fish digestion is also influenced by temperature, salinity, and waterborne nutrient availability, making aquatic feed formulation highly context-specific (Karasov& Douglas, 2013).

These physiological differences affect nutrient absorption efficiency, particularly for proteins, lipids, and minerals. For instance, ruminants derive essential amino acids indirectly from microbial biomass, while fish and monogastrics require dietary amino acids to be directly bioavailable. Furthermore, lipid digestion varies considerably: aquatic species generally utilize long-chain polyunsaturated fatty acids from marine sources more effectively, whereas terrestrial animals depend on plant-based lipids or saturated fats. These divergences demand species-specific adjustments in shared feed formulations or feed base materials to avoid deficiencies or waste.

Another critical aspect is gut morphology and immunity, especially in fish, where gut-associated lymphoid tissue plays a role in responding to dietary antigens. Batista *et al.* (2015) showed that gut morphology and immune responses in Senegalese sole varied significantly depending on whether the fish were fed monospecies or multispecies probiotic formulations, highlighting physiological plasticity and species-specific nutritional responses (Batista *et al.*, 2015).

Additionally, host-environment interactions further complicate nutrient metabolism. Wong and Rawls (2012) reported that intestinal microbiota composition in fish is strongly influenced by host ecology, including salinity and trophic level, with implications for digestion and nutrient assimilation (Wong & Rawls, 2012).

The comparative physiology of livestock and fish demands a nuanced approach to multispecies feed design. Differences in digestive strategies, metabolic pathways, and nutrient requirements must be reconciled to create synergistic, resource-efficient systems. While shared feed ingredients may be feasible, formulations must account for species-specific constraints to ensure optimal performance, health, and sustainability across integrated livestock-aquaculture systems.

2.2. Systems Thinking in Nutrient Optimization — Linking Biology, Economics, and Ecology

Nutrient optimization in feed systems is not merely a question of biological adequacy; it is inherently a systems-level challenge that intertwines metabolic efficiency, economic feasibility, and ecological resilience. Applying systems thinking allows researchers and practitioners to view feed formulation within a broader context—considering feedback loops, interdependencies, and trade-offs across sectors and species.

At its core, nutrient optimization involves maximizing the biological conversion of feed into usable animal products such as meat, milk, or eggs. However, biological efficiency alone cannot determine feed strategies in multispecies systems. Tedeschi *et al.* (2024) illustrate how modeling cattle production using a systems framework helped balance forage quality, animal performance, and ecosystem services such as carbon sequestration and nutrient retention (Tedeschi *et al.*, 2024). These findings stress the need to go beyond individual species productivity and incorporate landscape-level nutrient flows.

Economically, systems thinking reveals how feed choices affect production costs, market dynamics, and labor inputs. Stead (2019) argues that integrating open innovation with systems thinking in aquaculture policymaking can enhance adaptive capacity and align feed strategies with the UN Sustainable Development Goals, including poverty reduction and food security (Stead, 2019).

From an ecological perspective, nutrient optimization affects resilience—defined as a system's ability to withstand disturbances without losing function. Johnson *et al.* (2019) apply a social-ecological systems lens to aquaculture, highlighting how feed formulation, species interactions, and nutrient cycling co-determine ecosystem health, including the risk of eutrophication or pathogen outbreaks (Johnson *et al.*, 2019). This underscores the ecological trade-offs of poorly optimized feeds.

In integrated systems like livestock-fish farming, Edwards (1998) showed that pond-based polycultures can serve as nutrient sinks where livestock waste enhances aquatic productivity. Such systems close nutrient loops and reduce external input requirements, reinforcing circular economy principles (Edwards, 1998).

Finally, Zhang *et al.* (2018) argue that nutrient optimization must be embedded within "eco-agri-food systems" where biological, social, and economic factors are co-modeled. This integrated approach enables stakeholders to forecast the ripple effects of feed decisions across value chains and ecosystems (Zhang *et al.*, 2018).

2.3. Emerging Technologies and Data Tools for Multispecies Feed Formulation

The advancement of feed science has entered a new frontier with the integration of emerging technologies such as artificial intelligence (AI), big data analytics, precision nutrition systems, and metabolomics. These tools are enabling more refined, responsive, and sustainable approaches to feed formulation—particularly valuable in the context of multispecies systems, where nutritional needs, metabolic rates, and digestive capacities vary widely.

AI and machine learning are now central to precision nutrition, allowing for the dynamic adjustment of feed based on individual animal profiles or species combinations. Akintan*et al.* (2024) emphasize how AI-driven feed formulation systems integrate vast datasets—ranging from animal growth rates to environmental variables—to produce optimized rations in real time (Akintan*et al.*, 2024). Such systems improve feed efficiency, reduce waste, and adapt diets to specific physiological and ecological contexts.

Big data platforms and decision-support systems further facilitate this integration by aggregating data from sensors, laboratory analyses, and production records. Sonea*et al.* (2023) describe how digital twins and cloud-based feed formulation interfaces enable nutritionists to simulate various feed strategies across multispecies operations, optimizing both nutritional balance and economic returns (Sonea*et al.*, 2023).

Metabolomics—the comprehensive analysis of metabolites in biological systems—has also become an indispensable tool in feed science. It offers molecular-level insight into how different species metabolize nutrients, uncovering biomarkers for digestion efficiency, immune function, and nutrient uptake. Abd El-Hack *et al.* (2025) highlight how metabolomic profiling in poultry is being used to design targeted feed additives and personalized diets, which can be extended to integrated multispecies systems (Abd El-Hack *et al.*, 2025).

Additionally, linking feed formulation to broader health and productivity outcomes is now possible through data-driven decision tools. Akintan*et al.* (2025) show how integrated datasets—combining feed composition, animal health indicators, and production metrics—can forecast milk quality and animal resilience, offering a full-spectrum view of feed effectiveness (Akintan *et al.*, 2025).

These technologies are not just refining feed formulation; they are reshaping the entire paradigm of animal nutrition. For multispecies systems, they offer the precision and adaptability necessary to navigate complexity and optimize across biological, ecological, and economic dimensions.

2.4 Knowledge Gaps and Cross-Disciplinary Challenges

Despite advances in technology and systems thinking, substantial knowledge gaps persist in the development of multispecies feed systems. A major scientific challenge lies in the limited availability of comparative nutritional data across species. Most feed formulation databases are built around single-species models—typically poultry, swine, or ruminants—while nutrient requirements for integrated or non-conventional species, particularly in aquaculture, remain under-researched or poorly standardized (Pasumarthi*et al.*, 2024).

Another cross-cutting gap is the difficulty in integrating omics data with economic and ecological modeling. While metabolomics and microbiome analysis offer molecular insights into nutrient uptake and health, these are rarely translated into cost-effective feed strategies or linked to ecosystem service models. Highmore *et al.* (2022) highlight this translational bottleneck, noting that siloed disciplines often struggle to convert granular biological data into actionable feed design decisions (Highmore *et al.*, 2022).

Addressing these gaps will require collaborative efforts across biology, economics, and policy—moving from fragmented innovation to truly transdisciplinary feed design.

3. Integrated Poultry–Fish Farming in Southeast Asia

Integrated poultry–fish farming is a well-established and ecologically grounded model in many parts of Southeast Asia. This system capitalizes on the nutrient recycling potential of poultry waste to enhance aquaculture productivity, effectively creating a closed-loop system that improves resource use efficiency, reduces feed costs, and contributes to rural food and income security. Countries like Vietnam, Thailand, and Bangladesh have long relied on such integrated systems, often as part of broader mixed farming practices involving rice cultivation, small livestock, and aquaculture.

At the core of poultry–fish integration is the use of poultry droppings as a natural fertilizer for fishponds. Poultry waste enriches the water with nitrogen and phosphorus, promoting the growth of phytoplankton and zooplankton—key natural feeds for filter-feeding and omnivorous fish like tilapia and carp. This biological enrichment reduces the need for commercial feed and chemical inputs, enhancing both economic and environmental sustainability. As Little and Edwards (2003) explain, nutrient cycling in these systems not only improves feed conversion ratios (FCRs) but also diversifies on-farm outputs, buffering against market volatility and climate risks (Little & Edwards, 2003).

In Vietnam, for example, integrated systems around the Mekong Delta combine backyard poultry with household-scale fish ponds. Chicken houses are often constructed above or adjacent to the pond, allowing droppings to fall directly into the water. These systems are low-cost and highly accessible to smallholder farmers, providing both protein and income with minimal external inputs. Prein (2002) notes that this model improves nutrient use efficiency by turning what would be waste into a productive input, while also supporting livelihoods through fish sales in local markets (Prein, 2002).

In Bangladesh, integrated poultry–fish–rice systems are commonly practiced in flood-prone lowlands, where waterlogged conditions support multiple uses. Farmers cycle poultry manure into fish ponds during the dry season and grow rice in the same areas during monsoon months. This spatial and seasonal integration enhances land productivity while maintaining soil fertility. As reported by Kumar *et al.* (2024), such systems increase income by 20–40% over monoculture farming, while also reducing input costs and promoting multi-nutrient food security (Kumar *et al.*, 2024).

Thailand presents more commercial examples of poultry–fish integration, where medium-scale farms strategically manage nutrient flows to optimize fish yields. Little and Satapornvanit (1996) highlight how controlled dosing of poultry manure enhances pond fertilization without compromising water quality, especially when paired with aeration systems and sediment management (Little & Satapornvanit, 1996). These systems demonstrate that integrated farming can evolve beyond subsistence toward semi-intensive or even commercial scales, provided that management practices are appropriately adapted.

Environmental benefits are a major strength of poultry–fish integration. The use of biological fertilization reduces reliance on inorganic inputs, helping mitigate eutrophication risks associated with nitrogen runoff. Ramanathan *et al.* (2020) add that these systems foster biodiversity in the water column, supporting not only farmed fish but also beneficial aquatic organisms that contribute to ecological balance (Ramanathan *et al.*, 2020). Additionally, by recycling waste on-farm, integrated systems lower greenhouse gas emissions associated with waste treatment and transport, aligning with climate-smart agricultural goals.

Nonetheless, the success of integrated poultry–fish farming depends on local knowledge, training, and appropriate policy support. Water quality monitoring, disease management, and manure loading rates must be carefully managed to avoid pathogen spillover or fish stress. In some regions, biosecurity and food safety regulations now limit direct manure application in commercial aquaculture, prompting a shift toward manure processing (e.g., composting or anaerobic digestion) before use—balancing health risks with nutrient cycling benefits.

In conclusion, integrated poultry–fish systems in Southeast Asia represent a compelling model of circular, multispecies agriculture. They exemplify the core principles of sustainable intensification, whereby diverse biological processes are harnessed to improve nutrient use, productivity, and resilience. With proper governance, education, and adaptation to market and environmental pressures, these systems could be scaled further as a blueprint for sustainable food systems in tropical and subtropical regions.

4. Circular Feed Systems Using Agricultural By-products in Mixed Farming

Circular feed systems—those that reuse agricultural by-products, crop residues, and food waste—are reshaping the future of livestock and aquaculture nutrition across Asia, Africa, and Latin America. These systems not only reduce dependence on conventional feed ingredients like soy and maize but also contribute to nutrient recycling, greenhouse gas (GHG) mitigation, and economic sustainability in smallholder and commercial operations alike. By integrating livestock, crop, and aquaculture systems, circular approaches maximize the utility of biomass flows, minimize waste, and enhance the resilience of food systems.

At the heart of these systems is the reuse of agricultural by-products such as rice bran, cassava peels, maize husks, and molasses. These materials, once treated as waste, are now being upcycled into feed inputs through drying, fermentation, or bioconversion. According to Sandström *et al.* (2022), upcycling food system by-products in animal feed could increase global food supply by 6–13%, while significantly lowering the environmental impact of feed production (Sandström *et al.*, 2022). This is particularly impactful in Asia, where animal feed production places heavy demands on land and water resources.

In Asia, crop-livestock-aquaculture integration is common in countries like Vietnam, Indonesia, and China. For example, rice husks and fish processing residues are fed to poultry and pigs, whose manure is then used to fertilize fish ponds. Oosting *et al.* (2022) describe how these circular loops improve nitrogen retention in farming systems, reducing emissions and improving feed efficiency (Oosting *et al., 2022*). Aquaculture systems in Bangladesh and India have also begun incorporating fruit waste and spent grain into fish diets with promising results in terms of growth rates and water quality.

In Africa, food insecurity and limited access to conventional feeds have driven innovation in circular feed solutions. Chisoro *et al.* (2023) discuss the use of local resources such as brewer's spent grain, groundnut shells, and mango peels as feed components in smallholder systems, offering a cost-effective and locally available protein source (Chisoro*et al.*, 2023). Circular feed models also support climate adaptation goals by reducing methane emissions and making efficient use of limited biomass.

A standout example in Africa is the integration of insect-based feed, where black soldier fly larvae are raised on organic waste and used as protein-rich feed for poultry and fish. Barragán-Fonseca *et al.* (2022) highlight how this strategy is transforming circular agriculture in Colombia, linking waste reduction with rural livelihoods and aquaculture development (Barragán-Fonseca *et al.*, 2022).

In Latin America, the circular economy is being applied to livestock waste management through biodigestion and composting, creating energy and nutrient-rich by-products. Taron *et al.* (2025) present several business models where livestock slurry is converted into biogas and digestate, which is then used as pond fertilizer or crop supplement in mixed farming systems (Taron *et al.*, 2025). This has dual benefits: reducing methane emissions from waste decomposition and decreasing reliance on synthetic fertilizers.

Moreover, agro-industrial by-products—such as sugarcane bagasse, fruit pulp, coffee husks, and fishmeal leftovers—are increasingly valorized as functional feed components. Bonilla Cedrez and Andeweg (2023) describe Peru's circular food initiatives, where such materials are channeled into value-added products like fermented feeds and aquaculture pellets, supporting the country's broader goals for gastronomy and ecological stewardship (Bonilla Cedrez &Andeweg, 2023).

Despite these promising developments, policy and logistical challenges remain. In many regions, the use of certain by-products in animal feed is constrained by food safety concerns or regulatory gaps. Ndebele-Murisa*et al.* (2024) call for harmonized standards for by-product processing and storage to ensure microbial safety and nutrient consistency in aqua feeds, especially in emerging markets (Ndebele-Murisa*et al.*, 2024).

Economically, circular feed systems are more accessible to small and medium-scale farmers, who can avoid costly imports by using what is locally available. As Puente-Rodríguez *et al.* (2022) argue, supporting local circularity in feed not only enhances food sovereignty but also stabilizes feed supply chains under global trade disruptions (Puente-Rodríguez *et al.*, 2022).

Furthermore, advances in data analytics and circularity assessment tools are enabling more precise evaluation of environmental and economic returns. Sandström *et al.* (2024) estimate that substituting 25% of imported animal feed with domestic food system by-products in Northern and Latin America could reduce agricultural land use and improve system resilience without compromising productivity (Sandström *et al.*, 2024).

Circular feed systems leveraging agricultural by-products represent a pragmatic and scalable solution to the intersecting challenges of feed insecurity, environmental degradation, and economic marginalization. By transforming waste into value, these systems operationalize the principles of ecological intensification, offering a compelling pathway toward regenerative livestock and aquaculture development. Their success, however, hinges on supportive governance, food safety infrastructure, and knowledge exchange across sectors and continents.

5. AI-Driven Nutrient Optimization in Multispecies Aquaculture Hubs

The rise of artificial intelligence (AI) and digital tools is transforming nutrient management in multispecies aquaculture, offering new levels of precision, adaptability, and efficiency. Across leading aquaculture nations like China, Norway, and India, smart aquaculture hubs are deploying real-time data systems, machine learning algorithms, and integrated decision-support platforms to manage feed formulation dynamically. These technologies address long-standing challenges in multispecies systems—such as balancing nutrient requirements across species, optimizing feed conversion ratios (FCRs), and reducing environmental impact.

In China, the world's largest aquaculture producer, AI is central to its expansion of Integrated Multi-Trophic Aquaculture (IMTA) systems. These systems co-cultivate species from different trophic levels—such as finfish, mollusks, and seaweeds—requiring complex feed strategies. Digital tools use real-time water quality, biomass, and feeding behavior data to adjust feed dosage and composition automatically. As Pathak (2024) notes, China has pioneered floating AI-powered sensors and underwater cameras that optimize feed schedules, detect uneaten feed, and prevent overfeeding in multispecies environments (Pathak, 2024).

Moreover, India is making significant strides with AI-assisted feed formulation systems tailored to small- and medium-scale aquaculture hubs. Das *et al.* (2022) report the development of mobile platforms that integrate satellite data, weather forecasts, and pond nutrient profiles to guide feed mixing decisions on farms in Andhra Pradesh and Tamil Nadu (Das *et al.*, 2022). These tools are particularly valuable for managing species with divergent dietary needs—like rohu, catla, and mrigal—reared together in polyculture systems.

One Indian initiative focuses on nutrient-sensitive aquafeed design, where AI models learn from farm data and continuously refine least-cost feed formulations. By adjusting protein and energy levels based on species growth stages and pond dynamics, these systems can enhance feed efficiency while reducing nitrogenous waste. Kumar (2024) emphasizes that such approaches offer not only economic gains but also ecological benefits, as precision feeding minimizes nutrient loading into aquatic environments (Kumar, 2024).

Norwegian firms are also investing in AI-driven nutrient budgeting tools that simulate the impact of feeding strategies on both species performance and environmental indicators like sediment accumulation and oxygen demand. This modeling capability supports site-specific decision-making and regulatory compliance, crucial for sustainable expansion in sensitive fjord ecosystems. Ruiz-Vanoye*et al.* (2025) highlight how AI enables better integration of trophic relationships in IMTA systems by tracking nutrient flows and biomass dynamics across species (Ruiz-Vanoye*et al.*, 2025).

Cross-national collaborations further demonstrate the versatility of AI tools in supporting adaptive nutrient management. Gladju*et al.* (2023) document how data mining frameworks developed in China have been adapted for fisheries co-management in Norway, allowing for real-time resource sharing and feed optimization across clustered farms (Gladju*et al.*, 2023). Such frameworks can also facilitate automated inventory and supply chain coordination, reducing feed waste and energy use.

From an ecological standpoint, AI-driven nutrient optimization contributes to closed-loop efficiency, where feed inputs are synchronized with nutrient cycling in the system. Meinam*et al.* (2025) report that AI tools in China's IMTA setups monitor both nutrient outputs and secondary uptake by filter feeders or macroalgae, thus closing the loop on nitrogen and phosphorus loss (Meinam*et al.*, 2025). This integration reduces effluent discharge, improves water quality, and enhances the resilience of aquaculture ecosystems.

Despite these advances, challenges remain. Data standardization, cross-species nutrition modeling, and economic accessibility of AI tools for smallholders are ongoing concerns. Nonetheless, the convergence of biological, digital, and ecological data offers a powerful platform for transforming multispecies aquaculture into a more sustainable, efficient, and adaptive system.

AI is not just a tool for automation but a transformative enabler of multispecies nutrient intelligence—linking data from water, feed, and biology to improve decision-making at every level. Countries like China, Norway, and India are proving that smart aquaculture is not only viable but essential for feeding a growing global population within planetary boundaries.

6. Seaweed and Microalgae as Dual-Purpose Protein Sources for Livestock and Aquaculture

As pressure mounts to decouple feed production from deforestation, overfishing, and excessive land use, seaweed and microalgae are emerging as sustainable, circular alternatives to conventional protein sources. These aquatic biomass resources offer a high-protein, low-input option that is applicable across both terrestrial and aquatic species, particularly in integrated and multispecies farming systems. Their cultivation fits squarely within the circular economy, as they require no arable land, sequester carbon, and can be grown on nutrient-rich wastewater or aquaculture effluents.

The nutritional profile of seaweed and microalgae is strikingly diverse. Microalgae such as Spirulina and Chlorella boast protein contents of 50–70%, alongside essential amino acids, omega-3 fatty acids (EPA and DHA), and bioactive compounds with immunomodulatory properties. Seaweeds, particularly red and green macroalgae like Ulva, Gracilaria, and Palmaria, contain significant protein (10–35%) as well as polysaccharides, iodine, and trace minerals (Pereira *et al.*, 2024). These attributes make them attractive not only as supplements but also as partial replacements for soy, fishmeal, and synthetic additives in livestock and aquafeeds.

In aquaculture, particularly in Asia and Northern Europe, seaweed is increasingly integrated through Integrated Multi-Trophic Aquaculture (IMTA) systems. In this model, finfish or shrimp are co-cultured with macroalgae, which absorb excess nutrients (especially nitrogen and phosphorus) from fish waste, thereby improving water quality and enabling seaweed biomass to be harvested for use as feed. Norway, for example, has led the development of IMTA involving kelp (Saccharina latissima) and salmon, with trials demonstrating reductions in nutrient discharge and increased system resilience (Stedt, 2023).

In Chile, the cultivation of giant kelp (Macrocystis pyrifera) has opened new pathways for feed production. Cai *et al.* (2021) report on the integration of kelp into the salmon aquaculture value chain, either directly as feed or processed into meal or extracts with antioxidative and antimicrobial properties (Cai *et al.*, 2021). These seaweed-based ingredients not only promote fish health but may reduce reliance on antibiotics and synthetic growth promoters.

Meanwhile, Indonesia, one of the world's largest producers of tropical seaweed, is turning to domestic seaweed resources for feed applications. Islam *et al.* (2022) describe how Eucheuma and Gracilaria species, widely grown in coastal provinces, are being investigated for incorporation into poultry and ruminant diets. Early results suggest improved gut health, enhanced meat quality, and reduced methane emissions in ruminants when seaweed is included in rations (Islam *et al.*, 2022).

Microalgae also show significant promise for livestock nutrition. Lindberg *et al.* (2016) identify Spirulina and Nannochloropsis as scalable protein ingredients for pigs, poultry, and dairy cattle. In dairy systems, algae can enhance milk yield and quality while potentially modulating methane emissions. Notably, Asparagopsistaxiformis—a red seaweed rich in bromoform—has shown methane reduction levels of up to 80% in cattle trials, although its commercialization is still under regulatory scrutiny (Lindberg *et al.*, 2016).

Despite their potential, commercialization challenges persist. Key among them are variability in composition due to seasonal and environmental factors, high production costs (especially for microalgae), limited processing infrastructure, and regulatory hurdles around feed approval. As Lemessa (2022) notes, consistent quality control, standardized extraction protocols, and broader market integration are essential for scaling seaweed and algae as mainstream feed ingredients (Lemessa, 2022).

Economic viability also varies regionally. In Norway and Chile, seaweed feed applications are bolstered by established cold-water cultivation infrastructure and access to aquaculture markets. In contrast, Indonesia's seaweed sector is largely export-oriented for carrageenan and faces weak integration with domestic feed industries. Nevertheless, global initiatives are underway to build local bioeconomy strategies linking marine biomass to animal nutrition. Vigani (2020) highlights the role of algae in circular bioeconomy frameworks, especially where marine and agricultural systems intersect (Vigani, 2020).

Seaweed and microalgae represent a promising class of dual-purpose feed resources that align with sustainability, circularity, and food security goals. While not yet a panacea, their integration into multispecies livestock and aquaculture systems offers a low-footprint pathway to diversify protein sources and close critical nutrient loops in modern agriculture.

7. Insect-Based Protein Supply Chains for Multispecies Feed Formulation

Insect-based protein is rapidly emerging as a key component in circular and sustainable feed strategies, offering an ecologically viable alternative to conventional proteins such as soybean meal and fishmeal. Among the insect candidates, the black soldier fly larvae (BSFL) (Hermetiaillucens) has gained particular prominence due to its high nutritional profile, rapid growth on organic waste substrates, and low environmental footprint. Both livestock and aquaculture sectors are now integrating BSFL and other insect meals into feed formulations across Africa, Asia, and Europe, supporting multispecies nutrient optimization in a circular economy framework.

BSFL production is grounded in bioconversion systems that transform food waste, agro-industrial residues, and animal manure into high-quality protein and fat. These larvae thrive on diverse substrates, offering farmers and feed producers an effective waste-to-feed solution. In Europe, recent regulatory reforms have legalized the use of insect protein in pig and poultry feed (since 2021) and earlier in aquafeeds (since 2017), reflecting growing confidence in its safety and performance. Su *et al.* (2025) highlight that BSFL contains 35–60% crude protein, with an amino acid profile comparable to fishmeal, as well as lipids rich in lauric acid, which confer antimicrobial benefits (Su *et al.*, 2025).

In aquaculture, insect meals are gaining traction as fishmeal replacements in both carnivorous and omnivorous species. Auzins*et al.* (2024) report that replacing up to 50% of fishmeal with BSFL in trout and tilapia diets has shown no negative effects on growth performance or feed conversion ratios. Moreover, insect-based feeds help reduce pressure on wild fish stocks, an important concern in sustainable aquaculture policy (Auzins*et al.*, 2024).

In Africa, where feed costs represent a major bottleneck for smallholder production, BSFL production systems are being localized using household and market food waste. Iheanacho *et al.* (2025) note that BSFL-based aquafeeds in Nigeria, Kenya, and Ghana have demonstrated not only competitive growth outcomes in catfish and tilapia but also improved water quality due to lower nitrogen excretion (Iheanacho *et al.*, 2025). These features align with the need for climate-resilient aquafeeds in resource-constrained settings.

Asia remains the largest global producer of BSFL, particularly in China, Indonesia, and Vietnam. Raghuvaran *et al.* (2024) explain that large-scale insect farms in China process over 10,000 tons of food waste annually into larvae biomass for poultry, pig, and aquaculture feeds. In these systems, larvae are reared on controlled substrates, dried, defatted, and milled into standardized protein powders. The ability to integrate this biomass directly into multispecies feed mills offers enormous potential for circularity in mixed farming systems (Raghuvaran *et al.*, 2024).

Europe, particularly the Netherlands and France, has spearheaded commercial-scale insect farming, with automated BSFL rearing facilities using precision environmental controls. These operations have benefited from the EU's Circular Economy Package, which supports innovations that valorize organic waste streams into new bio-based products. Veldkamp *et al.* (2023) describe how EU projects like PROteINSECT and SUSINCHAIN are linking insect protein production with sustainability metrics such as carbon reduction, biodiversity conservation, and nutrient cycling (Veldkamp *et al.*, 2023).

Importantly, insect-based proteins offer life cycle advantages. Life cycle assessment (LCA) studies have consistently shown that BSFL production generates significantly lower GHG emissions, land use, and water use compared to soy or fishmeal production. Jagtap *et al.* (2021) emphasize that BSFL can be produced locally using decentralized, modular systems, reducing transport emissions and enhancing rural circular economies (Jagtap *et al.*, 2021).

Market acceptance, however, remains a hurdle. Thrastardottir*et al.* (2021) found that although consumer sentiment in Europe is generally favorable toward insects as feed, barriers persist related to cost, regulation, and awareness among farmers and feed manufacturers (Thrastardottir*et al.*, 2021). Further, safety considerations such as pathogen control, heavy metal accumulation, and allergenicity must be carefully managed, particularly when larvae are reared on heterogeneous waste streams.

Nevertheless, insect-based feed value chains are gaining institutional traction, with national policies and international donors increasingly supporting pilot projects. In Colombia, Barragán-Fonseca *et al.* (2022) document government-supported circular agriculture models where BSFL are used in rural aquaculture to reduce feed costs and generate income through compost by-products (Barragán-Fonseca *et al.*, 2022).

Black soldier fly and other insect proteins represent a viable, scalable, and multifunctional feed input for both livestock and aquaculture sectors. As part of a transdisciplinary strategy, they offer not just a protein source, but a model for localizing circular bioeconomies, enhancing food system resilience, and closing nutrient loops in multispecies feed formulation.

8. Cross-Case Synthesis — Shared Strategies and Divergent Paths

Sections 3.1 to 3.5 of this review have explored diverse case studies—ranging from integrated poultry–fish systems in Southeast Asia to insect-based protein in Europe and Africa—each demonstrating unique innovations in multispecies nutrient optimization. Yet across these geographies and modalities, several core strategies converge, reflecting the emergence of a shared global agenda around circularity, resource efficiency, and multispecies synergy. At the same time, stark regional divergences highlight differences in governance, technological capacity, and economic integration that shape the scalability and impact of these models.

Shared Strategies Across Regions

A foundational commonality is the emphasis on circular feed systems. Whether through direct nutrient recycling in integrated farming (e.g., poultry manure fertilizing fish ponds in Vietnam) or the use of agro-waste substrates for black soldier fly larvae (BSFL) in Kenya or the Netherlands, every case exemplifies efforts to close nutrient loops and reduce dependence on imported or synthetic inputs. This aligns with a broader transition toward circular food systems, as advocated in the EU's Circular Economy Action Plan (Friant *et al.*, 2020).

Local resource utilization is another unifying strategy. From kelp grown in Norwegian fjords to mango peels and brewery waste used as insect feed in sub-Saharan Africa, feed inputs are increasingly sourced from local by-products. This has economic benefits—lowering feed costs—and environmental ones—reducing transport-related emissions and waste accumulation. Across all regions, systems that valorize agricultural residues, food waste, or aquaculture effluents demonstrate improved nutrient recovery and feed efficiency.

Third, there is a growing interest in multispecies synergies—particularly in integrated or co-culture systems. The Asian examples (Sections 3.1 and 3.2) emphasized how polyculture enhances resource utilization, while the IMTA systems in Norway and Chile (3.3 and 3.4) show how multiple trophic levels can absorb, transform, and recycle nutrients within one production space. These strategies not only improve biological efficiency but also provide ecological services such as water purification and methane mitigation (Quevedo-Cascante, 2024).

Lastly, transdisciplinary approaches—combining biology, technology, economics, and governance—are gaining traction. This is evident in AI-driven feed platforms in India, insect protein regulations in the EU, and community-based waste recovery in Colombia. These initiatives illustrate the growing integration of systems thinking in feed design and food system transformation.

Divergent Regional Trajectories

Despite these overlaps, regional trajectories diverge due to institutional, ecological, and market dynamics. Asia, especially Southeast and South Asia, demonstrates high uptake of integrated, low-input systems driven by land scarcity, farmer innovation, and long-standing agroecological traditions. Here, feed circularity is often achieved through farmer-led models—like household-level poultry-fish integration in Vietnam or algae-based feed in Indonesia. However, the technical sophistication is mixed: while China leads in AI-enabled aquaculture, other parts of the region rely on manual nutrient cycling (Voyloshnikova, 2020).

Africa presents a contrasting picture: immense interest in novel protein solutions (e.g., BSFL), driven by feed cost inflation and food insecurity, but constrained by infrastructure, finance, and regulatory gaps. The continent's strength lies in grassroots innovations—such as insect farms using market waste in Nigeria—but these often lack the scale or support to transition into broader market ecosystems. Nevertheless, African systems are often more adaptive to resource scarcity, offering models of resilience under constraint (Petrakidou, 2021).

Europe leads in policy-aligned innovation and large-scale technology deployment. Circularity is institutionalized through funding, legislation (e.g., EU rules on processed animal proteins), and industrial automation. European feed systems—like insect farms or kelp-based aquafeeds—are characterized by standardization, traceability, and market integration, supported by consumer trust and regulatory clarity. However, Europe's reliance on high-capital, high-tech models may limit adaptability in regions with fewer resources (Thompson, 2021).

Latin America, particularly Chile and Colombia, occupies a hybrid space. On one hand, Chile's marine-based aquaculture innovations (kelp-salmon IMTA systems) are technologically advanced; on the other, Colombia's insect-based feed systems are rooted in social innovation and rural development. These dualities illustrate how policy and community-based pathways can coexist, and how multispecies systems can support both export-oriented industries and food sovereignty agendas (Barragán-Fonseca *et al.*, 2022).

Strategic Implications

This cross-case synthesis suggests that no single model fits all regions—yet strategic lessons can be shared:

- Low-tech nutrient recycling systems (e.g., poultry-fish integration) can be scaled and adapted with digital tools for broader impact.
- High-tech systems (e.g., AI in aquafeeds or large-scale insect farming) require local adaptation to match institutional and market readiness.
- Policy frameworks are crucial for scaling circular feed innovations—Europe demonstrates this clearly—but community agency, as seen in Africa and Latin America, remains equally vital.
- Moving forward, the challenge lies in leveraging shared strategies—like circularity and local resource use—while customizing models to regional constraints and capacities. Future transitions will depend not only on technical innovation but on institutional support, knowledge exchange, and inclusive governance.

8.1. Transdisciplinary Insights — Bridging Animal Science, Technology, and Policy

Designing effective multispecies feed systems is not simply a technical or biological challenge; it is a transdisciplinary endeavor that must weave together expertise from animal science, nutritional ecology, biotechnology, artificial intelligence (AI), circular bioeconomy, and public policy. As the complexity of global food systems intensifies, the development of sustainable, adaptive, and context-specific feed formulations increasingly depends on collaborations that cross traditional disciplinary boundaries and institutional silos.

A core insight emerging from the reviewed case studies is the synergistic role of AI and data science in connecting nutrient physiology with system-level sustainability. For example, AI-powered platforms in India and Norway enable real-time adjustment of feed formulations based on species-specific growth models, water chemistry, and waste production. Shah *et al.* (2025) describe how AI systems can integrate satellite data, aquaculture sensor networks, and machine learning algorithms to reduce feed waste, lower nutrient discharge, and enhance production efficiency—all while supporting circular bioeconomy principles (Shah *et al.*, 2025).

Beyond technical optimization, AI also plays a bridging role between disciplines. It enables data translation across domains—turning biological signals into economic forecasts, or policy metrics into actionable insights for farmers. This integration fosters systems thinking in practice and makes nutrient management responsive to both biological and economic realities.

Meanwhile, nutritional ecology provides the theoretical backbone for feed strategies in multispecies systems. Unlike single-species nutrition, multispecies feed design requires understanding how different organisms partition, assimilate, and excrete nutrients, often in shared environments. Henchion and Shirsath (2022) emphasize that aligning nutrient uptake across species—not just maximizing individual performance—is crucial for the success of co-culture or integrated systems (Henchion&Shirsath, 2022). This calls for cross-training in animal physiology, aquatic ecology, and soil–plant–microbe interactions—disciplines traditionally siloed in academic and institutional settings.

The circular bioeconomy framework serves as a transdisciplinary platform that brings together technological innovation with ecological sustainability and policy direction. Molden and Khanal (2025) argue that effective circular feed systems can only be achieved when local knowledge, supply chain design, waste stream mapping, and ecosystem modeling are considered together—requiring input from engineers, farmers, ecologists, and economists alike (Molden & Khanal, 2025).

A striking example is the development of black soldier fly (BSF) feed chains in Africa and Europe. Here, entomologists, waste managers, animal nutritionists, and regulatory bodies collaborated to create standardized protocols that allow food waste to be safely converted into insect-based feed. In Colombia, this approach was community-led and rooted in social innovation; in the Netherlands, it was industrialized with biotech automation and policy alignment. Both illustrate how transdisciplinary work can yield context-sensitive outcomes, depending on governance and economic context.

Transdisciplinary collaboration also enables policy harmonization—one of the most under-addressed but essential enablers of feed innovation. As Fernandez-Gómez *et al.* (2025) show, translating microbiome science into aquaculture policy requires coordinated action across environmental agencies, public health regulators, and farming communities (Fernández-Gómez *et al.*, 2025). Without aligned regulatory frameworks, promising innovations in nutrient recycling or alternative proteins often stall at pilot scale due to safety concerns, lack of standards, or market resistance.

Successful transdisciplinary initiatives also exhibit institutional innovation—new forms of organization that support long-term learning and integration. For instance, the red meat sector in Ireland has adopted facilitated transdisciplinary frameworks that bring together farmers, researchers, tech developers, and policymakers to co-develop sustainability pathways. This approach helped bridge gaps between consumer expectations, environmental goals, and production realities, and could serve as a blueprint for multispecies feed systems globally (Henchion&Shirsath, 2022).

Transdisciplinary collaboration is not a luxury—it is a necessity for developing feed systems that are nutritionally balanced, ecologically regenerative, economically viable, and socially equitable. Bridging the domains of science, technology, and policy allows for integrated problem-solving that matches the complexity of today’s food systems. Whether through AI integration, ecological modeling, or participatory policy design, the future of multispecies feed innovation lies in creating spaces for collaboration that are as diverse and dynamic as the systems they aim to support.

8.2. Implications for Sustainability, Ethics, and Global Food Systems

Multispecies feed design, especially within the frameworks of circularity and ecological intensification, carries transformative potential for achieving sustainability, equity, and ethical integrity in global food systems. These feed strategies—spanning integrated livestock-aquaculture, insect-based protein, and seaweed-algae supplements—offer practical routes to reduce environmental burdens, reshape human-animal relations, and reconfigure food justice across the Global North and South.

Sustainability Implications

The environmental stakes of feed production are considerable: animal feed accounts for significant shares of land use, freshwater withdrawal, and greenhouse gas (GHG) emissions. Conventional feed crops like soy and maize are often linked to deforestation, biodiversity loss, and nitrogen pollution. Multispecies feed systems, however, introduce opportunities for resource optimization by integrating nutrient flows between species and valorizing local biomass, including agricultural waste and food by-products.

As Levi (2025) notes, multispecies integration within agroecological models enables high productivity with minimal ecological footprints—particularly in the Global South, where low-input, diversified systems are more common (Levi, 2025). Integrated poultry–fish systems, insect-based feeds, and seaweed polycultures reduce dependency on globalized feed chains and improve nitrogen recovery and carbon sequestration.

Additionally, circular feed innovations align with global sustainability goals by promoting soil health, waste reduction, and reduced reliance on wild fish stocks. For instance, replacing fishmeal with black soldier fly larvae in aquafeeds addresses overfishing while leveraging food waste streams, creating a closed-loop solution that benefits ecosystems.

Ethical Considerations

The ethical dimensions of multispecies feed systems are multilayered. First is the issue of animal welfare. Integrating species in systems like IMTA or polycultures raises questions about interspecies interactions, stress, and disease management. However, well-managed systems often improve welfare by aligning feed composition with species-specific nutritional needs, reducing overfeeding, and minimizing harmful environmental fluctuations.

Second, the use of waste-based feeds (e.g., insect rearing on food scraps or manure reuse in fish ponds) triggers debates around health safety and species dignity. Beacham (2018) advocates for a more-than-human ethics of care—arguing that sustainability must also address the relational wellbeing of all species involved, not just productivity outcomes (Beacham, 2018). Ethical feed systems must therefore balance circular efficiency with transparency, safety, and respect for multispecies lives.

Finally, alternative protein strategies such as algae, microbes, or insects challenge anthropocentric views of edibility and feed hierarchies. Ethical frameworks that embrace diverse economies and multispecies co-flourishing are emerging, encouraging us to rethink what constitutes "acceptable" feed and who benefits from its use (Sarmiento, 2017).

Global Food System Equity

Equity and access are central to feed innovation. The Global South often suffers feed insecurity, where reliance on imported inputs restricts farmer autonomy, inflates costs, and exposes producers to market volatility. Multispecies feed systems—especially those based on local by-products—offer a pathway to feed sovereignty and more resilient rural economies.

However, disparities remain. In the Global North, high-tech solutions like AI-assisted feed optimization or automated insect farms are capital-intensive and embedded within industrial-scale operations. In contrast, Global South regions may rely on low-tech, labor-intensive circular strategies, as seen in smallholder aquaculture or community-based insect farming. Chung (2024) critiques this divide, calling for a decolonial multispecies climate justice approach that supports diverse models of feed production, based on local values, ecological knowledge, and food traditions (Chung, 2024).

Global feed justice also intersects with dietary transitions and planetary boundaries. Redirecting food waste into animal feed, or reducing reliance on monoculture crops, frees up land and nutrients for human-edible food production. Multispecies feed design, when aligned with systemic change, thus contributes to nutritional equity and food access, especially in vulnerable regions.

Multispecies feed design is more than a technical exercise in nutrient balancing—it is a moral, ecological, and geopolitical intervention. It reshapes how we view waste, value animals, and structure food access across continents. As global food systems face rising pressures—from climate shocks to protein demand—transdisciplinary and ethical feed strategies will be essential in forging a just and sustainable path forward.

8.3. Future Horizons — Scaling Innovation and Policy Integration

The future of multispecies feed design rests on how effectively successful innovations can be scaled, institutionalized, and embedded within national and global agri-food and climate policies. While case studies from previous sections demonstrate feasibility and impact across diverse contexts, moving from experimentation to transformation requires systemic support for innovation ecosystems, inclusive finance mechanisms, and coherent policy frameworks that align sustainability with economic viability.

Key to scaling is contextual flexibility. Multispecies feed systems—whether in the form of integrated poultry–fish farms, black soldier fly supply chains, or IMTA models—must be adapted to local ecological, social, and economic realities. Galanakis (2024) stresses the importance of "climate-smart scaling" that ensures innovations meet resilience goals while preserving local biodiversity and food cultures (Galanakis, 2024). For instance, while AI-based feed optimization systems work well in high-tech aquaculture hubs, low-tech bioresource cycling (e.g., manure-to-fishpond) may be more viable for smallholders in resource-limited regions.

Investment in infrastructure, extension services, and farmer training is critical to scaling. This includes building decentralized insect farming units, microalgae processing facilities, and data platforms for real-time nutrient monitoring. Innovation clusters—linking researchers, startups, cooperatives, and public agencies—can accelerate technology transfer and adaptation.

Transitioning toward multispecies and circular feed systems requires substantial financial support, especially for small and medium enterprises and producers. Public–private partnerships, carbon credit programs, green bonds, and development finance institutions have a role in de-risking early adoption and enabling long-term business models.

Balázs *et al.* (2021) emphasize the need for financing mechanisms that value ecological benefits (e.g., nutrient recycling, biodiversity enhancement) in cost–benefit assessments of feed innovations (Balázs *et al.*, 2021).
Feed systems are often overlooked in agri-food and climate governance, despite their large environmental footprint. Integrating feed explicitly into national determined contributions (NDCs), biodiversity targets, and sustainable agriculture strategies will be crucial. Policy innovation must support multispecies systems through regulatory clarity, safety standards, and fiscal incentives that reward nutrient efficiency and local feed sourcing.
Ultimately, multispecies feed strategies must be treated not as niche innovations, but as central components of sustainable food futures. Aligning them with international frameworks—such as the UN Food Systems Summit pathways and the Global Methane Pledge—can elevate their role in achieving planetary health goals.

9. Conclusion
Multispecies nutrient optimization represents a transformative shift in how we design and deliver feed systems for both livestock and aquaculture. By integrating biological diversity, circular resource flows, and adaptive technologies, multispecies feed design offers a strategic pathway to address pressing global challenges such as climate change, food insecurity, and ecological degradation. The case studies examined across regions reveal a convergence toward circularity, local resource use, and system resilience, while also highlighting regional disparities in infrastructure, governance, and innovation capacity.
Looking ahead, advancing multispecies feed systems requires sustained cross-sector collaboration, inclusive policy integration, and investment in scalable, context-sensitive solutions. Embracing transdisciplinary frameworks will be essential to bridge gaps between science, practice, and policy. Whether through AI-enabled precision nutrition or traditional integrated farming, the future of sustainable animal production hinges on our ability to co-create feed systems that are ecologically regenerative, ethically grounded, and socially equitable. Multispecies feed design is not merely an alternative—it is a critical frontier for reimagining the future of food systems within planetary boundaries.

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