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AQUATIC INSECT COMMUNITIES AND FUNCTIONAL FEEDING GROUPS AS INDICATORS OF ECOSYSTEM HEALTH IN TROPICAL VIETNAM STREAMS

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ABSTRACT

This study examined aquatic insect diversity, functional feeding organization, and ecosystem function across three stream environments in tropical northern Vietnam: forest-associated (FSE), agriculture-associated (ASE), and residential streams (RSE). A total of 104 species from 90 genera and 45 families were recorded, with significantly higher richness and diversity in FSE ($d: 4.5 \pm 0.5$; $H': 2.7 \pm 0.1$) compared with ASE ($d: 3.5 \pm 0.6$; $H': 2.4 \pm 0.1$) and RSE ($d: 2.6 \pm 0.4$; $H': 2.0 \pm 0.3$) ($P < 0.05$). Functional Feeding Group (FFG) composition varied greatly among environments: scrapers dominated in FSE (29.4%), collector-filterers in ASE (22.2%), and collector-gatherers in RSE (45.4%). Functional indices also showed clear gradients, with higher P/R and substrate stability in FSE, elevated TFPOM/BFPOM in ASE, and the highest predator ratios in RSE. These patterns closely corresponded with environmental parameters such as DO, turbidity, and organic load. The results demonstrate the strong diagnostic power of FFGs for detecting ecological change and emphasize their value for bioassessment and stream management in tropical regions.

Keywords: Aquatic insects; functional feeding groups; stream ecology; ecosystem function; Vietnam

ABSTRAK

Kajian ini meneliti kepelbagaian serangga akuatik, organisasi kumpulan pemakanan fungsian (FFG) dan fungsi ekosistem merentasi tiga jenis persekitaran sungai di kawasan tropika utara Vietnam: sungai berasosiasi hutan (FSE), sungai berasosiasi pertanian (ASE) dan sungai kawasan kediaman (RSE). Sebanyak 104 spesies daripada 90 genus dan 45 famili telah direkodkan, dengan kekayaan dan kepelbagaian yang jauh lebih tinggi di FSE ($d: 4.5 \pm 0.5$; $H': 2.7 \pm 0.1$), berbanding ASE ($d: 3.5 \pm 0.6$; $H': 2.4 \pm 0.1$) dan RSE ($d: 2.6 \pm 0.4$; $H': 2.0 \pm 0.3$) ($P < 0.05$). Komposisi FFG berbeza dengan ketara antara persekitaran: pengikis mendominasi di FSE (29.4%), penapis-pengumpul di ASE (22.2%) dan pengumpul-penggali di RSE (45.4%). Indeks fungsian turut menunjukkan kecerunan yang jelas, dengan nilai P/R dan kestabilan substrat yang lebih tinggi di FSE, peningkatan TFPOM/BFPOM di ASE, serta nisbah pemangsa tertinggi di RSE. Corak ini menunjukkan hubungan rapat dengan parameter persekitaran seperti DO, kekeruhan dan beban organik. Dapatan ini mengesahkan kuasa

diagnostik FFG dalam mengesan perubahan ekologi dan menekankan kepentingannya untuk bio-penilaian dan pengurusan sungai di kawasan tropika.

Kata kunci: Serangga akuatik; kumpulan pemakanan fungsian; ekologi sungai; fungsi ekosistem; Vietnam

INTRODUCTION

Tropical stream ecosystems host diverse aquatic insect assemblages that play integral roles in organic-matter processing, nutrient cycling, and energy transfer within freshwater food webs (Ramírez & Gutiérrez-Fonseca 2014). Because aquatic insects respond sensitively to changes in hydrology, substrate composition, riparian structure, and human disturbance, they are widely used as biological indicators in stream bioassessment (Camara et al. 2020; Thanee & Phalaraksh 2012; Ahmad & Suhaimi 2024). Beyond traditional taxonomic approaches, functional trait-based methods, particularly those involving Functional Feeding Groups (FFGs) have become increasingly important for evaluating ecological conditions. FFGs classify macroinvertebrates based on morphological and behavioral traits associated with feeding, linking benthic community structure to ecological processes such as resource availability, energy pathways, and trophic interactions (Merritt et al. 2008).

Studies across tropical and subtropical regions have shown that the structure of FFGs varies consistently among different stream environments shaped by surrounding landscape conditions. Forest-associated stream environments, with high canopy cover, coarse substrates, and abundant allochthonous inputs, typically support higher proportions of shredders and scrapers and maintain more stable trophic structures (Bui et al. 2015; Masese et al. 2014). In contrast, agriculture-associated stream environments frequently experience elevated sedimentation, nutrient runoff, and substrate disturbance from cultivation practices, resulting in increased dominance of collector-gatherers and filterers (Camara et al. 2020; Ilmi et al. 2023). Residential stream environments often exhibit organic pollution, altered riparian vegetation, and unstable substrates, leading to simplified communities dominated by tolerant taxa and reduced functional diversity (Liu et al. 2024; Zhang et al. 2024). These patterns have been documented in regions such as Morocco (El Yaagoubi et al. 2023), Kenya (Masese et al. 2023), South Africa (Guellaf & Kettani 2025), Brazil (Pastorino et al. 2020), and Thailand (Thanee & Phalaraksh 2012), underscoring the diagnostic value of FFGs in detecting ecological degradation.

Despite such international progress, research on functional feeding ecology in Vietnam remains limited. Existing Vietnamese studies have primarily focused on FFG composition (Bui et al. 2025; Hoang & Bae 2006; Nguyen & Duong 2025), while relatively few have examined the functional organization of aquatic insects. More importantly, there is a notable lack of studies comparing different stream environments-forest-associated, agriculture-associated, and residential stream environments-within the same watershed. As tropical streams in Vietnam are increasingly affected by agricultural practices, sediment enrichment, riparian alteration, and domestic activities, understanding how these environmental contexts shape both community structure and functional feeding mechanisms is essential. This gap is especially important because FFGs have been shown to provide early and sensitive indicators of ecological stress, even where taxonomic resolution is limited (Ohler et al. 2024; Zhang et al. 2023).

This study addresses these gaps by examining aquatic insect communities and functional feeding groups across three distinct tropical stream environments: (1) forest-

associated streams, (2) agriculture-associated streams, and (3) residential stream environments. By integrating taxonomic and functional approaches, the study evaluates how differences in surrounding environmental conditions influence community structure, FFG composition, and indicators of ecological health. Emphasis is placed on shifts in key FFGs such as scrapers, shredders, and collector-gatherers as functional signatures of habitat quality and anthropogenic disturbance. This research contributes one of the few comprehensive assessments of FFGs in tropical Vietnam and provides valuable insights for freshwater biodiversity conservation and ecological management in rapidly changing Southeast Asian landscapes.

MATERIALS AND METHODS

Study Area

This study was conducted at streams in Xuan Hoa ward, Phu Tho province located in northern Vietnam, where streams flow through three contrasting stream environments defined by the characteristics of the surrounding landscape: (1) Forest-associated Stream Environments (FSE), (2) Agriculture-associated Stream Environments (ASE), and (3) Residential Stream Environments (RSE) (Table 1).

Table 1. Location of 12 study sites in the study area

Stream Code	Location	Altitude (m)	Canopy (%)	Category
St1	21°23'40.7" N; 105°42'59.9" E	136	95	FSE
St2	21°23'49.7" N; 105°42'56.6" E	128	80	FSE
St3	21°23'57.3" N; 105°42'52.6" E	117	85	FSE
St4	21°23'37.0" N; 105°42'52.3" E	104	90	FSE
St5	21°22'53.5" N; 105°43'36.5" E	48	0	ASE
St6	21°21'05.8" N; 105°45'17.3" E	37	1	ASE
St7	21°22'34.9" N; 105°43'14.4" E	35	0	ASE
St8	21°18'21.1" N; 105°43'53.3" E	22	0	ASE
St9	21°18'17.8" N; 105°44'53.0" E	25	10	RSE
St10	21°19'03.1" N; 105°44'18.0" E	23	7	RSE
St11	21°18'13.9" N; 105°44'11.8" E	19	8	RSE
St12	21°17'51.4" N; 105°43'43.6" E	18	5	RSE

General characteristics of the streams are as follows:

FSE: These streams are located within natural forest areas, with primary forest on both sides and a high canopy cover (80%-95%). Stream width ranges from 3 m to 7 m. The streambed is mainly composed of cobbles and large gravel, occasionally with boulders, and sometimes small gravel and sand. Riparian soils are typically hard and compact, and the streams have a low gradient.

ASE: These streams flow through agricultural lands, with cultivated fields on both sides or with a field on one side and a footpath on the other. Canopy cover is extremely low (0%-1%). Stream width ranges from 2.5 m to 4.5 m. The streambed is dominated by small gravel, sand, and silt, while the banks consist of soft soil. The streams have a low gradient and slow flow velocity.

The streambed is also disturbed due to activities of local residents. These streams play an important role in supplying water for local agricultural production.

RSE: These streams flow through residential areas, with houses located along both banks. Canopy cover ranges from 5% to 10%. Stream width ranges from 3 m to 5 m. The streambed mainly consists of cobbles and large gravel, as well as small gravel and sand. Signs of organic pollution are evident due to intensive anthropogenic activities associated with daily household use. The streambed is disturbed.

Aquatic Insects Sampling

Aquatic insects were sampled at 12 sampling sites in January and February 2025. The study included three stream environment types: FSE, ASE, and RSE. For each environment type, two streams were selected, and two sampling sites were established within each stream, resulting in four sampling sites per environment type and 12 sampling sites in total.

Sampling was conducted twice at each site, once in January 2025 and once again in February 2025. At each sampling site, field sampling lasted approximately 60 minutes per sampling occasion. The sampling procedures followed the methods described by McCafferty (1983), Merritt and Cummins (1996), Nguyen (2003), and Nguyen et al. (2004).

Qualitative samples were collected using a pond net and a hand net to obtain additional taxa present in the sampling area. Quantitative sampling was conducted using a Surber net (200 μ m mesh size, 0.3 \times 0.3 m sampling frame). During each sampling occasion, two quantitative samples were collected at each site: one from riffle habitat and one from pool or slow-moving habitat. Each quantitative sample was collected within the full 0.3 \times 0.3 m Surber frame and required approximately five minutes. Thus, a total of 48 quantitative samples were obtained for the study, including 16 samples from each stream environment type. Substrate composition at each sampling site was characterized qualitatively based on field observations, following the substrate categories described by Hauer and Lamberti (1996). Dominant substrate types were recorded descriptively rather than quantified as percentage cover.

Sample Preservation and Identification

After collection, debris and excess sediment were removed. Because aquatic insect larvae often have delicate, soft bodies that are easily damaged, samples were handled gently in the field, and organisms were carefully picked out immediately after collection. All field samples were preserved in 70% ethanol, properly labeled, and transported to the Laboratory of Zoology, Hanoi Pedagogical University 2, Vietnam for storage, examination, and taxonomic identification. Specimens were identified based on external morphological characteristics using the keys and references (Cao 2008; Hoang 2005; Jacobus & McCafferty 2008; McCafferty 1983; Merritt & Cummins 1996; Morse et al. 1994; Nguyen 2003; Yule et al. 2004).

Functional Feeding Groups

Each taxon was assigned to a functional feeding group: Shredders (sh), scrapers (sc), collector-gatherers (c-g), collector-filterers (c-f), predators (p) based on Merritt and Cummins (1996). Taxa with mixed feeding behaviors were classified according to their dominant feeding mode.

Physico-chemical Analysis

Before sampling, the geographic coordinates and elevation of each site were recorded using a Garmin GPS unit. WT (Water temperature, $^{\circ}$ C), pH, DO (Dissolved Oxygen, mg/l), EC (Electrical Conductivity, mS/cm), and Turb (Turbidity, NTU) were measured *in situ* at the

sampling sites with a multi-parameter water quality meter (WQC-22A, TOA, Japan). Biochemical Oxygen Demand (BOD₅) and Chemical Oxygen Demand (COD) were analyzed in the laboratory using specialized analytical instruments: BOD Trak II (Hach) for BOD₅ and DRB 200 (Hach) for COD.

Biological and Functional Metrics

Species richness (S), abundance (N), Shannon diversity index (H'), and Margalef richness index (d) were calculated for each sampling site based on the quantitative samples (Hammer et al. 2001). The relative abundance of each FFG (%) and the FFG ratios are also used as indicators of stream ecological attributes (Cummins et al. 2005) (Table 2).

Table 2. Computed FFG ratios were applied as proxies for stream ecosystem function

Ecosystem Attributes	Symbols	FFG Ratios for Attributes	General Criteria Ratio Levels
Autotrophy to heterotrophy index	P/R	sc/(shredders+total collectors)	Autotrophic>0.75
Coarse particulate organic matter (CPOM) to fine particulate organic matter (FPOM) index	CPOM/FPOM	sh/total collectors	Shredder (sh) association with functioning riparian area >0.25
FPOM in transport (suspended) to FPOM storage in sediments	TFPOM/BFPOM	c-f/c-g	FPOM transpor>0.50
Substrate (Channel) stability	Channel Stability (CS)	(sc+c-f)/(sh+c-g)	Stable substrates plentiful>0.50
Predator-prey ratio	Pr	Predators to total all other groups	Typical predators-to-prey balance (0.10-0.20)

Statistical Analysis

Descriptive statistics, including means and standard deviations (SD), were calculated using Microsoft Excel 2017. Differences among stream environment types were evaluated using t-tests (α = 0.05). Diversity indices, including Shannon diversity index (H') and Margalef richness index (d), were calculated using PRIMER v6 (PRIMER-E Ltd., UK). Principal Component Analysis (PCA) was conducted using the R statistical program to identify the environmental variables that most strongly explained variation among sampling sites.

RESULTS

Structure and Biodiversity of Aquatic Insects

A total of 104 species, belonging to 90 genera and 45 families, were recorded across the study area (Table 3). The orders Ephemeroptera, Odonata, and Trichoptera constituted the dominant components of the aquatic insect fauna, together accounting for more than 72% of the total species richness. Ephemeroptera was the most diverse group, contributing 31 species (29.8%), followed by Odonata with 26 species (25.0%), and Trichoptera with 19 species (18.3%). Coleoptera, Hemiptera, and Diptera were moderately represented, each contributing between 6-8% of the total richness. Orders with minimal representation included Plecoptera, Megaloptera, and Lepidoptera, each with 1-3 species. This taxonomic pattern is consistent with typical tropical stream assemblages, where Ephemeroptera, Odonata, and Trichoptera dominate due to their broad ecological tolerance and high specialization in riffle microhabitats.

Table 3. Taxonomic composition of aquatic insects in the study area

Order	Families		Genera		Species	
	Number	%	Number	%	Number	%
Ephemeroptera	6	13.3	21	23.3	31	29.8
Odonata	11	24.4	26	28.9	26	25.0
Plecoptera	1	2.2	3	3.3	3	2.9
Hemiptera	5	11.1	7	7.8	7	6.7
Coleoptera	5	11.1	8	8.9	8	7.7
Megaloptera	1	2.2	2	2.2	2	1.9
Diptera	4	8.9	6	6.7	7	6.7
Trichoptera	11	24.4	1	1.1	19	18.3
Lepidoptera	1	2.2	16	17.8	1	1.0
Total	45	100	90	100	104	100

Across the three stream environments (FSE, ASE, and RSE), a total of 85, 64, and 68 species were recorded, respectively (Table 4). Species richness was highest in FSE, accounting (85 species) for 81.7% of all recorded taxa, reflecting the high habitat heterogeneity, stable substrates, and intact riparian canopy characteristic of these environments. Trichoptera (18.8%), Ephemeroptera (31.8%), and Odonata (24.7%) were particularly well represented in FSE. The presence of Plecoptera and Megaloptera, groups typically associated with cool, well-oxygenated, and structurally complex habitats, further indicates the high ecological integrity of forest streams.

Table 4. Taxonomic composition of aquatic insects recorded across the three stream environments (FSE, ASE, RSE)

Order	FSE		ASE		RSE	
	Species	%	Species	%	Species	%
Ephemeroptera	27	31.8	21	32.8	18	26.5
Odonata	21	24.7	15	23.4	15	22.1
Plecoptera	3	3.5	1	1.6	2	2.9
Hemiptera	6	7.1	5	7.8	6	8.8
Coleoptera	6	7.1	4	6.3	7	10.3
Megaloptera	2	2.4	2	3.1	0	0.0
Diptera	4	4.7	5	7.8	6	8.8
Trichoptera	16	18.8	10	15.6	13	19.1
Lepidoptera	0	0.0	1	1.6	1	1.5
Total	85	100	64	100	68	100

The ASE supported the lowest species richness (64 species), likely reflecting substrate disturbance, elevated fine sediments, and reduced canopy cover associated with rice-field landscapes. Despite this reduction, Ephemeroptera (32.8%) and Odonata (23.4%) remained

dominant, though with fewer sensitive taxa. The relatively high proportion of Diptera (7.8%) and moderate presence of Hemiptera (7.8%) suggest greater ecological stress and habitat simplification in these environments.

In RSE, species richness increased slightly compared to ASE, with 68 species recorded. This assemblage was marked by a strong representation of Trichoptera (19.1%) and a notable increase in Coleoptera (10.3%) and Hemiptera (8.8%). These patterns may reflect a mixture of moderately stable microhabitats alongside organic enrichment and fine-sediment accumulation caused by domestic activities. The absence of Megaloptera and the low representation of Plecoptera in RSE indicate reduced habitat quality relative to FSE. Overall, RSE assemblages appear to represent a transitional state between the natural forest condition and the more heavily altered agricultural condition. Patterns of diversity were further reflected in the values of Margalef richness index (d) and Shannon diversity index (H') (Figure 1). Both indices showed a consistent decreasing trend from FSE \rightarrow ASE \rightarrow RSE. FSE exhibited the highest values (d : 4.5 ± 0.5 ; H' : 2.7 ± 0.1), significantly greater than those of ASE (d : 3.5 ± 0.6 ; H' : 2.4 ± 0.1) and RSE (d : 2.6 ± 0.4 ; H' : 2.0 ± 0.3) ($P < 0.05$).

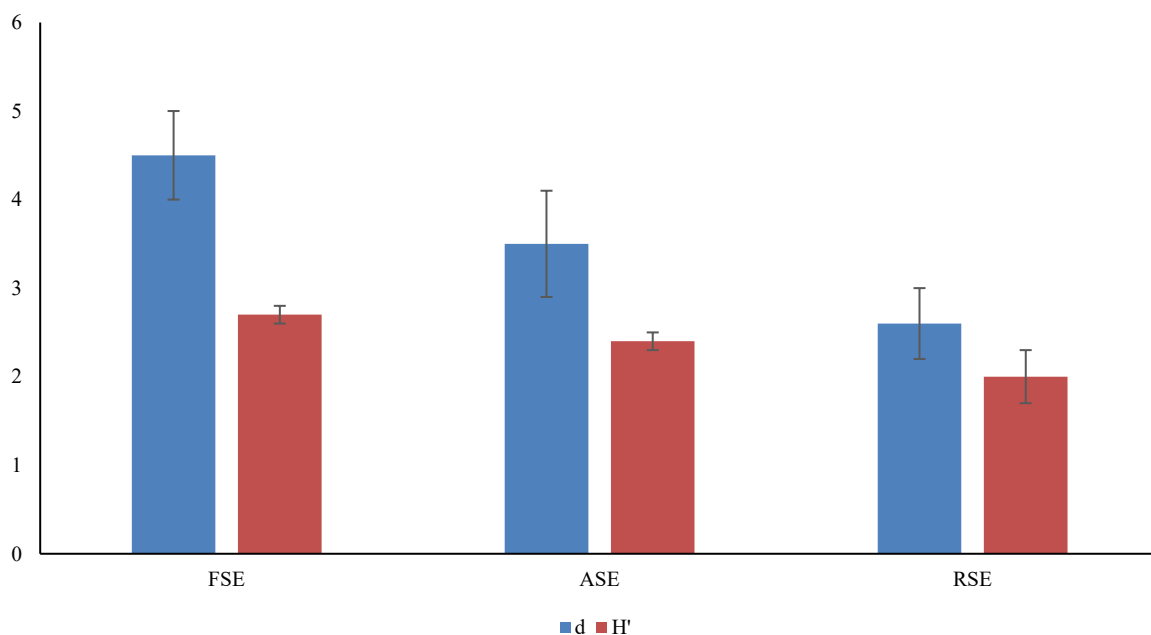


Figure 1. H' and d index of aquatic insects recorded across the FSE, ASE, RSE

These results indicate that FSE supports not only a larger number of species but also a more even distribution among taxa. Although ASE and RSE showed lower values, their diversity indices did not differ significantly from each other ($P > 0.05$), suggesting comparable levels of community simplification under agricultural and residential environmental conditions.

Collectively, these findings demonstrate a clear gradient in community structure and biodiversity, with FSE sustaining the highest richness and diversity, followed by RSE and ASE. The higher representation of sensitive taxa such as Ephemeroptera, Trichoptera, Plecoptera, and Megaloptera in FSE reflects superior ecological conditions, whereas shifts toward more tolerant groups in ASE and RSE indicate increasing anthropogenic influence. These patterns

provide a strong foundation for interpreting functional feeding group dynamics and assessing stream ecological health across the three stream environments.

FFG Composition

The composition of Functional Feeding Groups (FFGs) varied markedly among the three stream environments (Figure 2). Collector-gatherers (c-g) were the dominant group in all environments, but their relative abundance differed substantially. The highest proportion was recorded in RSE (45.4%), followed closely by FSE (43.8%), whereas ASE exhibited a considerably lower value (29.9%). The elevated abundance of c-g taxa in RSE indicates substantial accumulation of fine particulate organic matter (FPOM) associated with domestic waste inputs and substrate disturbance. In contrast, the reduced proportion of c-g in ASE likely reflects increased physical disturbance and sediment flushing associated with agricultural activities.

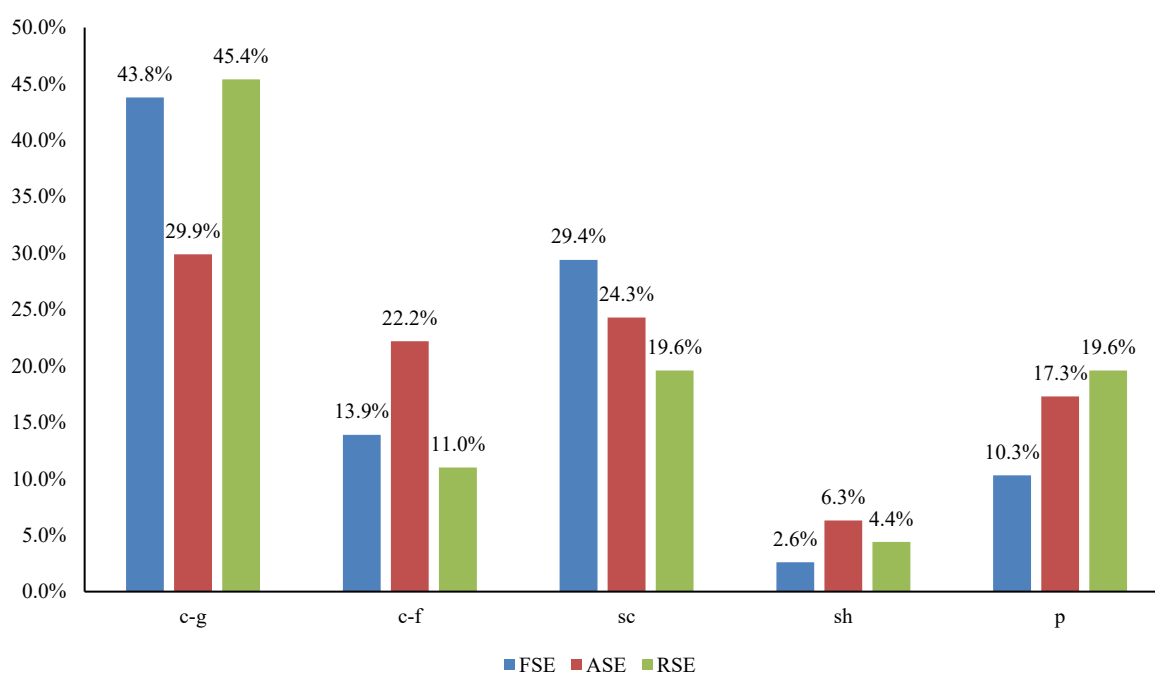


Figure 2. FFG composition of aquatic insects in the three stream environments

Collector-filterers (c-f) showed the greatest representation in ASE (22.2%), compared with only 13.9% in FSE and 11.0% in RSE. This pattern suggests that ASE conditions, characterized by slow flow, moderate turbidity, and elevated suspended particles, favor filter-feeding taxa. Scrapers (sc) were most abundant in FSE (29.4%), followed by ASE (24.3%) and RSE (19.6%). The high scraper proportion in FSE reflects stable coarse substrates and moderate periphyton development under partial canopy shading, whereas reductions in ASE and RSE indicate substrate instability and increased turbidity limiting periphyton growth.

Shredders (sh) constituted a minor component across all environments but exhibited distinct variation. Their relative abundance reached 6.3% in ASE, compared with 4.4% in RSE and only 2.6% in FSE. The low proportion in FSE corresponds with typical tropical patterns where warm temperatures accelerate leaf breakdown, reducing shredder dependence. The

moderate shredder representation in ASE may be linked to leaf litter inputs from scattered riparian vegetation along agricultural channels.

Predators (p) increased along the gradient from FSE (10.3%) to ASE (17.3%) and RSE (19.6%). Higher predator proportions in ASE and RSE suggest shifts in prey availability and greater dominance of tolerant taxa that often support opportunistic predatory assemblages typical of disturbed stream conditions.

FFG Ratios

FFG ratios revealed clear differences in functional ecological processes among the three stream environments (Figure 3).

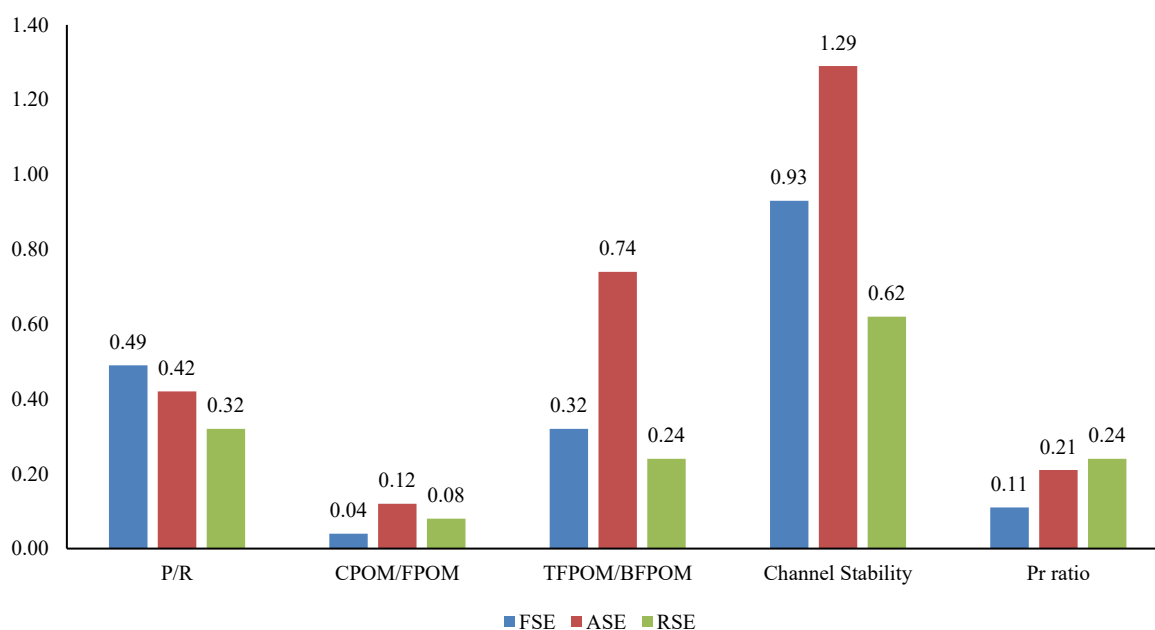


Figure 3. Functional feeding group ratios used as indicators of stream ecosystem function

The P/R ratio, reflecting the balance between autotrophic (scraper-based) and heterotrophic (detritus-based) production, decreased progressively from FSE (0.49) to ASE (0.42) and RSE (0.32). All values were below the autotrophy threshold (>0.75), indicating that all streams function primarily as heterotrophic systems, consistent with typical tropical headwater characteristics. The lowest P/R in RSE suggests reduced scraper contribution and greater reliance on detrital pathways under shaded or organically enriched conditions.

The CPOM/FPOM ratio was extremely low across all environments but showed a slight increase in ASE (0.12) and RSE (0.08) compared with FSE (0.04). Values far below the riparian-functioning threshold (>0.25) indicate limited coarse organic matter availability and low shredder abundance. This pattern aligns with the warm, fast-decaying leaf litter typical of tropical streams and the scarcity of riparian vegetation in agricultural and residential areas. Substantial differences were observed in the TFPOM/BFPOM ratio, which represents FPOM transport versus deposition. ASE exhibited a markedly higher value (0.74) compared with FSE (0.32) and RSE (0.24), indicating that the agricultural environment supports stronger

suspended FPOM transport, likely due to hydrological inputs from irrigation and sediment disturbance.

The Channel Stability Index (CS) showed the highest value in ASE (1.29), followed by FSE (0.93) and RSE (0.62). Although counterintuitive relative to natural conditions, the high ASE value reflects the dominance of filter-feeders and scrapers relative to gatherers and shredders, suggesting that portions of the agricultural channels maintain hydraulically stable microhabitats despite overall disturbance. The low RSE value (0.62) indicates notable substrate instability from domestic activities and organic deposition.

Finally, the Pr ratio increased markedly from FSE (0.11) to ASE (0.21) and RSE (0.24). Values above the reference range for natural streams (0.10-0.20) in ASE and RSE indicate intensified predator dominance and altered predator-prey dynamics, consistent with ecological stress and simplified food webs.

Functional Feeding Groups as Indicators of Ecosystem Function

Marked differences in environmental conditions among the three stream environments were reflected in the functional structure of aquatic insect assemblages (Table 5).

Table 5. Physicochemical parameters and ecological metrics

Sampling Site	S	N	d	H'	pH	DO	BOD ₅	COD	EC	Turb	WT	
FSE	St1	19	68	4.3	2.7	6.9	7.7	3.3	5.7	0.7	0.1	20.3
	St2	23	74	5.1	2.9	6.7	7.9	3.2	5.4	1.1	0.1	20.4
	St3	17	32	4.6	2.7	7.2	7.5	2.2	3.8	0.9	0.5	20.6
	St4	16	43	4.0	2.5	6.9	7.3	3.8	6.3	0.8	0.1	20.8
ASE	St5	14	58	3.2	2.5	6.8	7.1	1.5	3.9	0.9	0.8	21.3
	St6	12	18	3.8	2.4	6.9	6.8	3.4	6.4	0.8	0.9	21.7
	St7	16	39	4.1	2.4	6.5	6.5	4.1	9.8	0.9	1.3	21.5
	St8	12	59	2.7	2.3	6.8	6.5	5.5	11.3	1.1	1.9	21.6
RSE	St9	9	21	2.6	2.0	7.3	6.1	5.0	9.7	1.4	2.2	21.9
	St10	8	12	2.8	1.9	7.2	5.3	8.7	11.1	1.5	2.4	21.8
	St11	8	34	2.0	1.6	7.6	4.7	9.9	18.8	1.7	2.5	22.1
	St12	12	43	2.9	2.3	6.9	6.3	4.5	11.3	1.2	2.6	22.3

FSE exhibited the highest ecological quality, with elevated dissolved oxygen (DO: 7.3-7.9 mg/l), low turbidity (0.1-0.5 NTU), moderate conductivity (0.7-1.1 mS/cm), and comparatively low organic pollution (BOD₅: 2.2-3.8 mg/l; COD: 3.8-6.3 mg/l). These conditions corresponded with high species richness (S: 16-23), abundance (N: 32-74), and significantly higher values of d (4.0-5.1) and H' (2.5-2.9) compared with ASE and RSE ($P < 0.05$). Functionally, FSE was characterized by elevated proportions of scrapers (29.4%), reflecting stable coarse substrates and moderate periphyton development, and relatively low predator abundance (10.3%), indicating a balanced trophic structure (Figure 2). The corresponding P/R ratio (0.49) and moderate Channel Stability (0.93) (Figure 3) collectively indicate that FSE maintains a functionally intact heterotrophic system with stable substrate conditions and efficient energy transfer.

In contrast, ASE showed more variable physicochemical characteristics, including slightly lower DO (6.5-7.1 mg/l), higher turbidity (0.8-1.9 NTU), elevated BOD₅ (1.5-5.5 mg/l), COD (3.9-11.3 mg/l), and increased conductivity (0.8-1.1 mS/cm). These conditions were associated with reduced species richness (S: 12-16) and diversity (d: 2.7-4.1 and H': 2.3-2.5). The functional structure in ASE was dominated by collector-filterers (22.2%) and exhibited the highest TFPOM/BFPOM ratio (0.74), indicating strong fine particulate organic matter transport, likely driven by irrigation runoff and sediment disturbance. Shredders also exhibited their highest proportion in ASE (6.3%), consistent with moderate inputs of mixed leaf litter along agricultural channels. The elevated Pr ratio (0.21) reflects intensified predator dominance relative to prey, signaling a degree of food-web alteration typical of moderately disturbed systems.

RSE displayed the poorest water quality, with the lowest DO values (4.7-6.3 mg/l), highest turbidity (2.2-2.6 NTU), and markedly elevated COD (9.7-18.8 mg/l) and BOD₅ (4.5-9.9 mg/l). These sites also recorded the lowest diversity indices (d: 2.0-2.9 and H': 1.6-2.3) and moderate species richness (S: 8-12). Functionally, RSE assemblages were dominated by collector-gatherers (45.4%), reflecting substantial FPOM deposition and organic enrichment from domestic activities.

The PCA biplot provides an integrated visualization of the relationships among physicochemical variables, diversity indices, FFG composition, FFG ratios, and the distribution of sampling sites from St1 to St12 (Figure 4). The first two PCA axes explained 42.4% (Dim1) and 20.9% (Dim2) of total variation, capturing the major environmental and functional gradients among the three stream environments.

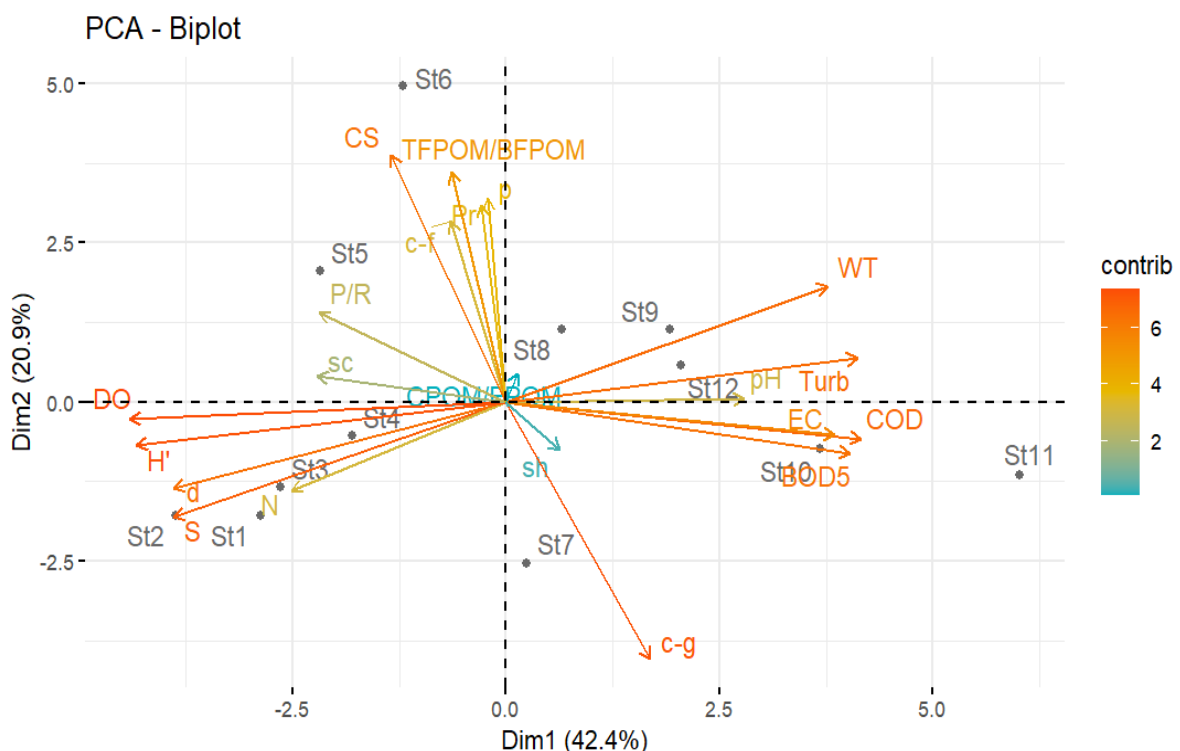


Figure 4. Principal Component Analysis (PCA) biplot illustrating the major environmental gradients and their associations with physicochemical parameters, diversity indices, FFG composition, FFG ratios, and sampling sites

Along Dim1, a clear gradient from high water quality to degraded conditions is evident. Sites St1-St4 cluster on the negative side of Dim1 and are strongly associated with dissolved oxygen (DO), higher diversity indices (H' and d), and moderate contributions from scrapers (sc) and the P/R ratio, reflecting the ecological integrity of forest-associated stream environments (FSE). These variables indicate stable substrates, low turbidity, and efficient energy pathways. In contrast, sites St9-St12, located on the positive side of Dim1, align with elevated turbidity (Turb), electrical conductivity (EC), COD, BOD₅, and water temperature (WT). This pattern is characteristic of residential stream environments (RSE) and reflects organic enrichment, substrate instability, and reduced oxygen availability.

Dim2 differentiates agricultural influences. Sites St5-St7 cluster positively along Dim2 and correlate strongly with TFPOM/BFPOM, collector-filterers (c-f), and the predator ratio (Pr). These associations suggest enhanced FPOM transport and trophic restructuring driven by agricultural runoff and disturbed hydrology in ASE. The weak association with DO and moderate pH values further supports their intermediate ecological status between FSE and RSE. The vectors for collector-gatherers (c-g) and shredders (sh) extend toward opposite quadrants, indicating contrasting ecological roles, with c-g linked to degraded RSE conditions and sh weakly associated with forested habitats.

DISCUSSION

The present study revealed clear and consistent differences in the taxonomic composition, biodiversity, functional feeding structure, and ecosystem functional attributes of aquatic insects among the three stream environments (FSE, ASE, and RSE). These differences highlight the sensitivity of both community-level metrics and functional trait-based indicators to environmental gradients shaped by forest cover, agricultural activity, and residential influences. The findings align with well-established ecological theory and corroborate patterns reported in tropical streams across Asia, Africa, and South America (El Yaagoubi et al. 2023; Masese et al. 2023; Ramírez & Gutiérrez-Fonseca 2014).

The strong representation of Ephemeroptera, Odonata, and Trichoptera (EOT) across all sites, and especially in FSE, is consistent with the dominance of these orders in tropical headwater streams characterized by stable substrata and well-oxygenated waters (Dudgeon 1999; Dudgeon 2008; Jarjees et al. 2019; Nguyen et al. 2024; Thanee & Phalaraksh 2012). The significantly higher richness and diversity indices (d and H') observed in FSE compared with ASE and RSE ($P < 0.05$) likely reflect the more favorable environmental conditions associated with intact riparian forest. These conditions include higher dissolved oxygen, lower turbidity, and the observed predominance of relatively coarse substrates such as cobbles and gravel in forest-associated stream sites. These observations align with previous research demonstrating that forested stream environments support greater habitat complexity, cooler temperatures, and more stable hydrological and substrate conditions, all of which promote high insect diversity (Bui et al. 2015; Li et al. 2024).

In contrast, the reduced richness and diversity observed in ASE and RSE indicate degraded ecological conditions. Agricultural streams often experience sedimentation, nutrient enrichment, and riparian degradation, leading to loss of sensitive taxa and declines in EPT richness (Addo-Bediako 2022; Camara et al. 2020; Ilmi et al. 2023; Taghinejad et al. 2017). Residential streams typically display organic pollution, unstable substrates, and altered hydrology, which further simplify community structure and favor tolerant taxa such as Hemiptera, Diptera, and certain Coleoptera (Liu et al. 2024; Zhang et al. 2024). The absence

of Megaloptera and low Plecoptera occurrence in RSE are particularly indicative of ecological stress, given the known sensitivity of these taxa to pollution and substrate disturbance.

FFG patterns provided deeper ecological insights beyond taxonomic data alone. The dominance of scrapers and moderate representation of collector-filterers in FSE indicate stable substrate conditions with sufficient periphyton and low turbidity. Similar trends have been documented in forested tropical streams in Kenya, Brazil, and Thailand (Leelahakriengkrai & Peerapornpisal 2011; Masese et al. 2014; Oliveira & Nessimian 2010; Pastorino et al. 2020). Conversely, the elevated proportion of collector-filterers in ASE reflects enhanced suspended FPOM transport, likely resulting from agricultural runoff and irrigation-driven hydrological fluctuations.

The strong dominance of collector-gatherers in RSE (45.4%) reflects heavy FPOM deposition associated with organic enrichment and low current velocity. This pattern has been widely described in urbanized and suburban tropical streams, where fine sediments and organic particulates accumulate due to domestic wastewater discharge and riparian degradation (El Yaagoubi et al. 2023; Guellaf & Kettani 2025).

Predator proportions (Pr) increased from FSE to RSE, which is consistent with functional simplification in disturbed systems. In such environments, tolerant prey taxa proliferate, supporting elevated predator abundance and altering natural predator-prey ratios (Masese et al. 2023). The sharp increase in Pr values in ASE (0.21) and RSE (0.24), above the expected reference range for natural streams (0.10-0.20), further confirms food-web imbalance.

The complementary use of FFG ratios provided strong evidence of functional shifts across environments. In FSE, moderate P/R values (0.49) and relatively high substrate stability (0.93) indicate a balanced heterotrophic system with structurally stable habitats-conditions characteristic of tropical forest streams (Ramírez & Gutiérrez-Fonseca 2014; Merritt & Cummins 1996). These values are consistent with stable DO levels (7.3-7.9 mg/l), low turbidity (≤ 0.8 NTU), and the presence of diverse scraper and EPT communities.

ASE exhibited markedly different functional signatures, including the highest TFPOM/BFPOM ratio (0.74), suggesting strong FPOM transport. This pattern aligns with increased turbidity (0.9-2.2 NTU), higher conductivity (0.8-1.4 mS/cm), and elevated organic parameters (BOD₅ up to 5.0 mg/l), reflecting disturbed hydrodynamics due to agricultural practices. These results are similar to findings from agricultural streams in Indonesia, Brazil, and India where irrigation, sediment runoff, and chemical inputs influence FFG composition (Barman & Gupta 2015; Camara et al. 2020; Ilmi et al. 2023).

RSE displayed functional indicators of the most degraded conditions. The lowest P/R ratio (0.32) and channel stability value (0.62) indicate reduced scraper contribution and unstable substrates, while the highest Pr ratio (0.24) suggests a disrupted predator-prey balance, and very low CPOM/FPOM (0.08) all correspond to impaired ecological function. Physicochemical measurements support this interpretation: DO values were lowest (5.8-6.7 mg/l), turbidity highest (2.2-2.6 NTU), and COD markedly elevated (up to 18.8 mg/l). Together, these metrics strongly support the interpretation that RSE experiences the strongest anthropogenic stress among the three environments. Integrating FFG composition, FFG ratios, and environmental variables reveals consistent ecological patterns: Higher scrapers, higher diversity (H' , d), higher DO, and low turbidity jointly characterize ecologically intact FSE. Higher filterers and elevated FPOM transport indicate hydrological disturbance in ASE.

Dominant gatherers, high turbidity, low DO, and high Pr ratios confirm organic enrichment and substrate instability in RSE. These results collectively demonstrate that FFGs and FFG ratios serve as reliable indicators of stream ecosystem function, effectively capturing shifts in energy pathways, substrate stability, and trophic dynamics across the three stream environments. Similar functional deterioration has been reported in urban and suburban streams in Morocco, South Africa, and Thailand (El Yaagoubi et al. 2023; Guellaf & Kettani 2025; Thanee & Phalaraksh 2012).

Correlations between diversity indices and functional attributes reinforce the diagnostic value of FFGs. High d and H' values in FSE correspond with higher scraper abundance and greater functional evenness, suggesting efficient resource partitioning under stable conditions. In contrast, low diversity in ASE and RSE aligns with dominance of single functional groups (c-g in RSE; c-f in ASE), indicating functional homogenization, a common symptom of ecological degradation (Ohler et al. 2024; Zhang et al. 2023).

Similarly, FFG ratios showed strong correspondence with environmental parameters. The decrease in P/R along the gradient from FSE to RSE mirrors the decline in DO and increase in turbidity and organic load. Substrate stability values reflect shifts in substrate composition, with RSE characterized by unstable, fine-sediment substrates and FSE by stable cobble, gravel substrata. Functional indices therefore captured ecological processes that taxonomic metrics alone may not fully reveal.

The PCA results further support the ecological differentiation among the three stream environments and highlight the sensitivity of functional metrics to environmental gradients. Forest-associated sites (St1-St4) grouped clearly with high DO, greater diversity (d , H'), and scraper dominance, consistent with stable substrates and high ecological integrity typically observed in forested tropical streams (Ramírez & Gutiérrez-Fonseca 2014; Thanee & Phalaraksh 2012). Agricultural sites (St5-St7) aligned with TFPOM/BFPOM and collector-filterers, reflecting enhanced FPOM transport and hydrological disturbance, a pattern also reported in agricultural streams elsewhere (Ilmi et al. 2023). Residential sites (St9-St12) clustered with high turbidity, COD, EC, and c-g dominance, indicating organic enrichment and substrate instability, consistent with studies in urbanizing tropical catchments (El Yaagoubi et al. 2023; Masese et al. 2023). The PCA clearly distinguishes the three stream environments and demonstrates strong correspondence between environmental gradients and functional ecological responses. FFGs and FFG ratios effectively capture functional ecosystem shifts and serve as robust indicators of stream health (Merritt & Cummins 1996; Pastorino et al. 2020).

This study provides one of the most detailed evaluations of functional ecological responses of aquatic insects in tropical Vietnamese streams. The alignment between FFG metrics, environmental variables, and diversity patterns underscores the utility of FFG approaches for assessing stream health in regions with limited taxonomic resources. Similar conclusions have been drawn in tropical studies in Costa Rica, Thailand, China, Brazil, and Kenya (Chiangthong & Phalaraksh 2017; Li et al. 2024; Pastorino et al. 2020; Masese et al. 2014; Ramírez & Gutiérrez-Fonseca 2014).

The findings highlight that FSE represents a functional reference condition, while ASE and RSE exhibit increasing levels of ecological stress. The study demonstrates that functional metrics, especially FFG ratios such as P/R, CPOM/FPOM, TFPOM/BFPOM, substrate stability, and Pr, offer sensitive and ecologically meaningful indicators for monitoring tropical streams.

CONCLUSION

This study provides a comprehensive assessment of the taxonomic structure, functional feeding organization, and ecosystem functional attributes of aquatic insect assemblages across three contrasting stream environments in tropical northern Vietnam. Forest-associated stream environments (FSE) exhibited the highest species richness, diversity, and functional integrity, supported by stable physicochemical conditions, well-oxygenated waters, and heterogeneous cobble-gravel substrates. Agriculture-associated streams (ASE) showed moderate levels of disturbance, reflected in reduced diversity, increased FPOM transport, and elevated proportions of collector-filterers. Residential stream environments (RSE) displayed the strongest signals of ecological stress, including low dissolved oxygen, high turbidity and organic load, functional homogenization dominated by collector-gatherers, and disrupted predator-prey balance. Functional Feeding Groups (FFGs) and FFG ratios proved highly effective in diagnosing ecological conditions, capturing shifts in energy pathways, substrate stability, and trophic dynamics more sensitively than taxonomic indices alone. The strong correspondence between functional metrics, diversity patterns, and physicochemical parameters underscores the value of FFG-based approaches for bioassessment in tropical regions with limited taxonomic resources. The study establishes FSE as a functional reference condition and highlights clear degradation gradients in ASE and RSE. These findings contribute essential baseline data for stream management and provide a robust functional framework for future biomonitoring initiatives in Vietnam and other tropical landscapes undergoing rapid environmental change.

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AUTHORS DECLARATION

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Conflict of Interest

The authors declare no conflict of interest.

Ethics Declarations

No ethical issue is required for this study.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Authors' Contributions

Hieu Van Nguyen (HVN) conceived and designed the study, conducted field sampling, identified the specimens, analyzed the data, and prepared the manuscript. Hien Thi Thu Nguyen

(HTTN) contributed to data analysis and conducted field sampling. Both authors read and approved the final version of the manuscript.

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