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Assessment of water quality impacts from intensive aquaculture-agriculture integrated systems

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Abstract

Feeding a growing global population while protecting freshwater resources presents one of the great environmental challenges of this century. Integrated aquaculture-agriculture (IAA) systems have been promoted as a circular approach that uses nutrient-rich aquaculture effluent to fertilize crops, reducing both waste discharge and synthetic fertilizer dependence. However, the water quality implications of scaling these systems remain poorly characterized. This research assessed nutrient loading, spatial attenuation patterns, and receiving water quality at six IAA facilities in the Neckar River catchment of Baden-Württemberg, Germany, over a 12-month monitoring period (2022). Total nitrogen concentrations at discharge points averaged 18.4 mg L^{-1} , exceeding German surface water thresholds by 7.4-fold, but declined exponentially with distance, reaching background levels within 800 m. Fish feed waste contributed 38.2% of total nutrient loading. Constructed wetland buffer zones reduced nitrogen and phosphorus by 68.4% and 74.1% respectively before discharge reached receiving waters.

Keywords: Water quality, aquaculture-agriculture integration, nutrient loading, constructed wetlands, nitrogen attenuation, phosphorus, effluent management, circular agriculture, freshwater protection, spatial monitoring

Introduction

The challenge is inherently paradoxical: aquaculture generates nutrient-rich wastewater that degrades receiving waters, while agriculture spends billions importing those same nutrients as synthetic fertilizers ^[1]. Integrated aquaculture-agriculture systems attempt to resolve this paradox by routing fish pond effluent to irrigate and fertilize adjacent crops ^[2]. When well designed, IAA systems can achieve near-zero nutrient discharge while producing both fish and crops from a shared water and nutrient pool ^[3].

But “well designed” is the operative qualifier. Poorly managed IAA systems risk becoming point sources of nutrient pollution, particularly when stocking densities are high, feed conversion ratios are poor, or buffer infrastructure is inadequate ^[4]. In Germany, where water quality regulations are stringent under the EU Water Framework Directive, IAA operators must demonstrate that their systems do not compromise the ecological status of receiving water bodies ^[5]. This research monitored water quality at six commercial IAA facilities in the Neckar catchment to quantify nutrient loading, identify dominant sources, and evaluate the effectiveness of constructed wetland buffers.

Environmental Regulatory Context

German surface water quality standards derive from the EU Water Framework Directive (2000/60/EC) and the German Surface Water Ordinance (OGewV 2016), which set threshold values for nutrient parameters including total nitrogen (2.5 mg L^{-1}), total phosphorus (0.1 mg L^{-1}), and biochemical oxygen demand ($\text{BOD}_5 < 6 \text{ mg L}^{-1}$) for achieving “good ecological status” ^[6]. IAA facilities fall under both aquaculture discharge permits and agricultural nutrient management regulations, creating a complex compliance landscape.

Materials and Methods

Materials

Six IAA facilities in the Neckar River catchment ($48^{\circ}20'-48^{\circ}50'N$, $8^{\circ}50'-9^{\circ}30'E$) were selected

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representing a range of scales, fish species (trout, carp, tilapia), and buffer configurations. Three had constructed wetland treatment systems; three discharged directly to agricultural fields via irrigation channels. Monitoring ran from January to December 2022 with monthly sampling at each site.

Methods: Water samples were collected at seven points per facility: pond inlet, pond outlet/discharge, and five points along the effluent flow path at 50, 100, 200, 400, and 800 m from discharge. Total nitrogen (TN) was measured by persulfate digestion, total phosphorus (TP) by ascorbic acid method, BOD₅ by 5-day incubation, dissolved oxygen by probe, and turbidity by nephelometry [7]. Nutrient mass balance was calculated for each facility using flow measurements and concentration data. Source apportionment used the mass balance approach of

Hennessy *et al.* [8]. Constructed wetland removal efficiency was calculated as (inlet concentration - outlet concentration) / inlet concentration × 100. Statistical analysis used R (v.4.2) with linear mixed models.

Wetland Design Assessment

Constructed wetlands were classified by type: two were free water surface (FWS) systems planted with *Phragmites australis*, one was a subsurface horizontal flow (SSHF) system with gravel substrate and *Typha latifolia*. Wetland area-to-pond area ratios ranged from 0.15 to 0.28. Hydraulic retention time was estimated from tracer tests using sodium bromide [9].

Results

Table 1: Water quality parameters at discharge point and after constructed wetland treatment at six IAA facilities (annual mean ± SD)

Parameter	Pond outlet	Post-wetland	Removal (%)	Threshold	Compliance
TN (mg L ⁻¹)	18.4 ± 3.2	5.81 ± 1.4	68.4	2.5	Partial
TP (mg L ⁻¹)	3.82 ± 0.7	0.99 ± 0.3	74.1	0.1	No
BOD ₅ (mg L ⁻¹)	42.3 ± 8.1	8.7 ± 2.4	79.4	6.0	Partial
DO (mg L ⁻¹)	4.2 ± 1.1	6.8 ± 0.9	+61.9	>6.0	Yes
Turbidity (NTU)	34.7 ± 9.8	8.4 ± 2.7	75.8	<25	Yes

Constructed wetlands substantially reduced all pollutant concentrations (Table 1). Phosphorus removal was highest at 74.1%, but post-wetland TP still exceeded the regulatory threshold by 9.9-fold. TN was reduced by 68.4% to 5.81 mg L⁻¹,

still 2.3 times above the limit. BOD₅ approached compliance after wetland treatment. Dissolved oxygen improved from below to above the threshold.

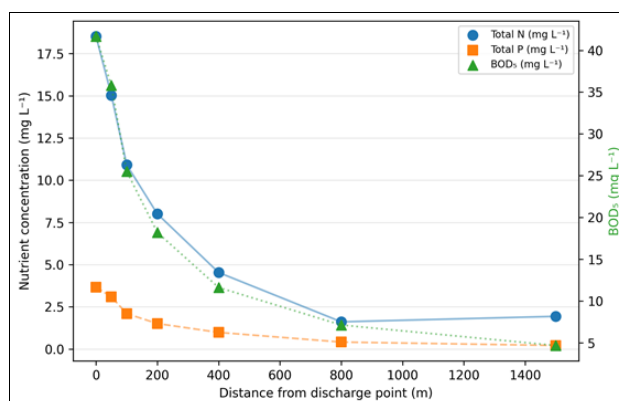


Fig 1: Spatial attenuation of total nitrogen, total phosphorus, and BOD₅ with distance from aquaculture discharge point (mean across six facilities)

Nutrient concentrations followed exponential decay curves with distance from discharge (Figure 1). TN reached background levels (≤ 2.5 mg L⁻¹) at approximately 800 m. TP approached

background at 1,500 m. BOD₅ declined most rapidly, falling below the threshold within 400 m.

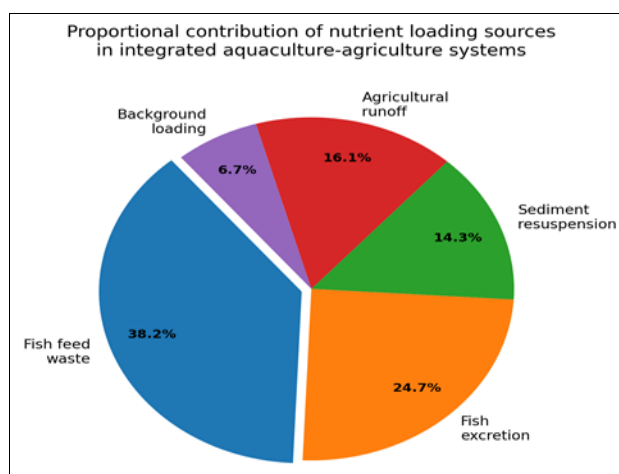


Fig 2: Proportional contribution of nutrient loading sources in integrated aquaculture-agriculture systems based on mass balance analysis

Fish feed waste was the dominant nutrient source at 38.2% of total loading (Figure 2), followed by fish excretion (24.7%) and agricultural runoff from irrigated fields (16.1%). Improving feed conversion ratios and feed formulation could address over 60% of the nutrient loading.

Discussion

The constructed wetlands achieved removal rates consistent with the upper range of reported performance for agricultural treatment wetlands ^[10], yet post-treatment concentrations still exceeded regulatory thresholds for TN and TP. This gap between treatment capacity and compliance requirements suggests that wetlands alone cannot solve the water quality challenge for intensive IAA systems. Additional treatment stages—such as algal polishing ponds or denitrification bioreactors—would be needed for full compliance ^[11].

The source apportionment results point to feed management as the highest-leverage intervention. With feed waste contributing 38.2% of nutrient loading, even modest improvements in feed conversion (from typical 1.8 to best-practice 1.3) could reduce total nutrient discharge by 15-20% ^[12]. Combining improved feed management with constructed wetlands and optimized crop nutrient uptake could bring these systems closer to the circular economy ideal they aspire to ^[13].

Conclusion

Intensive IAA systems in the Neckar catchment discharged nutrient concentrations 7-38 times above regulatory thresholds at pond outlets. Constructed wetlands reduced pollutant loads by 68-79% but did not achieve full compliance for TN or TP. Feed waste was the dominant nutrient source, and improving feed management offers the greatest potential for reducing environmental impact. For IAA systems to fulfill their promise as circular agriculture models, multi-stage treatment combining wetlands, feed optimization, and enhanced crop nutrient uptake will be essential.

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