Study on technical model, ecological benefit and sustainable agricultural application of fish and vegetable symbiotic system

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Abstract. As an integrated aquaponics system combining aquaculture and hydroponics, the Fish-Egg System (FES) achieves synergistic effects of fish waste recycling and water purification through microbial-mediated nitrogen-phosphorus conversion. This technology significantly reduces chemical fertilizer usage by 60-80% and water consumption by 90%. This paper systematically reviews the technical models, ecological benefits, and sustainable agricultural applications of FES, with a focus on analyzing the characteristics and applicability scenarios of five operational modes: media beds, deep-water cultivation, nutrient film technology, floating boards, and modular systems. Future efforts should address bottlenecks in technical standardization, cross-climate adaptability, and policy coordination to propel this technology as a core driver for sustainable agricultural transformation.

Keywords: fish-vegetable symbiosis system; sustainable agriculture; nitrogen and phosphorus cycle; modular design; artificial intelligence integration.

1. Introduction

According to the 2024 State of the World's Fisheries and Aquaculture report released by the United Nations Food and Agriculture Organization (FAO), the total output of global fisheries and aquaculture reached 223.2 million tons in 2022, among which the output of aquatic animals exceeded that of fishing for the first time, accounting for 51%[1].This milestone marks a significant increase in the importance of aquaculture in global food supply. Specifically, inland aquaculture accounts for 62.6% of total aquatic animal production, mainly due to the widespread use of freshwater aquaculture systems, especially in Asian countries or regions (e.g., China)[2].As the world's largest aquaculture country, China's aquaculture output reached 74.1 million tons in 2024, an increase of 3.5% compared with 2023. The proportion of its freshwater aquaculture was more than 50%, reflecting the dominant position of inland aquaculture[3].

However, the cumulative pressure of traditional agricultural models on ecosystems has triggered multiple crises. In aquaculture, intensive high-density production leads to excessive accumulation of leftover feed and waste, causing eutrophication and biodiversity decline. A typical case of tilapia pond farming in China shows that feeding amounts exceed fish metabolic capacity by 30%-40%. Increased water renewal frequency instead exacerbates nitrogen and phosphorus diffusion, raising aquatic product quality safety risk index by 28%[4]. Similar ecological issues are prevalent in tidal flat and wetland aquaculture, prompting global fisheries policies to shift toward stricter controls. The World Fisheries and Aquaculture Report (2024) explicitly states the need to reconstruct production-ecological balance through "blue transition" [1].

The planting industry is also facing severe challenges. The extensive application of chemical fertilizers and pesticides causes double resource loss: the utilization efficiency of nitrogen is less than 35%, and the loss rate of phosphorus is as high as 60%-70%[2]. This linear production mode not only aggravates non-point source pollution, but also leads to soil degradation and the decline of ecosystem service function.In this context, the fish-vegetable symbiosis system demonstrates innovative potential by reconstructing the "aquaculture-plantation" metabolic network: Fish waste is mineralized by microorganisms into plant-available nutrients, replacing 60%-80% of external fertilizer input. Simultaneously, plant roots efficiently absorb nitrogen and phosphorus, achieving in-situ water purification through a "pollution reduction-resource regeneration" bidirectional gain mechanism[5]. Although current research primarily focuses on agricultural-aquaculture integrated systems, the revealed circular logic provides a theoretical framework for standardizing fish-vegetable symbiosis technology, marking a paradigm shift from proof-of-concept to large-scale application in sustainable agriculture.

To achieve green development of aquaculture, China is promoting eco-healthy farming models, including optimizing stocking density, promoting precision management technologies, and strengthening environmental supervision [6].For instance, data from China's second national pollution source census revealed that the 2018 analysis of aquaculture discharge characteristics provided scientific evidence for structural adjustments, driving the industry's transition toward "resource-efficient and environmentally friendly" practices[7]. Moreover, while global aquaculture growth has slowed, technological innovations (such as biotechnology breeding and smart equipment) combined with regional collaboration could still help alleviate pressure on wild fisheries and enhance food security.

2. Concept and development of fish-vegetable symbiosis system

Aquaponics (AQUAPONICS) is an innovative integrated agricultural technology that combines aquaculture and hydroponic cultivation. Its core lies in the synergistic effect of fish metabolic waste and plant nutrient absorption through ecological cycle.The system uses fish excrement to decompose and transform into nitrogen, phosphorus and other nutrients required by plants through microorganisms, while the plant root system absorbs nutrients and purifies the water, forming a closed-loop "fish breeding-water purification-vegetable planting" cycle system [8,9].

The evolution of fish-vegetable symbiosis technology exemplifies the profound integration of agricultural wisdom and ecological philosophy. Its origins can be traced back to China's ancient integrated farming practices. The "Four Seasons Public Regulations of Wei Wu" from the Three Kingdoms period documents scenes of rice paddies being used for fishing, reflecting early agricultural societies' rudimentary understanding of ecological cycles[10].By the end of the Ming Dynasty and the beginning of the Qing Dynasty, the mulberry-based fishpond system increased the land utilization rate by more than 30% through the circular chain of "mulberry planting in the pond, silkworm feeding with mulberry leaves, silkworm feed feeding fish, and mulberry fertilizer with pond mud", laying the embryonic form of modern circular agriculture[11].At the same time, the Aztec civilization built a "floating farm" in Mexico to cope with land shortage by carrying soil on rafts, showing the wisdom of early soilless cultivation [12].

The theoretical construction of modern fish-vegetable symbiosis system began in the 1970s, and American scholars took the lead in carrying out systematic research, which organically combined aquaculture and hydroponic cultivation technology [12].From 1990 to 2010, the system entered the global expansion stage. Norway, Australia and other countries successively established commercial production bases, and the yield per unit area increased by more than 40% compared with the traditional mode [13].At present, there are two major technical schools of "decoupled" and "coupled" systems. In decoupled systems, nitrogen utilization rate reaches 98.2% by independently regulating aquatic and planting units, which is 15.3% higher than that of coupled systems [10].

With the deep application of Internet of Things technology, the benefits brought by continuous technological innovation are significant. Modern fish-vegetable symbiosis system is developing in the direction of three-dimensional and urbanization, with more and more models. Its production capacity per unit area has reached 4-6 times that of traditional soil cultivation, becoming an important practice mode of sustainable agriculture[13].

3. Main models of fish-vegetable symbiosis systems

3.1 Basic system composition

Fish and vegetable symbiotic system is a sustainable ecological model integrating aquaculture and plant cultivation. Its core structure usually consists of four parts: aquaculture unit, plant hydroculture unit, operation power unit and biological filtration unit [14].

Aquaculture units primarily cultivate fish species. Fish waste and residual feed are transported through water flow to the biofiltration unit, where nitrifying bacteria gradually convert ammonia nitrogen (NH^3) into nitrite (NO^{2-}) and nitrate (NO^{3-}), providing nutrients [15] for aquatic plants. The hydroponic cultivation units predominantly utilize NFT (Nutrient Focused Tissue Culture) or DWC (Deep Water Cultivation) technologies. The circulation system relies on pumps, pipelines, and valves to maintain water flow, with some systems equipped with sensors to monitor water temperature, pH levels, and water level, ensuring stable operation.In addition, in order to improve production efficiency, the system can be configured with supplementary lighting systems, such as LED lights to adjust light intensity and duration [16]; supplemental oxygenation equipment, such as air pumps and foam stone to increase dissolved oxygen [8]; and heating devices to maintain water temperature[17].

3.2 Main operation modes

Based on different combinations of technologies and spatial layouts, there are five main models for fish-vegetable symbiosis systems.

2.2.1 Media Bed System (MBS)

The media bed model, a hallmark of aquaponic systems, achieves synergistic circulation between fish farming and plant cultivation through porous substrate beds. In this setup, granular media like gravel and clay pellets not only provide physical support for root systems but also create habitats for beneficial microbial communities including nitrifying bacteria (e.g., Nitrosomonas and Nitrobacter) and Bacillus spores[18]. These microorganisms convert ammonia nitrogen (NH_3^+) from fish waste into nitrite (NO_2^-) and nitrate (NO_3^-) via ammonia oxidation and nitrite oxidation processes, ultimately producing plant-ready nitrogen nutrients.The water circulation system pumps the water containing fish manure into the planting bed through the pump. After physical filtration and microbial biochemical transformation of the substrate layer, the purified water is returned to the fish tank by gravity, forming a closed water-fertilizer cycle [19,20].

From the perspective of ecological structure, the media bed system forms a three-level trophic level: fish as primary producers output organic waste, microorganisms as decomposers realize material transformation, and plants as final consumers remove nutrients. This structure can achieve a total nitrogen removal efficiency of 70-85%.In small-scale household applications, the media bed system is often equipped with mechanical filters as a pretreatment unit to physically intercept large particles [17, 23]such as fish scales and residual bait, so as to prolong the service life of the matrix bed [21,22].The media bed model realizes fish-vegetable symbiosis through porous substrate planting bed and microbial flora. It has the advantages of stable water quality, complete ecological structure, high nitrogen conversion efficiency and suitable for organic production of leafy vegetables, so it is an ideal choice for family and small-scale application.

2.2.2 Deep Water Culture (DWC)

The Deep Water Culture (DWC) system is an advanced hydroponic technology that immerses plant roots in oxygen-rich nutrient solution while suspending the upper sections above water using floating boards or frames. Typically, plants are placed on polystyrene or foam rafts with drilled holes for securing netted plantings, allowing their root systems to hang vertically in the water[24].

The system continuously injects oxygen into the nutrient solution through a pump combined with a gas stone or diffuser to ensure root respiration needs, which is key to maintaining healthy plant growth [25].DWC is especially suitable for leafy vegetables and some crops that require a lot of water (such as cucumber and tomato), whose root systems can fully absorb evenly distributed nutrients and oxygen in deep water [26].Studies have shown that deep water environment can buffer temperature fluctuations and nutrient concentration changes, improve the stability of growth[27].However, the system has high requirements for water quality management, requiring real-time monitoring of dissolved oxygen, pH value, salinity and nutrient concentration to prevent algae growth and mold contamination [26].In addition, if the aeration is insufficient or the equipment fails, the root is prone to decay due to lack of oxygen [28].Although DWC is known for its simple structure and low maintenance cost[29], its commercial application still faces challenges.For example, large plants (e.g., ripe tomatoes) may have insufficient floating raft space due to excessive root growth, resulting in entanglement and disease risk [30], while high energy consumption recirculation pumps and aeration systems also increase operating costs [31].In general, DWC has become one of the important technologies in vertical agriculture and urban cultivation due to its high yield potential and adaptability[32,33].

2.2.3 Nutrient Film Technique (NFT)

Nutrient Film Technique (NFT) is an efficient hydroponic technique. Its core is to keep the plant root system in contact with a thin and flowing nutrient solution film, and realize circulation through inclined pipes or tanks [17].

The NFT system consists of a liquid reservoir, water pumps, growth chambers, and circulation pipelines. Nutrient solution is pumped from a high-level tank to the top of an inclined trough, where gravity forms a 0.3-5mm liquid film that flows over exposed plant roots before returning to the reservoir for recycling[34]. First developed by Alan Cooper in 1965, NFT initially utilized concrete trenches with polyethylene linings before evolving to PVC-lined channels. Modern systems are typically equipped with automated control modules that precisely regulate the EC value, pH level, and irrigation cycles of nutrient solutions, while enabling remote monitoring[35,36].This technology boasts remarkable advantages: Its compact structure makes it particularly suitable for space-constrained urban agriculture and multi-layer vertical farming[36]. The high resource utilization rate, combined with nutrient solution recycling that reduces water and fertilizer waste[37], ensures efficient resource management. Moreover, the simultaneous exposure of plant roots to both nutrient solutions and air prevents oxygen deficiency issues, which proves especially beneficial for rapid growth of shallow-rooted leafy vegetables like lettuce, spinach, and strawberries[35,38].

2.2.4 Raft system (or floating raft system)

The Raft System, a cutting-edge aquaponics technology, integrates hydroponic cultivation with aquatic nutrient cycling. This innovative approach anchors plants on foam or polystyrene rafts floating on water surfaces, allowing root systems to directly absorb nutrients from fish waste-derived solutions. This dual mechanism achieves both nutrient absorption and water purification[39].Similar to deep water culture (Deep Water Culture), the system is more suitable for large-scale commercial fish-vegetable symbiosis systems in deeper water (e.g., over 30 cm) due to the stability and scalability of its floating plate structure [25].

The structure of the floating board system has significant technical characteristics: polystyrene board is usually used as the buoyancy support body, planting holes are reserved on the board and net basin is equipped to fix plants. The root system is completely immersed in the circulating water of the fish pond to absorb nutrients such as ammonia nitrogen and phosphate [40,41].Studies have shown that the substrate formula of foam board combined with peat, perlite and organic fertilizer (4:1:1) can significantly improve the root vitality and nutrient absorption efficiency of leafy vegetables, and increase the fresh weight of lettuce above ground by 20% and chlorophyll content by 25%[42].However, in long-term operation, attention should be paid to the problem of hypoxia caused by the accumulation of pollutants at the root. It can be alleviated by adding a gas pump or periodically cleaning the root system [43].Studies have shown that foliar spraying of nutrient solution can make up for the lack of nutrients in bare root hydroponic culture, and increase the yield of lettuce in fish-vegetable symbiosis system by 25%, without affecting the ecological balance of water[42].Despite the challenges of limited crop selection in high summer temperatures (only suitable for leafy vegetables with short roots), its low maintenance cost and high resource efficiency make it an important practice direction of sustainable agriculture [44].

2.2.5 Modular Aquaponics (MA)

The Modular Aquaponics (MA) system achieves independent operation and dynamic adjustment of its modules by physically separating fish tanks from plant cultivation areas. This design breaks through the rigid structure of traditional integrated systems, with three core advantages: First, standardized interfaces enable flexible expansion of fish ponds or planting areas according to production needs[45,46]; Second, each module is equipped with independent filtration units (e.g., Clarifier clarifiers and biofilters), utilizing nitrifying bacteria to convert ammonia nitrogen in fish waste into plant-absorbable nitrate, while precise control of water temperature, level, pH value, and other parameters through PID controllers ensures stable operations[8]; Finally, the modular architecture significantly reduces maintenance complexity. When a unit malfunctions, individual repairs can be performed without affecting overall operation. The LabVIEW-developed monitoring system also enables real-time tracking of water quality parameters and early warning alerts[47].

From the perspective of ecological benefits, this model achieved a 90% water saving rate through the closed-loop water cycle (fish tank → filter → planting bed → fish tank), and the utilization rate of total nitrogen and phosphorus produced by fish metabolism could reach 75% and 68% respectively [47].In terms of intelligent management, the modular system integrates temperature sensor, water level sensor and fuzzy control algorithm, which can automatically adjust the conductivity and dissolved oxygen concentration of nutrient solution, so that the growth cycle of vegetables is shortened by 30% (for example, the maturation period of lettuce is compressed from 50 days to 35 days)[48].In terms of space utilization, this model adopts three-dimensional vertical layout (such as passive climate regulation combination), which can realize high-density aquaculture and production with 1m2 planting area and 0.45m3 water body [49].

4. Influencing factors of fish-vegetable symbiosis system operation

The stable operation of the fish-vegetable symbiotic system is regulated by multiple environmental and biological factors, with the dynamic balance of nitrogen and phosphorus cycles serving as the core mechanism for maintaining system efficiency. As primary nutrient absorption units, plants directly assimilate dissolved nitrogen and phosphorus compounds from aquatic environments through their root systems. Simultaneously, their attached substrates provide biofilm formation sites for microbial communities such as nitrifying bacteria and denitrifying bacteria[15].Through ammonia oxidation, nitrite oxidation and denitrification, microbial metabolic activities gradually mineralize the organic nitrogen in fish excrement into plant available nitrate, forming a "fish-microorganism-plant" three-level nutritional cascade effect [50].In this process, the concentration threshold of ammonia nitrogen (TAN) and nitrite (NO_2^-) should be strictly controlled below 0.5 mg/L to avoid toxic effects on aquatic organisms [51].

Nitrogen conversion efficiency is influenced by multi-parameter coupling: microbial community structure determines the stability of nitrification pathways; the carbon-to-nitrogen ratio (C/N) regulates the competitive relationship between denitrification rates and plant growth; hydraulic loading rate (HLR) affects material retention time; seasonal temperature fluctuations cause significant variations in total ammonia nitrogen (TAN) concentration (18%-22% higher in summer than autumn); when pH reaches 6.0, nitrification efficiency peaks at 50.9%, while dissolved oxygen (DO) concentration must be maintained at 5-7 mg/L to ensure aerobic bacterial activity[52,53].

The optimization of phosphorus cycling depends on the chemical adsorption and biotransformation at the sediment-water interface. The plant roots absorb soluble phosphate through active transport, while the porous structure of the volcanic rock matrix can enhance the phosphorus adsorption capacity (26.14%) and inhibit the release of endogenous phosphorus in the sediment [54].Microbial mineralization decomposes organic phosphorus into PO_4^{3-}, but its conversion efficiency is regulated by pH (optimal range 6.5-7.2) and REDOX potential (Eh>200 mV)[55,56].

Biological interactions significantly influence system efficiency. Experimental data shows that tilapia farming density exceeding 16 fish/m^3 reduces lettuce leaf nitrogen content by 9.7%[57]. Meanwhile, water spinach cultivation at 45 plants/m^2 achieves remarkable removal rates of 72.63% for ammonia nitrogen and 55.62% for total phosphorus, outperforming cherry tomatoes (69.17%) and purple amaranth (55.25% nitrite removal rate)[5,58].In the coupled system, the layered filler design combined with functional bacterial inoculation can reduce the N_2O emission coefficient to 1.54%, while increasing the economic yield rate by 18%-22%[50].

Environmental benefit assessments demonstrate that compared to traditional intensive aquaculture, the fish-vegetable symbiosis system reduces total nitrogen (TN) and ammonia nitrogen (NH_3-N) emissions by 99.45% and 99.73% respectively [52,53]. To optimize this system further, measures should include expanding hydroponic cultivation areas (with a recommended plant-to-water ratio of 1:3), implementing precision feeding (using 2.5%-3.0% of biomass as feed), and dynamically adjusting the species-to-crop ratio (fish biomass/botanical biomass = 1:1.2-1.5) to maximize material recycling efficiency[52,59].

5. Future development trends

5.1 Innovation in application fields

The technological evolution of the Fish-vegetable symbiotic system demonstrates multidimensional innovation, expanding beyond traditional agriculture to emerging fields like post-disaster emergency production and urban vertical farming. In disaster response scenarios, the modular system achieves simultaneous food and water supply through rapid deployment (24-hour completion) and closed-loop resource recycling (ammonia nitrogen removal rate $\geqslant 80.59\%$), significantly enhancing disaster recovery efficiency. Its foldable container design combined with solar power systems further reduces deployment time to 72 hours, meeting extreme environmental demands[60].

5.2 Breakthrough of technical bottleneck

The technological breakthrough of fish and vegetable symbiotic system is advancing in multiple dimensions around intelligent monitoring, cost intensification and system stability.

In water quality monitoring, the integration of multimodal optical sensors (e.g., microspectrometers) with deep learning algorithms (CNN) has enhanced ammonia nitrogen detection accuracy to ± 0.1 mg/L. Meanwhile, the biomimetic robotic fish equipped with STM32 microcontrollers enables real-time monitoring in complex aquatic environments (coverage radius $\geqslant$ 500 m)[61,62], while its self-calibration algorithm reduces manual intervention frequency by 60%[8].In terms of cost control, photovoltaic integration ("fish and light integration") reduces energy consumption by 40%, the algal symbiosis system (AA system) reduces aeration demand by 30% through microalgae photosynthesis, and the intelligent wind feeding technology optimizes feed utilization rate (the coefficient is reduced to below 1.2), reducing the comprehensive operating cost by 28%[63].In terms of system stability, the innovation of microbiome engineering made the nitrogen conversion efficiency reach 98.2%, and the anti-interference design stabilized the total nitrogen fluctuation after heavy rainfall [59].

Future research will focus on integrating AI-driven knowledge graph prediction models (error $\leqslant$ 5%) with low-carbon technologies: achieving a 70% substitution rate for biodegradable materials and enhancing off-grid system energy autonomy through hydrogen fuel cells (range $\geqslant$72 hours). Through a three-dimensional strategy of "technology iteration, standard setting, and industrial integration," the aquaponics system is expected to achieve 30% market penetration by 2030, becoming the core paradigm of sustainable agriculture[49].

5.3 Combined application with artificial intelligence

The deep integration of the fish-vegetable symbiotic system with artificial intelligence (AI) is driving its evolution towards smarter and more efficient operations. Through IoT sensor networks, AI monitors real-time water parameters including ammonia nitrogen, dissolved oxygen, and pH levels. By leveraging deep learning models like Long-Term Short-Term Memory Networks (LSTM), it predicts dynamic trends with an error margin of $\leqslant$4.68%, while coordinating equipment adjustments to maintain nitrogen balance. For instance, reinforcement learning algorithms optimize aeration frequency, effectively suppressing N_2O emissions from denitrification processes (reducing by 48.7%)[64] while boosting nitrate conversion efficiency to 98.2%.

In modular system design, AI-driven genetic algorithms optimize three-dimensional spatial layouts, achieving a 25% increase in nitrogen recovery efficiency for vertical farming units (1 m^2 planting area coupled with 0.45 m^3 water volume) (Hati & Singh, 2021). The intelligent decision-making system utilizes computer vision to analyze plant growth patterns, dynamically adjusting nutrient solutions (with leaf deficiency detection accuracy $\geqslant 90\%$) while collaborating with photovoltaic energy management to reduce energy consumption by 30%. Alibaba's "FFM Future Ranch" AIoT platform has validated the feasibility of multi-source data fusion and automated control, with its edge computing devices providing tailored solutions for small and medium-sized systems.

To achieve future breakthroughs, we must overcome data standardization bottlenecks (e.g., sensor interference-resistant calibration algorithms) and model generalization limitations (cross-climate zone adaptability), while promoting large-scale adoption through policy support. The interdisciplinary integration of synthetic biology and AI (e.g., CRISPR-edited functional strains + digital twin models) will further enhance system stability, accelerating progress toward realizing the "zero-emission farm" goal.

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