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Baseline Soil and Water Quality for Sustainable Agriculture–Aquaculture Systems in Keerom, Papua, Indonesia

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ABSTRACT

Tropical frontier regions such as Keerom Regency in Papua, Indonesia, face increasing pressure to expand food production under the National Strategic Projects (PSN) for food security. However, the absence of baseline data on soil fertility and water quality constrains the design of sustainable management practices. This study evaluated the temporal variation in soil chemical properties and aquaculture water quality to establish scientific benchmarks for site-specific interventions. Soil samples from chilli pepper (*Capsicum annuum*) farms were collected across resting, early growth, pre-harvest, and intercropping stages, while water samples from catfish (*Clarias s*pp.) ponds were obtained during larval, grow-out, and harvest phases. Soil pH declined from 6.5 to 4.4, accompanied by reductions in total N, P, and K and a gradual rise in EC, indicating nutrient depletion and increasing acidity. In aquaculture ponds, DO levels decreased while NH_4^+ and NO_2^- accumulated during intensive feeding, suggesting excessive organic loading and incomplete nitrification. These results reveal critical limitations in both systems that reduce productivity and environmental resilience. The findings provide essential baseline data for nutrient management, fertilizer optimization, and water-quality control, forming a scientific foundation for future integrated agriculture–aquaculture (IAA). Further analysis and spatially detailed studies are needed to map land suitability and guide effective, efficient, and ecologically responsible land-use planning, ensuring agricultural expansion does not encroach upon primary or intact forest ecosystems.

Key words: food security; integrated agriculture–aquaculture; Papua; soil fertility, water quality.

INTRODUCTION

Keerom Regency in Papua, Indonesia, is undergoing rapid socio-environmental transition as agricultural and aquacultural activities expand across its tropical frontier landscapes. The region holds substantial natural capital—fertile soils, abundant freshwater systems, and favorable climatic conditions—alongside rich biological and ethnobotanical diversity that supports indigenous food systems and cultural practices (Suharno *et al.*, 2025; Kadir *et al.*, 2025). These attributes align closely with Indonesia's National Strategic Projects (Proyek Strategis Nasional, PSN), which prioritize food security, rural economic development, and climate-resilient resource

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management. Despite this potential, more than 60% of Keerom's population depends on agriculture and aquaculture (BPS Papua, 2023), yet productivity remains low due to the limited use of localized, evidence-based management.

A major constraint is the absence of diagnostic baseline data on soil fertility and water quality. Key soil indicators—pH, electrical conductivity (EC), and macronutrients (N, P, K)—govern nutrient bioavailability, microbial processes, and crop performance (Dobermann & Fairhurst, 2000; Sanchez, 2019). Highly weathered tropical soils such as those in Papua typically exhibit acidity, nutrient leaching, low base saturation, and strong phosphorus fixation (Lal, 2006; Fageria & Baligar, 2008), conditions that suppress nutrient-use efficiency without targeted soil amendments.

Water quality is equally critical for aquaculture, determining fish metabolism, growth, and survival. Parameters such as dissolved oxygen (DO), ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), pH, and total dissolved solids (TDS) strongly influence pond performance (Boyd, 2015; APHA, 2017). Poor aeration and nutrient accumulation can increase toxic forms of nitrogen, particularly ammonia and nitrite (Colt & Armstrong, 1981; Timmons & Ebeling, 2010). However, empirical water-quality data for Papua remain scarce, leading producers to rely on generalized assumptions rather than localized diagnostics.

This lack of integrated soil–water assessments represent a significant scientific and policy gap. Without foundational biophysical data, efforts to enhance food security and meet PSN targets risk being inefficient or environmentally unsustainable. Input decisions are often intuitive, contributing to nutrient imbalance, soil degradation, and variable aquaculture yields.

To address this gap, this study uses two representative commodities that are central to Keerom's food system: chilli pepper (*Capsicum annuum*) and catfish (*Clarias* spp.). Chilli is a nutrient-intensive, high-value crop that influences household income and national price stability, whereas catfish is Indonesia's most widely cultured freshwater species due to its adaptability and affordability (Suryani *et al.*, 2020; MMAF, 2022). By examining these commodities, this research provides a factual foundation for broader agricultural and aquacultural applications.

Accordingly, the objectives of this study are to: (1) quantify temporal changes in key soil chemical properties (pH, EC, N, P, K) during chilli cultivation; (2) assess water-quality variation (DO, COD, TDS, pH, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}) across different catfish pond stages; and (3) establish a scientific baseline for site-specific nutrient and water management. Although the two systems are not formally integrated, their spatial proximity highlights opportunities for future integrated agriculture–aquaculture (IAA) approaches, which can enhance resource efficiency and climate-adaptive food production (Prein, 2002; Edwards, 2015). These findings contribute essential baseline knowledge for advancing sustainable, climate-adaptive food systems in Papua and other frontier regions of Indonesia, while supporting national priorities in food security and strategic rural development under the Indonesia National Strategic Projects framework.

MATERIALS AND METHODS

Study site and sampling design

This study was conducted in Keerom Regency, Papua, Indonesia (2°50′S–3°10′S; 140°30′E–141°10′E), a tropical lowland region characterized by high rainfall, acidic soils, and widespread smallholder agricultural activity. Soil and water samples were collected in July 2025 from Arso III, VI and VIII, Keerom Regency, Papua. Soil samples were obtained from a chilli pepper (*C. annuum*) cultivation plot, while water samples were collected from a nearby catfish (*Clarias* spp.) aquaculture site. Although the systems were not integrated, they were situated within the same agroecological zone, allowing for contextual analysis.

Soil sampling and rapid field analysis

Soil samples were collected at seven key cultivation stages: pre-planting (resting), days 7, 14, 21, and 30 after planting, harvest, and intercropping. At each stage, five subsamples (0–20 cm depth) were composited for field analysis.

Rapid field testing was conducted using the Midorikun Kit (Tokyo University of Agriculture, Japan), a semi-quantitative colorimetric diagnostic tool designed for soil nutrient screening. Two kit types were used:

1. Midorikun N for measuring pH (H_2O) and nitrate-nitrogen (NO_3^-–N)
2. Midorikun PK for water-soluble phosphorus (P) and potassium (K).

For each analysis, at each stage, five subsamples (0–20 cm depth) were mixed, 5 g of fresh mixed soil was mixed with 50 mL of distilled water (1:10), shaken for 1 minute, and allowed to settle for 5 minutes. The supernatant was tested using reagent strips, and the resulting color was compared against a standardized color chart. Results were interpreted to the nearest match in mg kg^{-1} (for NO_3^-–N, P, K) or pH unit (for acidity).

To reduce observer bias, measurements were made by two trained evaluators under daylight, and the average value was recorded. While the Midorikun Kit provides only semi-quantitative estimates, it was selected due to its portability, cost-effectiveness, and field applicability in remote areas such as Keerom, where laboratory facilities are limited.

Water sampling and field-based water quality analysis

Water samples were collected from seven aquatic sources: raw and settled groundwater, well water (within the chilli field), irrigation water, and aquaculture ponds at different culture stages (1-week larvae, grow-out, and harvest-ready). Surface water was collected at 20–30 cm depth using clean polypropylene containers, avoiding disturbance of sediments and surface films. Observational temperature and weather were recorded in situ.

Water quality was assessed using Pack Test® reagent kits (Kyoritsu Chemical-Check Lab., Japan), a semi-quantitative colorimetric system validated for field use in tropical environments. Parameters analyzed included: pH, chemical oxygen demand (COD), ammonium-nitrogen (NH_4^+–N), nitrate-nitrogen (NO_3^-–N); phosphate

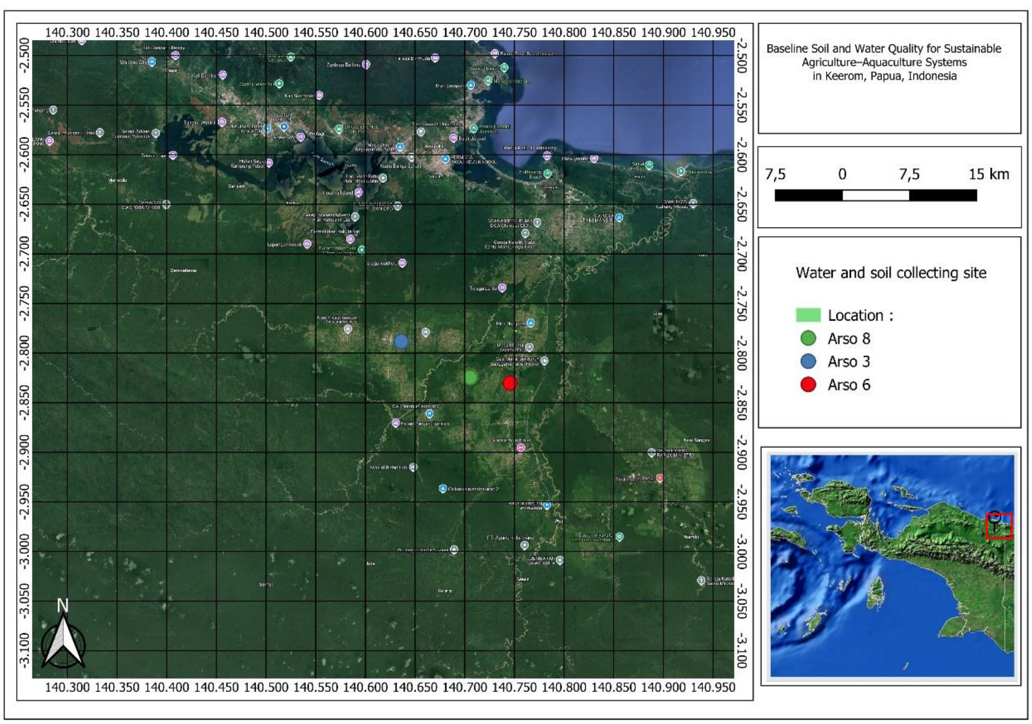

Figure 1. Soil and water sampling location.

(PO_4^{3-}–P).

For each test, the sealed tube was filled by gentle suction from the sample water, the reaction was timed (1–10 minutes depending on parameter), and the developed color was visually matched against a manufacturer-provided standard chart. Measurements were performed in duplicate, and diluted (1:1 or 1:10) if color intensity exceeded the detection range. Results were interpreted under daylight by two independent observers. This method enabled rapid estimation of key water quality parameters without laboratory instrumentation and has been validated in participatory and educational water monitoring programs (Kikuchi *et al*., 2010; Rahman, 2011).

Data Interpretation

Results for both soil and water quality were expressed in mg kg^{-1} (soil) or mg L^{-1} (water) based on the color scale interpretation. Descriptive statistics (mean values) were used for each sampling stage and source. Findings were compared against recommended thresholds for tropical agriculture and aquaculture systems, based on field standards and published studies.

RESULTS AND DISCUSSION

Soil quality dynamics in chilli pepper cultivation

Soil pH and electrical conductivity (EC)

Rapid soil-quality assessment was conducted in chili pepper cultivation systems to characterize soil chemical dynamics in Keerom Regency. Soil pH and electrical conductivity (EC) were measured at seven cultivation stages: pre-planting (resting), 7, 14, 21, and 30 days after planting (DAP), harvest, and intercropping. Soil pH showed a pronounced acidification trend, declining from 6.5 at resting to 4.44 by 14 DAP and stabilizing between 4.45–4.87 during subsequent stages (Table 1). This pattern reflects cumulative acidifying processes associated with nutrient uptake, rhizosphere acidification, and fertilizer inputs. Soil pH values below 5.0 are known to

Table 1. Soil quality parameters, pH and EC.

Parameter	Resting soil	Use soil (7 days)	Use soil (14 days)	Use soil (21 days)	Use soil (30 days)	Soil harvest period	Intercrop soil
pH	6.5	5.75	4.44	4.87	4.45	4.77	4.45
EC	1	0.8	0.53	0.3	0.45	0.35	0.45

Unit: dS/m; n = 5 composite samples from one field; no statistical comparison

Table 2. Macro-nutrient (NPK) in soil.

Parameter	Resting soil	Use soil (7 days)	Use soil (14 days)	Use soil (21 days)	Use soil (30 days)	On use soil (harvest period)	Intercrop soil
N	3	3	20	3	3	3	0
P	37.5	25	17	17	17	33	33
K	0	0	0	0	0	0	0

Table 3. Main water quality paramters in freshwater aquaculture.

Parameter	Ground water	Well water	Irrigatio n water	Earthen pond water with ready to harvest fish	30-day settled groundwater	Pond water with larvae 1 weeks	Pond water ready to harvest (3 Months)
DO (mg/l)	5.9	4.1	6.9	4.1	4.4	11.6	2
COD (mg/l)	8.0	8	6	6	6	8	6
TDS (mg/l)	358.7	230	76	420	360	111	227
pH	7.2	6.8	7.1	6.6	7.3	7.81	7.11

Table 4. Nutrient parameters in feshwater aquaculture.

Parameter	Ground water	Well water	Irrigation water	Earthen pond water (with fish)	30-day settled groundwater	Pond water with larvae 1 weeks	Pond water ready to harvest (3 months)
NH_4	2.4	2	5	10	0.5	1	10
NH_4-N	2.1	2	3	10	0.5	0.5	10
NO_2	0.1	0.5	0.05	0	0.02	1	0.02
NO_2-N	0.0	0.1	0.01	0	0.005	0.5	0.005
NO_3	3.7	45	1	0	0	20	1
NO_3-N	0.7	10	0.2	0	0	5	0.2
$PO_{4\text{-}3}$	0.1	0.2	2	2	0.5	0.05	2
$PO_{4\text{-}3}$-N	0.1	0.1	1	1	0.1	0.02	1

restrict nutrient availability—particularly phosphorus—due to Al and Fe oxide fixation (Sanchez, 2019). The decline to ~4.4 observed in this study is substantially lower than the typical 5.0–6.0 range reported for cultivated tropical soils (Anwar *et al*., 2023; Hanudin *et al*., 2025). Although similar acidity (pH 4–5) has been documented in Indonesian ultisols (Fageria & Baligar, 2008; Anwar *et al*., 2023), the severity of acidification observed here suggests heightened risks of nutrient depletion and potential Al^{3+} toxicity unless liming practices are implemented (JIRCAS, 2018).

Electrical conductivity (EC), a proxy for soluble salts and nutrient ion content, declined sharply from 1.0 dS/m at resting stages to 0.3 dS/m by 21 DAP, followed by a minor recovery to 0.45 dS/m at harvest and intercropping stages. EC values below 0.5 dS/m indicate severe nutrient exhaustion in the rhizosphere, consistent with nutrient removal and leaching processes characteristic of highly weathered tropical soils (Hartati *et al*., 2019). Comparable EC reductions have been documented in annual cropping systems in Central Java, where Soil Fertility Index (SFI) values ≤ 0.51 indicate low-fertility conditions (Dewi *et al*., 2024). The EC trends observed in Keerom therefore reflect similarly depleted—or even more nutrient-poor—soil status.

Overall, the combined pH and EC patterns indicate that Keerom soils are highly susceptible to acid-driven nutrient limitations. Compared with other Indonesian studies (Pulunggono *et al*., 2024; Hanudin *et al*., 2025), soils in this region exhibited more rapid acidification and lower ionic strength, underscoring the vulnerability of frontier agroecosystems to unmanaged fertilizer inputs and declining organic matter. These results highlight the urgent need for site-specific nutrient budgeting, liming programs, and improved fertility management to sustain crop productivity in Keerom.

Soil macronutrients (N, P, K)

Nitrogen concentrations showed a transient increase at 14 DAP (20 mg kg^{-1}), likely reflecting rapid mineralization of early fertilizer inputs, but subsequently returned to 3 mg kg^{-1}, indicating fast plant uptake and/or substantial leaching losses. Phosphorus declined sharply from 37.5 mg kg^{-1} at resting to 17 mg kg^{-1} during 14–30 DAP before rising again to 33 mg kg^{-1} at harvest, a pattern that may be attributed to organic P mineralization or reduced demand during late growth stages. Potassium remained undetectable (0 mg kg^{-1}) at all sampling points. Although K deficiency is common in highly weathered Indonesian soils, complete absence of available K is rarely reported. For example, Hartati *et al*. (2019) observed available K of ~0.25 cmol(+) kg^{-1} in rice soils, while Hanudin *et al*. (2025) documented sub-critical exchangeable K values in Yogyakarta clay soils. Severe K deficiency is known to constrain fruit development, physiological resilience, and yield formation in *Capsicum annuum* (Dobermann & Fairhurst, 2000).

Collectively, these findings position Keerom soils at the extreme low end of Indonesia's fertility gradient—acidic, nutrient-poor, and strongly depleted in exchangeable cations. Such characteristics highlight an urgent need for soil reclamation strategies that include liming, K-enriched fertilizer formulations, and improved organic matter inputs (JIRCAS, 2018). Lessons from Bali's GIS-based fertility mapping (Iieta, 2023) further demonstrate that spatial nutrient diagnostics can effectively guide targeted corrective interventions. Applying similar spatial mapping approaches in Keerom could support precise land-use planning, fertilizer zoning, and long-term nutrient budgeting.

Water quality in catfish aquaculture systems

General physicochemical parameters

Measurements were conducted on various water sources (shallow wells, boreholes, irrigation water) and catfish (*Clarias* sp.) cultivation ponds, during both the larval phase and the pre-harvest phase. The main parameters measured were dissolved oxygen (DO), pH, total dissolved solids (TDS), and chemical oxygen demand (COD). A summary of the measurement results is presented in Table 3.

The dissolved oxygen (DO) level in the ready-to-harvest catfish pond (2 mg/L) was critically low compared to the DO levels in other water sources. This value falls below the minimum water quality standard for catfish farming (SNI 6484.3:2014), which is >3 mg/L for survival and >5 mg/L for optimal growth (Boyd & Tucker, 1998; Wibowo *et al.*, 2020; Sugianti & Hafiludin, 2022). The depletion of DO in the cultivation pond can be attributed to the accumulation of leftover feed, fish waste, and other organic matter decomposing through microbial activity, coupled with high stocking density (Bastian *et al.*, 2025; Yu *et al.*, 2025; Rahman *et al.*, 2025).

The Chemical Oxygen Demand (COD) value indicates the level of organic pollution in a water body. According to Government Regulation No. 22 of 2021 concerning the National Water Quality Standards for lentic water bodies such as ponds, the measured COD values were low and remain within the quality standards for Water Class 1 through Class 4. Furthermore, Efdaswarni *et al.* (2025) state that a suitable COD value for catfish farming in ponds should be below 50 mg/L.

Total Dissolved Solids (TDS) represent the total concentration of dissolved solids in water. The observed TDS values were below the national water quality standard threshold, indicating a good status. While TDS below 50 mg/L is typically recommended for drinking water sources, a range of 300 mg/L to 1,200 mg/L is still tolerable for catfish cultivation (Hidayat *et al.*, 2023; Syakir *et al.*, 2024). The presence of TDS in this study indicates an accumulation of dissolved materials in both the water sources and cultivation ponds; however, the levels remain within acceptable limits.

The optimal pH range for catfish metabolism and growth, according to SNI 6848.3:2014, is 6.5 to 8.5. The measured pH values across all sampled sites—including water sources (groundwater, well water, irrigation water) and catfish cultivation ponds—fell within this optimal range, indicating suitable conditions for catfish growth and farming operations. However, when combined with low dissolved oxygen (DO), even neutral pH levels can exacerbate the toxicity of un-ionized ammonia (NH_3), particularly under conditions of elevated pH and temperature (Ebeling & Timmons, 2012).

Nutrient pollution and eutrophication risk

Ammonium (NH_4^+) concentrations were highest in ponds with harvest-stage fish (10.0 mg/L), a value well above the recommended maximum of 1–2 mg/L for intensive systems. This suggests a high organic load from uneaten feed, feces, and nitrogenous waste, especially under reduced nitrification conditions (Hargreaves, 1998). Similar values (8–12 mg/L) were reported in tropical aquaculture wastewater in Bali (Ejabf Journal, 2023) and tilapia ponds in West Java (Rahman *et al.*, 2025). On the other hand, Nitrate (NO_3^-) was exceptionally highest in well water (45 mg/L), surpassing WHO's 10 mg/L limit, consistent with agricultural leaching from nearby chilli fields. Un-ionized NH_3 derived from NH_4^+ becomes highly toxic at higher temperatures and pH—conditions likely present in Keerom's tropical climate. Conversely, NO_3^- was nearly absent in most pond waters, suggesting either rapid denitrification or limited nitrification efficiency due to oxygen limitations.

Phosphate (PO_4^{3-}) levels reached 2.0 mg/L in both irrigation and pond waters. Such elevated concentrations, in tandem with high NH_4^+, are symptomatic of eutrophic conditions that can trigger harmful algal blooms and anoxic events in aquaculture ponds (Boyd, 2015). Bastian *et al*. (2025) concluded that unbalanced nutrient loads and poor aeration accelerate eutrophication in Indonesian freshwater systems, mirroring these results.

These elevated nutrient levels align with observations from Lake Maninjau, West Sumatra, where aquaculture-induced eutrophication caused DO fluctuations and ammonia accumulation (Wojewódka-Przybył *et al*., 2024). Similarly, tropical aquaculture systems often experience ammonia levels above acceptable limits in > 70% of cases (Nagaraju *et al*., 2023). Hence, the Keerom data confirm a broader pattern of nutrient overloading and poor aeration in tropical aquaculture.

CONCLUSION

This study provides a rapid analysis designed to characterize preliminary baseline knowledge of soil and water quality in agriculture and aquaculture systems in Keerom Regency, Papua. The results reveal pronounced soil acidification (pH 6.5 to 4.4), declining EC, severe macronutrient depletion, and undetectable potassium in chili cultivation soils—patterns consistent with the strong fertility constraints of highly weathered tropical soils. Conversely, aquaculture ponds exhibited critically low dissolved oxygen alongside elevated ammonium and phosphate, reflecting organic overloading and limited nitrification efficiency.

Although the two systems are managed independently, their contrasting nutrient dynamics highlight the potential benefits of integrated agriculture–aquaculture (IAA) approaches. Recycling nutrient-rich pond water for irrigation and utilizing crop residues within aquaculture could enhance nutrient cycling, improve resource-use efficiency, and reduce environmental stress.

As this assessment represents an initial rapid diagnostic, broader and more detailed spatial studies are urgently needed. Comprehensive mapping of soil fertility, water quality, and land suitability will be essential for generating effective and efficient land-use recommendations and for ensuring that agricultural expansion does not encroach upon or degrade primary or intact forest ecosystems.

Overall, these findings establish an essential early foundation for site-specific nutrient management, water-quality improvement, and the development of sustainable, climate-adaptive food systems aligned with Indonesia's national food-security priorities.

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