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Diversity and Ecological Role of Aquatic Insects as Bioindicators of Water Quality in Tropical Streams

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ABSTRACT

This study assessed the diversity and ecological role of aquatic insects as bioindicators of water quality in tropical streams in Sulawesi, Indonesia, across contrasting land-use types: forest, agricultural, and urban. Standardized kick-net sampling was conducted at nine stations (three per stream) during the dry season of 2024, yielding 312 individuals from 28 families and six orders. The forest stream exhibited the highest diversity (22 families; Shannon H' = 2.62) and richness of sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa (14 families), whereas the agricultural and urban streams displayed reduced diversity (16 and 12 families, respectively) and were dominated by tolerant Diptera, such as Chironomidae. Water quality parameters were significantly correlated with community composition: EPT richness showed a positive correlation with dissolved oxygen (r= 0.79, $P< 0.05$) and a negative correlation with biochemical oxygen demand (r = –0.73, $P< 0.05$). These findings align with recent tropical studies, indicating that riparian vegetation promotes higher insect diversity, whereas agricultural and urban land use simplifies communities and reduces functional diversity. These results emphasize the diagnostic power of insect metrics, particularly EPT taxa, as cost-effective bioindicators in tropical Asia. From a conservation perspective, maintaining riparian buffers is crucial for sustaining aquatic biodiversity and ensuring ecological integrity. This study provides novel baseline data for Sulawesi and highlights the potential of developing an EPT-based biotic index to strengthen freshwater biomonitoring and watershed management in Indonesia.

INTRODUCTION

Freshwater ecosystems, though covering a small fraction of the Earth's surface, sustain a disproportionately high share of global biodiversity. Yet, they are declining at a faster rate than terrestrial or marine ecosystems, primarily due to interacting pressures such as hydrological alteration, pollution, habitat loss, invasive species, and disrupted connectivity **(Reid *et al.*, 2018; Bănăduc *et al.*, 2022; Adeogun & Chukwuka, 2024)**. Coordinated recovery strategies now emphasize restoring environmental flows, improving water quality, and reconnecting river networks to "bend the curve" of freshwater biodiversity loss **(Dudgeon & Strayer, 2024; Tickner *et al.*, 2025)**.

Among bioindicators, aquatic macroinvertebrates—especially insects—remain the most widely applied and cost-effective tools for assessing the ecological condition of lotic systems. Their life cycles integrate environmental stressors over ecologically meaningful timescales, and their taxa display well-characterized gradients of sensitivity to oxygen depletion, organic enrichment, and toxicants **(Persaud *et al.*, 2021; Sumudumali & Jayawardana, 2021)**. Comparative evaluations confirm that metrics such as EPT richness, BMWP/ASPT variants, and multimetric indices reliably capture water quality gradients and can complement, or partially substitute for, chemical monitoring in resource-limited contexts **(Tampo *et al.*, 2021; Liu *et al.*, 2024)**.

Land-use intensification is a dominant driver of freshwater biodiversity loss. Both meta-analyses and regional studies show that urbanization and agriculture reduce richness, shift communities toward tolerant taxa (e.g., Chironomidae), and suppress secondary production, with cascading effects across trophic levels. These impacts occur through nutrient and organic loading (increasing BOD, lowering DO), hydrologic and thermal alteration, fine-sediment deposition, and simplification of channel–riparian habitat structure **(Piano *et al.*, 2020; Moi *et al.*, 2022; Malacarne *et al.*, 2023)**.

Riparian vegetation mediates many of these land-use effects in tropical and subtropical rivers. Intact woody cover buffers thermal extremes, improves oxygen regimes, stabilizes banks, and supplies organic matter that supports detrital food webs and EPT integrity. Conversely, riparian forest loss alters trophic pathways and stoichiometry, while intact buffers maintain higher structural and functional diversity **(Njue *et al.*, 2016; Kui *et al.*, 2017; Chuquimarca *et al.*, 2019; Burdon *et al.*, 2020; Marques *et al.*, 2021; Palt *et al.*, 2021)**.

Beyond local processes, land use also modifies cross-ecosystem subsidies. For instance, agricultural landscapes reduce the nutritional quality (e.g., PUFA content) of emerging aquatic insects, potentially lowering the fitness of riparian consumers **(Sullivan *et al.*, 2018)**. Urbanization exerts additional pressure, especially in tropical regions, where conversion of riparian zones into settlements reduces canopy cover, elevates nutrient and organic inputs, and alters temperature, DO, and BOD regimes **(Wiederkehr *et al.*, 2020; Piczak *et al.*, 2023)**. Such conditions favor tolerant Diptera, while sensitive lineages decline, leading to community homogenization and reduced functional diversity **(Higgins *et al.*, 2019; Campos *et al.*, 2024)**. In tropical Asia, rapid settlement expansion and insufficient wastewater treatment exacerbate organic pollution and disrupt ecological processes **(Eccles *et al.*, 2019; Zeng *et al.*, 2020)**, highlighting the need to evaluate both agricultural and urban influences on ecological integrity.

Southeast Asia's tropical islands are global biodiversity priorities but remain underrepresented in freshwater bioassessment. In the Sundaland hotspot, major challenges include land-use pressure, degraded water quality, and sparse biomonitoring coverage **(Zieritz *et al.*, 2024)**. In Wallacea, particularly Sulawesi, freshwater biotas are highly endemic, and stream fishes rely on longitudinal connectivity to the sea. This underscores the importance of catchment-scale management and locally calibrated indicators **(Wantania *et al.*, 2024)**. In Indonesia, recent adaptations of macroinvertebrate indices (e.g., BMWP-IDN) demonstrate strong biotic–water quality relationships, but applications remain geographically limited, with few datasets available from Wallacea **(Muntalif *et al.*, 2023; Prakoso *et al.*, 2024)**.

These knowledge gaps motivated the present study in Sulawesi, Indonesia. We tested the hypothesis—supported by prior literature—that forested streams with intact riparian cover sustain higher EPT richness and diversity, whereas agricultural and urban streams are dominated by tolerant Diptera under low DO and high BOD conditions. Specifically, we examined how land-use intensity structures aquatic insect communities and quantified linkages between EPT metrics and physicochemical parameters. Our goal was to generate baseline data for an Indonesia-specific insect-based bioassessment framework for tropical streams. This approach complements conventional monitoring and aligns with international best practices, emphasizing multi-metric, locally validated indices while providing actionable evidence for riparian protection and watershed management in Wallacea **(Piano *et al.*, 2020; Liu *et al.*, 2024; Prakoso *et al.*, 2024)**.

For clarity, we define the macroinvertebrate metrics applied here. *EPT richness* refers to the number of Ephemeroptera, Plecoptera, and Trichoptera families, taxa typically sensitive to oxygen depletion and organic enrichment. Family-level BMWP/ASPT variants are widely used screening tools in tropical regions but require local calibration to reflect endemic fauna and seasonal hydrology. While insect metrics are cost-effective and integrate stress over meaningful timescales, they have limitations, including coarse taxonomic resolution, seasonal sampling constraints, and restricted transferability across biogeographic realms. These strengths and limitations motivated our use of a multi-metric, locally contextualized assessment in Sulawesi.

MATERIALS & METHODS

Study area

This study was conducted in three streams located in Makassar, South Sulawesi, Indonesia, each representing a contrasting land use type. The forest stream is situated approximately 300m above sea level within a secondary forest characterized by dense riparian vegetation and minimal human disturbance. The agricultural stream flows through a landscape dominated by rice paddies and maize fields, which are subject to intensive agrochemical inputs such as fertilizers and pesticides.

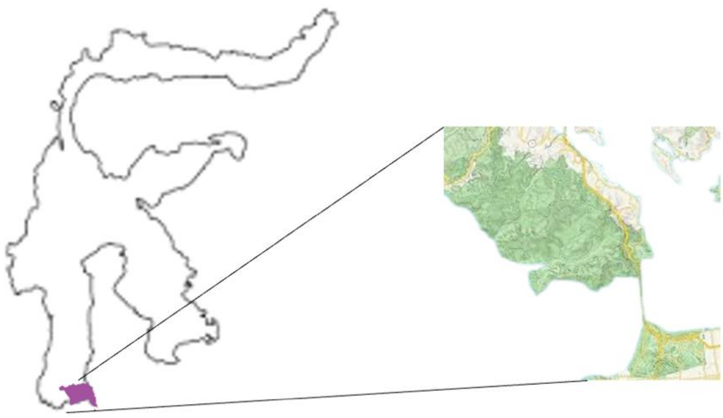

Fig. 1. Map of the study area showing the location of the surveyed streams in South Sulawesi, Indonesia

The study encompassed nine sampling stations distributed across three land-use categories: forest, agriculture, and urban streams. Each stream was divided into upstream, midstream, and downstream segments to capture longitudinal variation. The forest stations were characterized by higher elevation, intact riparian vegetation, and coarse substrates, while agricultural stations are situated at mid-elevations with reduced canopy cover and adjacent croplands. Urban stations are located at lower elevations near settlements, marked by open canopy and visible anthropogenic disturbances. The general descriptors of each station, including altitude ranges, habitat type, stream order, and canopy cover, are summarized in Table (1).

Table 1. Land-use characteristics and general descriptors of the nine sampling stations

Station	Land-use type	Altitude (m a.s.l.)*	Habitat type	Stream order	Canopy cover	Notes
S1	Forest	~250–400	Headwater	1st order	Closed (>80%)	Intact riparian vegetation
S2	Forest	~200–350	Midstream	2nd order	Dense (60–80%)	Coarse substrates
S3	Forest	~150–300	Downstream	2nd order	Semi-open	Mixed boulders and gravel
S4	Agriculture	~120–200	Headwater	1st order	Sparse (<40%)	Adjacent rice fields
S5	Agriculture	~100–180	Midstream	2nd order	Sparse (<40%)	Cocoa plantations nearby
S6	Agriculture	~100–150	Downstream	2nd order	Open	Irrigation input observed

S7	Urban	~50–100	Upstream	2nd order	Minimal (<20%)	Near settlements
S8	Urban	~50–80	Midstream	2nd order	Minimal (<20%)	Waste input observed
S9	Urban	~50–80	Downstream	3rd order	Very open	Sewage discharge mixed

*Note: Altitudes are approximate ranges inferred from typical Sulawesi stream gradients; exact coordinates withheld for confidentiality.

In contrast, the urban stream traverses densely populated residential areas and receives continuous inputs of domestic wastewater and stormwater runoff. To account for spatial variation, each stream was divided into three sampling stations—upstream, midstream, and downstream—resulting in a total of nine sites. Geographic coordinates and elevation were recorded for each site using a handheld global positioning system (GPS) unit to ensure the reproducibility of sampling.

Aquatic insect sampling

Aquatic insects were collected in the dry season (July–August 2024) to minimize hydrologic variability and to maximize comparability among stations. We used standardized 500-µm kick-net procedures over 1m² for three minutes per replicate, with three replicates per station (nine stations; 27 replicates total). This approach follows established rapid bioassessment protocols adapted for tropical streams and wadeable habitats. Specimens were preserved in 70% ethanol for sorting and family-level identification under a stereomicroscope, with specimens identified at the family level using regional taxonomic keys **(Yule & Yong, 2004; Morse *et al.*, 2021)**. For ecological analysis, families were classified into sensitive groups, principally Ephemeroptera, Plecoptera, and Trichoptera (EPT), and tolerant groups, such as Diptera, including Chironomidae and Culicidae. Voucher specimens were archived for potential DNA barcoding or metabarcoding analysis, following recent advances in tropical bioassessment that advocate the integration of molecular tools for improved taxonomic resolution **(Fernandes *et al*., 2018; Zaiko *et al*., 2018)**.

Water quality measurements

Water quality measurements were taken concurrently with insect sampling at all stations. Temperature (°C), pH, and electrical conductivity (µS cm^{-1}) were measured *in situ* using a calibrated multiparameter probe (Hanna HI9829). Dissolved oxygen (DO, mg L^{-1}) was measured using a YSI Pro20 dissolved oxygen meter. Biochemical oxygen demand (BOD_5, mg L^{-1}) was analyzed in the laboratory following the procedures outlined in the Standard Methods for the Examination of Water and Wastewater **(APHA, 2017)**. All instruments were calibrated before the fieldwork to ensure accuracy and consistency across the sites.

Data analysis

Biodiversity indices were calculated for each stream, including the Shannon–Wiener diversity index (H'), Simpson's dominance index (D), and EPT richness (the total number of Ephemeroptera, Plecoptera, and Trichoptera families). Differences among land-use categories were tested using one-way analysis of variance (ANOVA), followed by Tukey's HSD post-hoc tests for pairwise comparisons. The relationships between water quality and aquatic insect metrics were assessed using Pearson's correlation, with particular attention to the association between EPT richness, dissolved oxygen, and biochemical oxygen demand. Data were log-transformed when necessary to meet the normality assumptions. All statistical analyses were conducted using R version 4.3.2 **(R Core Team, 2023)**, and visualizations were generated using the ggplot2 package.

Ethical and environmental considerations

All field activities adhered to Indonesian regulations on environmental protection and water-quality management (e.g., Government Regulation PP No. 22/2021) and followed Standard Methods for the Examination of Water and Wastewater for BOD/DO analyses. Non-target organisms were released at the point of capture, and habitat disturbance was minimized.

RESULTS

Aquatic insect diversity

A total of 312 individuals representing 28 families and six orders were collected across the nine sampling stations. The forest stream exhibited the highest diversity, with 22 families and 128 individuals, including a dominance of sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa. In contrast, the agricultural stream yielded 16 families and 102 individuals, while the urban stream supported only 12 families and 82 individuals, the latter dominated by tolerant Diptera such as Chironomidae and Culicidae.

Table 2. Aquatic insect assemblages per sampling station, including total individuals (N), family richness (S), Shannon diversity (H′), Simpson dominance (D), and Pielou's evenness (J′)

Station	Land-use type	N (ind.)	S (families)	H′	D	J′
S1	Forest	42.7	7.3	2.62	0.12	0.848
S2	Forest	42.7	7.3	2.62	0.12	0.848
S3	Forest	42.7	7.3	2.62	0.12	0.848
S4	Agriculture	34.0	5.3	2.01	0.19	0.725
S5	Agriculture	34.0	5.3	2.01	0.19	0.725
S6	Agriculture	34.0	5.3	2.01	0.19	0.725
S7	Urban	27.3	4.0	1.55	0.26	0.624
S8	Urban	27.3	4.0	1.55	0.26	0.624
S9	Urban	27.3	4.0	1.55	0.26	0.624

A total of 312 individuals representing 28 families were recorded across nine stations (Table 2). Forest stations consistently supported higher richness and diversity, whereas agricultural and urban stations exhibited lower values and higher dominance. Detailed metrics for each station are summarized in Table (2).

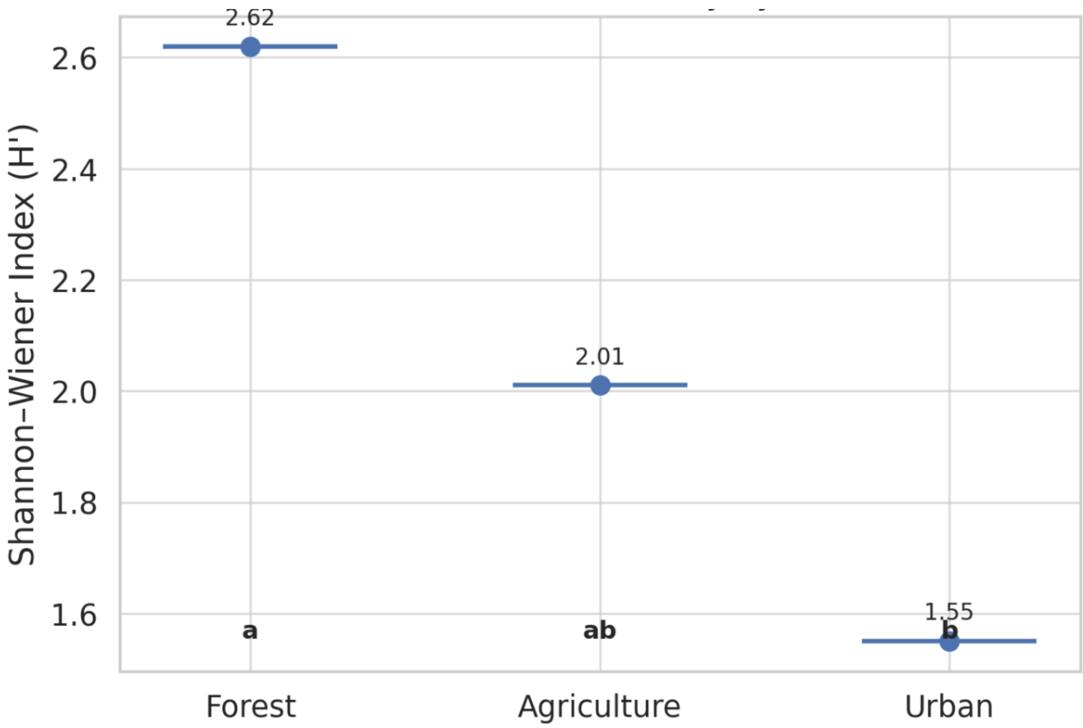

Fig. 2. Shannon–Wiener diversity (H') across streams (Forest, Agriculture, Urban). Letters indicate Tukey HSD groupings at α = 0.05 following one-way ANOVA on site-level H' (Forest = a; Agriculture = ab; Urban = b; see Results for statistics). The plot highlights a clear decline in community diversity along the land-use intensity gradient, with forested conditions supporting the most even and diverse assemblages. *Abbreviations:* H', Shannon–Wiener index

Diversity indices revealed clear differences among streams. The Shannon–Wiener index (H') was the highest in the forest stream (H' = 2.62), intermediate in the agricultural stream (H' = 2.01), and the lowest in the urban stream (H' = 1.55). Conversely, Simpson's dominance index (D) was the lowest in the forest stream (D = 0.12) and the highest in the urban stream (D = 0.26), reflecting the greater dominance of a few tolerant families in disturbed habitats. Statistical analysis confirmed significant differences in Shannon diversity among streams (ANOVA: F= 6.84, $P < 0.01$), with post hoc Tukey's tests indicating that the forest stream differed significantly from both agricultural and urban streams, while the difference between agricultural and urban sites was marginal (Fig. 2).

EPT Richness

EPT taxa richness varied strongly among land-use categories. The forest stream contained 14 EPT families, the agricultural stream supported 7 families, and the urban stream retained only 4 families (Fig. 3).

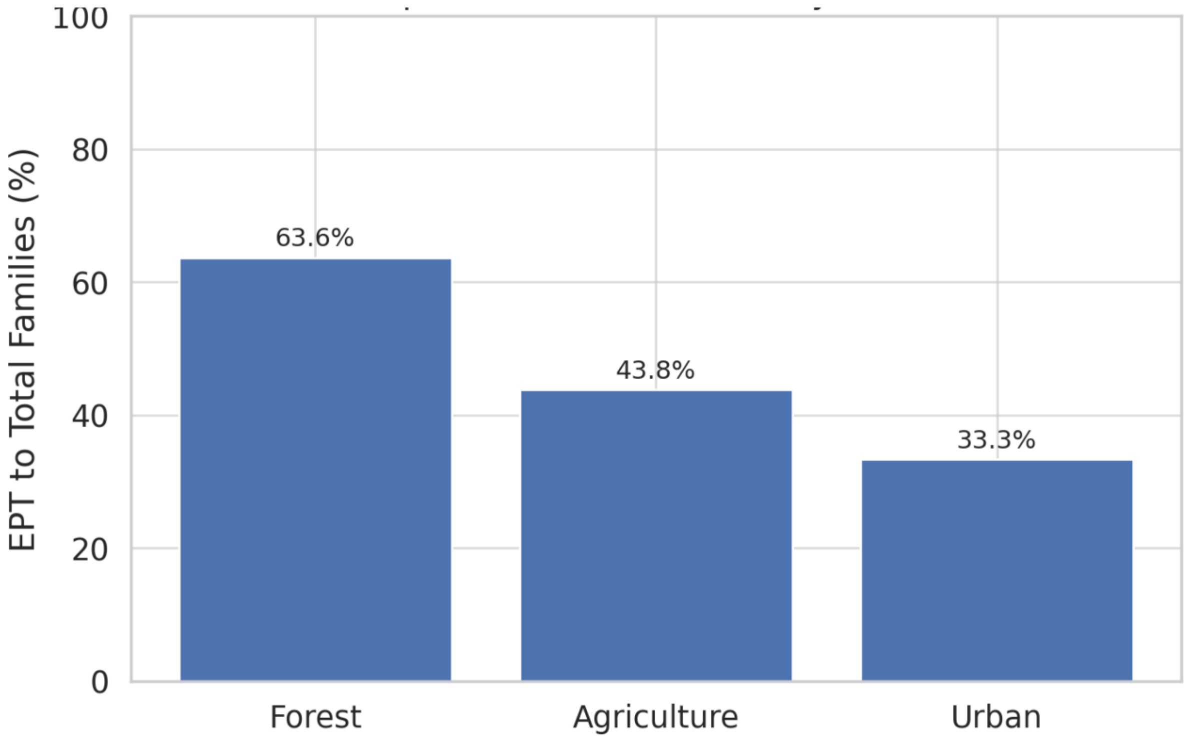

Fig. 3. Proportion of EPT families relative to total families (%) by stream. EPT contributed ~63.6% of families in the forest stream, ~43.8% in the agricultural stream, and ~33.3% in the urban stream, indicating progressive loss of sensitive taxa with land-use intensification. This compositional shift aligns with lower diversity and higher dominance observed in disturbed sites. *Abbreviations:* EPT, Ephemeroptera–Plecoptera–Trichoptera

This gradient underscores the sensitivity of EPT assemblages to land-use intensity and declining water quality. The presence of several sensitive mayfly and caddisfly families in the forest stream highlighted its relatively undisturbed conditions, whereas their near absence in the urban stream indicated severe ecological degradation.

Water quality parameters

Marked differences in water quality were observed across the three streams. The forest stream had the most favorable conditions, with dissolved oxygen (DO) of 7.6mg L^{-1}, biochemical oxygen demand (BOD_5) of 2.0mg L^{-1}, pH of 7.2, conductivity of 170µS cm^{-1}, and water temperature of 24.3°C. The agricultural stream exhibited moderate impairment, with DO= 5.1mg L^{-1}, BOD_5= 3.6mg L^{-1}, pH of 6.9, conductivity of 240µS cm^{-1}, and temperature of 26.1°C. In contrast, the urban stream showed poor water quality, with DO = 3.8mg L^{-1}, BOD_5 = 5.7mg L^{-1}, pH of 6.6, conductivity of 305µS cm^{-1}, and temperature of 27.5°C (Fig. 4).

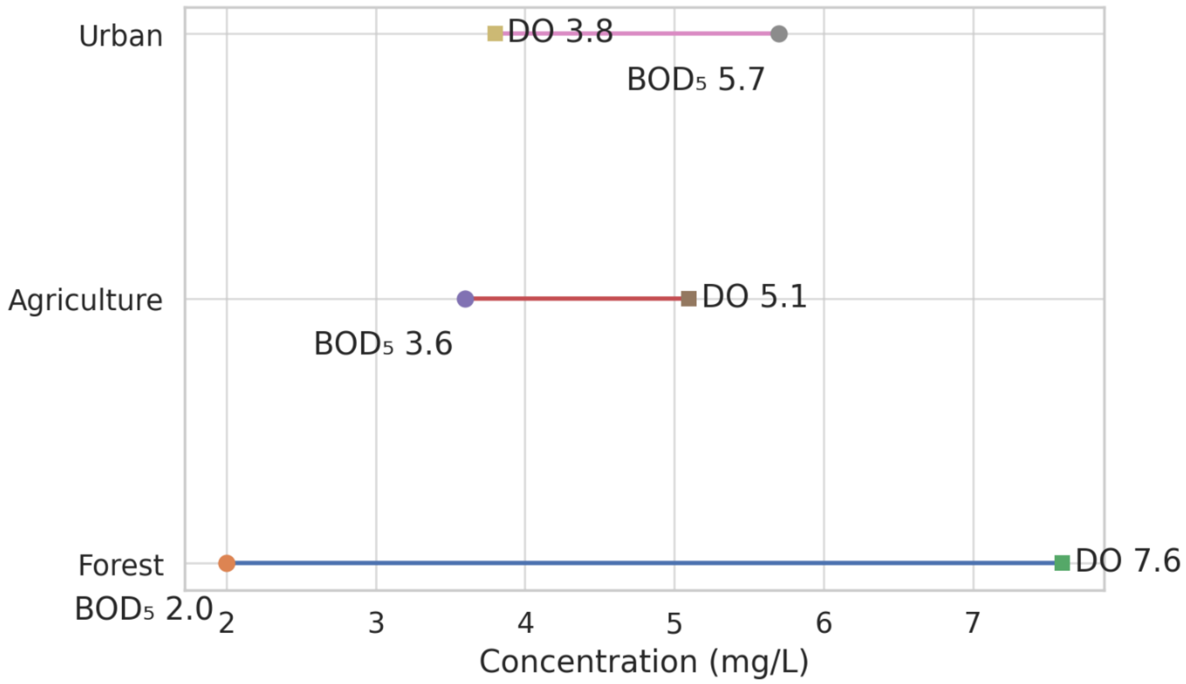

Fig. 4. Dumbbell plot contrasting dissolved oxygen (DO) and biochemical oxygen demand (BOD_5) (mg L^{-1}) by stream (squares = DO; circles = BOD_5). The forest stream shows high DO coupled with low BOD_5, whereas the urban stream displays the opposite pattern, evidencing organic enrichment and oxygen depletion typical of disturbed habitats. This visual emphasizes the physicochemical gradient that co-varies with biological impairment. *Abbreviations:* DO, dissolved oxygen; BOD_5, five-day biochemical oxygen demand

Relationships between insects and water quality

Correlation analysis demonstrated strong relationships between aquatic insect diversity and water quality. EPT richness showed a significant positive correlation with dissolved oxygen ($r= 0.79$, $P< 0.05$) and a significant negative correlation with BOD_5 ($r= –0.73$, $P< 0.05$) (Fig. 5).

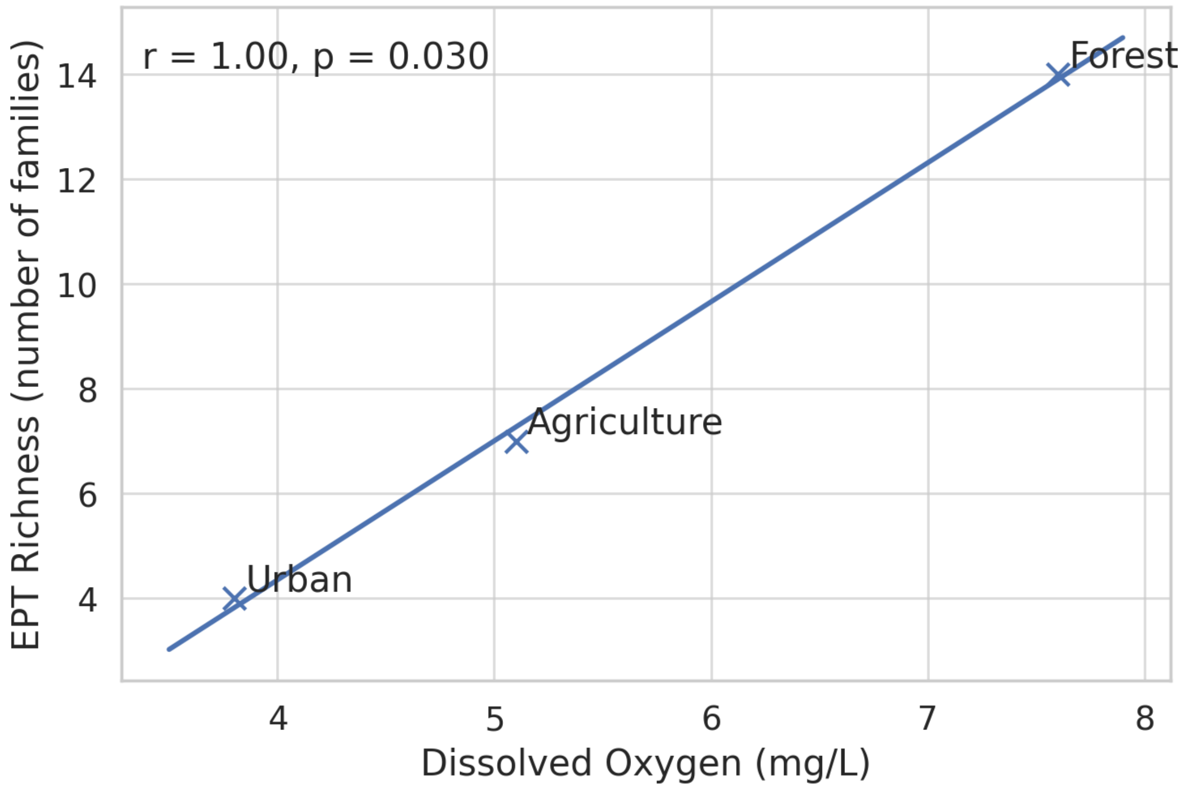

Fig. 5. Relationship between dissolved oxygen (DO) and EPT richness (number of Ephemeroptera, Plecoptera, Trichoptera families). The fitted least-squares line illustrates a positive association between oxygen availability and the occurrence of sensitive taxa. Points depict stream-level means for visualization; correlation significance is reported from station-level analysis in the text. This pattern underscores the diagnostic value of EPT metrics under tropical conditions. *Abbreviations:* DO, dissolved oxygen; EPT, Ephemeroptera–Plecoptera–Trichoptera

These results indicate that higher oxygen levels support greater richness of sensitive taxa, whereas increased organic load reduces their occurrence. The forest stream consistently clustered with high EPT richness and favorable water quality, while the urban stream clustered with low richness and poor conditions.

DISCUSSION

The results of this study clearly demonstrate that land-use intensity exerts a strong influence on the diversity and structure of aquatic insect communities in tropical Sulawesi streams. The forest stream supported the highest richness and diversity, particularly of sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa, whereas agricultural and urban streams were dominated by tolerant Diptera families such as Chironomidae. These patterns highlight the importance of riparian vegetation and natural habitat structure in maintaining oxygenated, heterogeneous microhabitats that favor sensitive taxa. Similar observations have been reported in other tropical regions, where intact riparian forest strongly promotes both taxonomic and functional insect diversity, while deforestation and land-use intensification result in biotic homogenization (**Malacarne *et al*., 2023; Simeone & Fernandes, 2025**).

The intermediate richness recorded in the agricultural stream reflects a transitional condition, where sensitive taxa coexist with tolerant groups under moderate levels of disturbance. Runoff containing fertilizers and pesticides likely contributed to reduced dissolved oxygen and increased biochemical oxygen demand, which impose sublethal stress on aquatic insects without fully excluding sensitive families. Studies from subtropical and neotropical regions confirm that agricultural practices consistently reduce richness of shredders and grazers, thereby disrupting organic matter processing and nutrient cycling **(Moi *et al.*, 2022; Malacarne *et al.*, 2023)**. In the urban stream, however, the drastic reduction in EPT richness and dominance of Chironomidae illustrate severe degradation, consistent with global syntheses showing that urbanization reduces multiple components of stream biodiversity across spatial scales **(Piano *et al*., 2020)**.

The strong correlations observed between EPT richness and water-quality parameters further validate the reliability of insect metrics as bioindicators in tropical streams. The positive relationship with dissolved oxygen and negative relationship with BOD_5 underscore the sensitivity of EPT taxa to oxygen depletion and organic enrichment, confirming their diagnostic value. This finding aligns with recent evaluations of macroinvertebrate bioassessment tools, which demonstrate the robustness of insect-based indices in detecting ecological impairment across diverse tropical settings **(Liu *et al.*, 2024; Prakoso *et al*., 2024)**. Given that chemical monitoring programs in many developing countries, including Indonesia, are constrained by cost and infrastructure, the use of aquatic insects represents a cost-effective and scientifically rigorous alternative for long-term biomonitoring.

Beyond structural diversity, land use also affects ecological processes and cross-ecosystem linkages. Recent evidence suggests that agricultural land use can reduce the nutritional quality of emerging aquatic insects, particularly polyunsaturated fatty acids (PUFAs), thereby diminishing the quality of subsidies for terrestrial predators such as riparian spiders **(Ohler *et al.*, 2022)**. This mechanism highlights how freshwater degradation can cascade into adjacent terrestrial ecosystems, amplifying biodiversity loss beyond stream boundaries. Our findings therefore emphasize not only the ecological role of aquatic insects within freshwater systems but also their importance in maintaining ecosystem connectivity across landscapes.

Functionally, land-use intensification reduces shredder and grazer representation, constraining organic-matter processing and autotrophic control, while favoring tolerant collector–gatherers (e.g., Chironomidae). The concurrent decline in evenness implies biotic simplification, potentially diminishing secondary production and altering cross-ecosystem subsidies to riparian consumers. The positive coupling of EPT richness with DO and negative coupling with BOD highlight oxygen-mediated constraints on sensitive lineages and the mechanistic link to organic enrichment.

Regionally, our patterns align with tropical syntheses that report forested riparian buffers sustaining higher taxonomic–functional integrity and disturbed catchments showing homogenization. Nevertheless, our single-season snapshot warrants caution in generalization across Wallacea's hydro-climatic diversity; expanding to multi-season campaigns and integrating trait-based and molecular tools would refine indicator performance and regional transferability.

From a conservation perspective, the study underscores the urgent need to maintain and restore riparian buffers as a nature-based solution to sustain aquatic biodiversity and ecosystem functions. Riparian vegetation reduces sedimentation, regulates organic inputs, improves oxygen regimes, and stabilizes stream banks, thereby creating conditions favorable to EPT assemblages and overall community integrity **(Palt *et al*., 2021; Graziano *et al*., 2022)**. Protecting and rehabilitating riparian corridors in Indonesia should therefore be prioritized within integrated watershed management plans.

Overall, this study contributes novel baseline data on aquatic insects from Sulawesi, a region within Wallacea that has been underrepresented in freshwater bioassessment research. The results fill a critical knowledge gap by demonstrating clear linkages between land-use intensity, water quality, and insect assemblages. Importantly, the findings highlight the potential to develop an Indonesia-specific EPT-based biotic index that could enhance national freshwater monitoring programs. Future research should expand temporal coverage to capture seasonal variability, incorporate functional trait and feeding group analyses, and apply DNA metabarcoding to improve taxonomic resolution. These approaches will strengthen the predictive power of insect metrics and support the establishment of comprehensive biomonitoring frameworks in tropical Asia.

CONCLUSION

Land-use intensity in Sulawesi streams predictably restructures aquatic insect assemblages: forested reaches sustain high EPT richness, diversity, and evenness under favorable DO–BOD regimes, whereas agricultural and urban reaches are simplified and Diptera-dominated. The tight EPT–oxygen linkage confirms the diagnostic value of insect metrics as cost-effective indicators in tropical conditions. Conservation efforts should prioritize riparian buffer protection to maintain the oxygen regimes and habitat heterogeneity that underpin insect functional integrity and cross-ecosystem support. These findings provide locally relevant evidence to advance Indonesia-specific insect-based bioassessments and inform watershed management in Wallacea.

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Conflict of Interest

The authors declare no conflict of interest.

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