

IMPACT OF PEATLAND MANAGEMENT ON WATER QUALITY AND TROPHIC PLASTICITY OF FRESHWATER FISH IN NORTHERN SARAWAK, BORNEO

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ABSTRACT

Water quality assessment and fish diet composition were employed to quantify the ecosystem changes within an oil palm landscape in northern Sarawak, Malaysian Borneo, focusing on feeding guild plasticity. The study aimed to assess fish food availability and dietary shifts as indicators of functional responses across varying levels of habitat transformation. Three plantation management practices were examined: Buffer zones (native forest buffers), modified buffer zones (reduced native forest buffers) and drainage systems. *Clarias leiacanthus* and *Helostoma temminckii* were selected due to their high occurrence and occupation of benthic and pelagic niches, respectively. The buffer maintained the highest-quality aquatic environments (water quality index [WQI] = 61.35; slightly polluted; Class III), with a decrease in the modified buffer (WQI = 58.84; polluted; Class III) and drainage systems (WQI = 48.85; polluted; Class IV). Dissolved oxygen was significantly reduced at drainage (1.73 ± 0.45 mg/L) compared to the buffer (4.30 ± 0.39 mg/L) (Dunn's test, $p < 0.001$). Dietary analysis (frequency of occurrence) revealed both species maintained natural feeding patterns in buffer, while at drainage shifted from high-energy prey (fish, zooplankton) to low-energy resources (debris, plant matter). Shifting demonstrates feeding plasticity in response to reduced habitat quality and altered food availability. These findings highlight the ecological importance of maintaining native forest buffers as natural filters that sustain water quality and trophic structure, mitigating agricultural land-use impacts on peatland habitats.

Keywords: feeding guilds, freshwater ecosystem, oil palm landscape, peatland, peat swamps.

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INTRODUCTION

Freshwater ecosystems are highly sensitive to environmental disturbance, and shifts in organism population density are commonly

used as indicators of ecological change (Corrigan et al., 2010). However, population-level measures often fail to capture the underlying mechanisms driving these changes, particularly when responses are subtle. Such responses may include reduced foraging efficiency, elevated predation risk (Roth et al., 2007) or increased physiological stress under unfavourable environmental conditions (Forson & Storfer, 2006). Analysing fish diet studies is often used to understand these subtle ecological responses, as the stomach content provides valuable insight into trophic interactions within aquatic ecosystems. Bibak et al. (2021) stated that the stomach contents of fish represent aquatic, small and invertebrate vertebrates in the lower class of the food network, thereby serving as a

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proxy for human impacts on the food web. Diet composition with feeding guild plasticity provides additional insight by revealing how species adjust their feeding strategies, such as shifting in diets and foraging behaviour, in response to environmental disturbance and changes in resource availability.

These environmental disturbances and changes in food availability are often affected by spatial, seasonal and human changes in habitats such as agriculture (Whitehouse et al., 2017). Although oil palm plantation agriculture drives Malaysia's economy (Lee et al., 2023), its productivity threatens peat swamps, including deforestation and habitat destruction in recent decades. In 2019, the government introduced a suite of policies to promote sustainable oil palm production by capping the total oil palm plantation area at 6.5 million hectares by 2023, prohibiting new cultivation on peatlands while enforcing stricter management of existing plantations and banning the conversion of Permanent Forest Reserves into oil palm or other agricultural uses. Under the requirements of the Roundtable on Sustainable Palm Oil (RSPO), land clearing for new or existing plantations after 15 November 2018 must be preceded by assessments of High Conservation Value (HCV) areas and High Carbon Stock (HCS). However, downstream management practices remain inadequate. Unsustainable practices and poor land management, such as excessive use of pesticides and fertilisers, promote nutrient leaching, causing algal blooms, affecting fish and their insect prey (Kurniawan et al., 2018). Understanding how fish respond to these pressures is therefore critical for effective aquatic ecosystem management (Maitland et al., 2007). In particular, a species' ability to adjust its use of preferred food resources plays a key role in determining its persistence under changing environmental conditions (Zeni et al., 2019).

The effectiveness of the conservation programs implemented within oil palm buffer riparian reserves and adjacent native forests remains unclear, largely due to the provision of such reserves not being extensively studied. To better understand how fish populations adapt to environmental change and management interventions, the availability of food resources for fish communities across three management systems within oil palm landscapes, namely buffer zones (native forest buffers), modified buffer zones (reduced native forest buffers) and drainage systems was investigated. The extent of dietary adaptability among fish communities inhabiting these managed peat swamp habitats was further assessed. Specifically, the hypothesis that fish feeding guilds exhibit trophic plasticity

was tested, whereby species shift from their typical diets to alternative prey resources in response to altered food availability under disturbed environmental conditions.

MATERIALS AND METHODS

Study Site

Sabaju Oil Palm Estate (SOPE), located in the Bintulu Division of Northern Sarawak, Borneo, is established on 204 km² of secondary peatland and intersected by several small streams that drain into the main channel of the Batang (major river) Kemena River (Figure 1). The plantation is divided into three management zones, namely buffer (native forest buffers), modified buffer (reduced native forest buffers) and main drain (drainage system), each experiencing varying degrees of ecological changes. The Land Survey Department permits cultivation only in areas suitable for long-term drainage, excluding less drainable sections, riparian buffer and conservation reserves. Accordingly, SOPE implemented mitigation measures to conserve the aquatic ecosystem by establishing three management systems, which are (1) river channels within intact buffer zones, (2) river channels within modified buffer zones and (3) plantation drainage systems (hereafter referred to as buffer zones, modified buffer zones and drainage systems, respectively). The Belungai, Sujan and Ngiat rivers represent buffer zones, where approximately 50 m stretches of each stream were sampled. Belungai is a small river bordered by oil palm plantations and located adjacent to roadways. Sujan is a medium-sized river, approximately 15–20 m wide at its mouth, which drains runoff from the southern portion of the study area and flows westward to join the Pandan River, a tributary of the Batang Kemena. Ngiat is a small tributary situated at the outer edge of the oil palm estate, in a relatively undisturbed part of the landscape and is surrounded by secondary forest.

In the modified buffer zones, a 40 m stretch of the Sabaju River was sampled, characterised by a slow-flowing blackwater. Its upstream section is relatively deep and bordered predominantly by oil palm vegetation, while downstream relatively shallower and transitions into a plantation drainage channel. Vegetation along the downstream is characterised by a mixture of grasses, shrubs, and oil palm trees. In compliance with the Malaysian Sustainable Palm Oil (MSPO) guidelines, riparian vegetation in buffer zones is maintained to protect the riverbank ecosystem. Harvesting of fresh fruit bunches (FFB) is permitted; however, pruned fronds must not be disposed of in waterways. The application of fertilisers and pesticides is prohibited in both

buffer and modified buffer zones. Nevertheless, the reduced presence of native vegetation in modified buffer zones may allow significantly increased runoff from surrounding oil palm activities.

Sampling in the drainage systems was conducted at two main drains, MD 11/13 and MD 10/28, where the banks are primarily lined with oil palm and grasses. These drainage channels regulate

water levels within plantations, which are drained to facilitate cultivation. This system is maintained through periodic excavation, manages excess rainfall and conserves water during dry periods using check gates. The drains are positioned approximately 1 km apart, receiving water from perimeter or collecting drains and discharging into Sebungan, Batang Kemena, Sabaju or Sujan rivers.

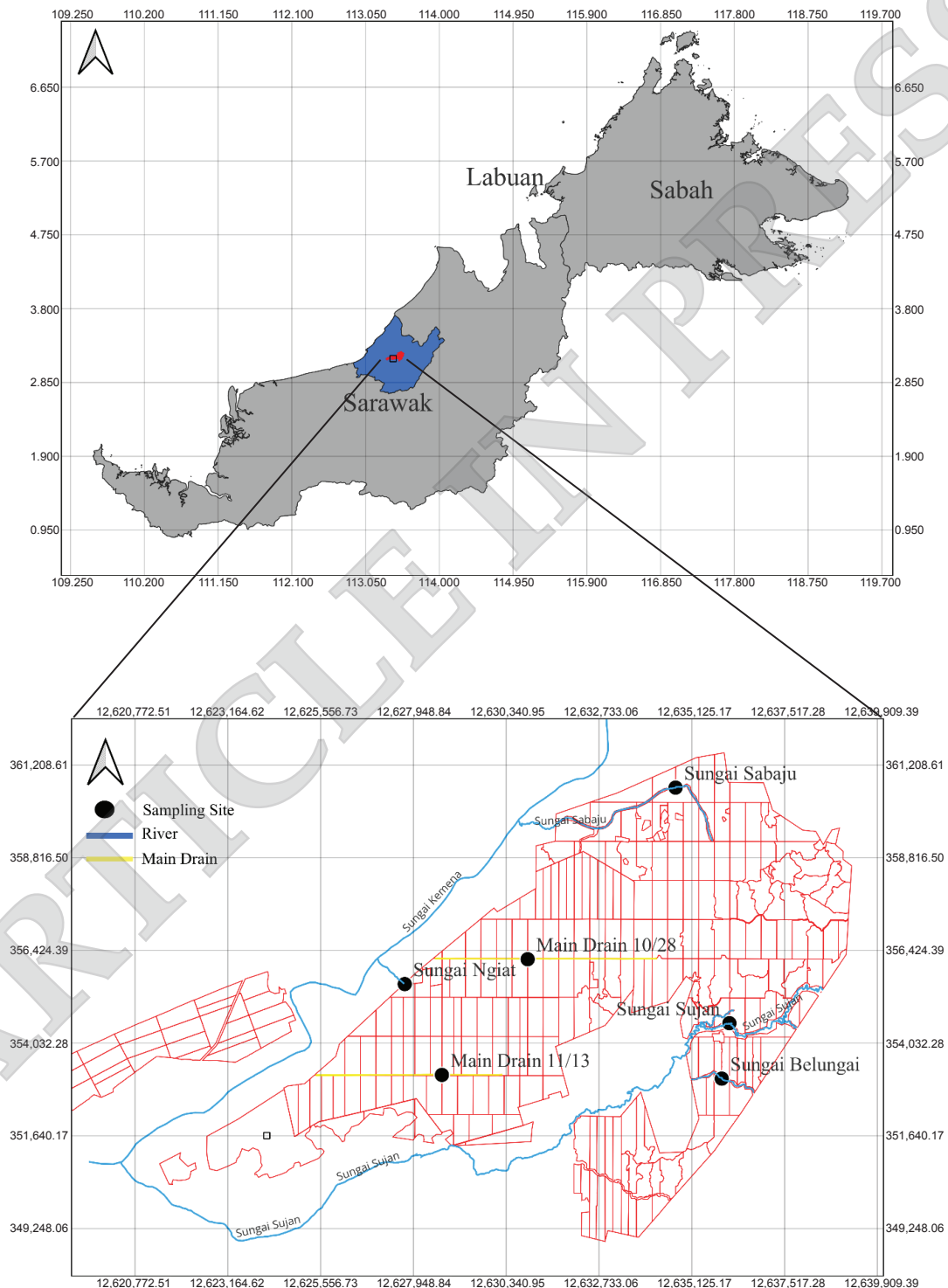


Figure 1. Study sites in Sabaju Oil Palm Estate.

Fish Sampling Design

To investigate trophic plasticity among fish feeding guilds, sampling was conducted across the three plantation management systems using a completely randomised design. Fish were collected using three types of fishing gear; two passive methods (gill nets and wooden traps locally known as *bubu*) and one active method (cast net). Sampling effort was adjusted among sites throughout the study period to account for habitat heterogeneity and variations in water conditions.

During the first trip (25–30 April 2023), three gill nets with mesh sizes of 2.5, 6.4 and 7.6 cm and two wooden traps were deployed at each site. No bait was used during sampling to avoid influencing fish fishing behaviour and to ensure that diets reflected natural in situ food availability. During the second sampling trip (18–26 September 2023), sampling effort varied among sites. At Sungei Belungai, Sungei Sabaju and Main Drain 11/13, the same gear configuration as the first trip was used, with the addition of two gill nets of 10.16 cm mesh size at each site. At Main Drain 10/28, two gill nets (2.5 and 6.4 cm) and one wooden trap were deployed. At Sungei Ngiat, one set of gill nets (2.5, 6.4 and 7.6 cm mesh size) and one wooden trap were used. Gill nets were consistently deployed for 48 hr, and cast nets were thrown 10 times at each site in both sampling trips.

Fish Species Identification

Fish specimens were identified in the field following the taxonomic literature by Kottelat et al. (2013), Kottelat (1993), and Ng (1999). For identification of *Clarias leiacanthus*, Kottelat (2013, p. 243) and Ng (1999, p. 26) were followed, who treated it as the senior synonym of *C. teijsmanni*, reflecting the high morphological similarity and lack of consistent diagnostic differences between the two nominal taxa. *C. leiacanthus* can be distinguished from the peat swamp-associated species *C. nieuhoftii*, which exhibits a narrower head and a more elongated, slender body.

Standard length was measured using a ruler calibrated against a Vernier calliper for accuracy, while weight was recorded using a digital balance to the nearest 0.01 g. No sex-related differences in the consumption of different food types were observed. Following the procedure of Mahesh et al. (2018), the stomach of each fish was dissected, and the gut contents were preserved in 10% formalin. The contents were then examined under the dissecting microscope at X10 magnification. Prey items were identified and recorded, classified to the taxonomic order. After classification, the prey items were preserved in 70% ethanol in glass containers for subsequent examination.

Water Quality Sampling

Prior to fish sampling, *in-situ* water parameters: Temperature (°C), pH, dissolved oxygen (DO, mg/L), and conductivity ($\mu\text{S}/\text{cm}$) were measured using a YSI ProDSS multiparameter water quality meter. *Ex-situ* water parameters: Ammonia nitrogen ($\text{NH}_3\text{-N}$, mg/L), orthophosphate (PO_4^{3-} , mg/L), total Kjeldahl nitrogen (TKN, mg/L), total phosphorus (TP, mg/L), biochemical oxygen demand (BOD_5 , mg/L), chemical oxygen demand (COD, mg/L), total dissolved solids (TDS, mg/L), total suspended solids (TSS, mg/L) and chlorophyll-a (Chl-a, $\mu\text{g}/\text{L}$) were analysed in the laboratory following standard methods outline in American Public Health Association (APHA) et al. (2017).

Data Analysis

Water quality parameters. Variations in water quality parameters among the three plantation management types were assessed using one-way analysis of variance (ANOVA) for normally distributed data and the Kruskal–Wallis test for non-normally distributed data, following assessment of normality using the Shapiro–Wilk test. When significant differences were detected, pairwise comparisons were conducted using Dunn's test with Bonferroni correction. All analyses were performed at a 5% significance level using JASP version 0.17.3 (JASP Team, 2021).

Water quality index (WQI). The WQI was calculated following the standard method of the Department of Environment (DOE, 2022), Malaysia [Equations (1)]. The indices derived were DO, BOD_5 , COD, pH, $\text{NH}_3\text{-N}$ and TSS.

$$\text{WQI} = \frac{(0.22 \times \text{SIDO}) + (0.19 \times \text{SIBOD}_5) + (0.16 \times \text{SICOD}) + (0.15 \times \text{SINH}_3\text{-N}) + (0.16 \times \text{SITSS}) + (0.12 \times \text{SIpH})}{6} \quad (1)$$

where, SI is a sub-index value for each parameter. The SI values were calculated using standard empirical equations defined by DOE, which transform measured parameter values into normalised sub-index scores ranging from 0 to 100. The coefficients assigned to each sub-index are fixed weighting factors established by the department, reflecting the relative importance of each parameter in determining overall water quality. Based on the WQI values, each management type was classified as clean (81–100), slightly polluted (60–80) or polluted (0–59) according to the DOE classification scheme and based on DOE Water Quality Index Classification, WQI values of >92.7 are classified as Class I (very good), 76.5–92.7 as Class II (good), 51.9–76.5 as Class III (average), 31.0–51.9 as Class IV (polluted) and <31.0 as Class V (highly polluted).

Multivariate analysis. Principal Component Analysis (PCA) was performed to explore patterns and relationships among the 13 measured water quality parameters across plantation management types. Prior to analysis, all variables were standardised to z-scores to eliminate differences in measurement units and scales. Non-normally distributed variables were log-transformed where necessary to reduce skewness. PCA was conducted based on the correlation matrix to identify the main gradients in water quality variation. Principal components with eigenvalues greater than 1 were retained for interpretation. Loadings of variables on principal components were examined to identify the parameters contributing most to observed patterns, while score plots were used to visualise the distribution of samples according to plantation management types. The analysis was performed using Paleontological Statistics (PAST) version 5.3 (Hammer et al., 2001).

Feeding guilds analysis. Feeding guilds were determined based on gut content analysis. Prey items were identified to the lowest possible taxonomic level and quantified using the Frequency of Occurrence (FO%), defined as the proportion of stomachs containing a given prey item (Baker et al., 2014). The FO% is useful for describing dietary composition within a fish population (Mahesh et al., 2018). However, this metric provides limited information on the relative importance or volumetric contribution of each food category (Hyslop, 1980), compared to the Index of Relative Importance (IRI), which integrates multiple measures to better describe diet composition (Prince, 1975).

The presence (1) or absence (0) of each prey item was recorded for all stomachs. The FO% was calculated as Equation (2):

$$FO\% = (N_i / N) \times 100 \quad (2)$$

where, N_i is the number of stomachs containing prey item i and N is the total number of non-empty stomachs. The of each prey item was compared among plantation management types to assess dietary shifts. Of the 20 recorded fish species caught, detailed stomach content analysis focused on two species, *C. leiacanthus* ($n = 17$) and *Helostoma temminckii* ($n = 16$), as they were well represented in the samples and occupy distinct ecological benthic and pelagic niches, respectively. This approach enabled a more robust evaluation of dietary variation across habitat strata and provided insights into the influence of management practices on feeding ecology.

Clarians leiacanthus is a demersal catfish, native to Sarawak, typically associated with slow-moving or swampy habitats (Dosi et al., 2019; Nyanti &

Bali, 2004; Nyanti et al., 2006) and like most clariid species, is capable of air-breathing. Although species-specific dietary information is unknown, this species may be considered an omnivorous and opportunistic feeder, as reported for other catfish (Wakil et al., 2014). *H. temminckii* was introduced to Sarawak in the 1960s through aquaculture programs. It is now widely distributed in various freshwater habitats in Sarawak, including swamps (Dosi et al., 2019; Nyanti & Bali, 2004), natural lakes, and slow-moving, vegetated rivers (Abdul Rahim et al., 2009; Nyanti et al., 2006). This air-breathing species is omnivorous, feeding on algae, zooplankton and aquatic insects, typically in the surface and mid-water zones.

RESULTS AND DISCUSSION

The water quality parameters measured across the three management types are summarised in Table 1. Mean Chl-a concentrations did not differ significantly among management types according to ANOVA ($p > 0.05$). In contrast, temperature, DO, TDS, COD and PO_4^{3-} differed significantly among the three management types based on the Kruskal-Wallis test ($p < 0.005$). These variables also exhibited large effect sizes ($\varepsilon^2 = 0.16$ – 0.29), indicating that management type explained approximately 16%–29% of the variation in these water quality parameters. DO was significantly different between buffer and drainage ($p < 0.001$). TDS differed significantly ($p < 0.05$) between buffer and modified buffer ($p = 0.03$). PO_4^{3-} was significantly different ($p < 0.05$) between buffer and modified buffer ($p = 0.02$) and significantly different ($p < 0.05$) between buffer and drainage ($p = 0.04$). While Kruskal-Wallis indicated a significant difference for DO ($p = 0.04$), post-hoc Bonferroni adjustment yielded no significant pairwise differences ($p > 0.05$); therefore, no unique superscripts are shown. Temperature, pH, DO, conductivity, TDS, Chl-a, COD, NH_3 -N, and PO_4^{3-} showed large effect sizes, indicating a strong influence of management system on these parameters, while TSS, BOD_5 , TKN and TP showed small to moderate effect sizes, suggesting these parameters remain stable among managements.

The overall water quality patterns among management types as revealed by PCA showed that the first two principal components explained 59% of the total variation (Figure 2). PC1 was primarily associated with DO (loading = -0.32), conductivity (loading = 0.35), TDS (loading = 0.39), COD (loading = 0.33), NH_3 -N (loading = 0.38), and PO_4^{3-} (loading = 0.29). The opposing directions of these variables in the biplot indicate the presence of multiple water quality gradients across the

TABLE 1. SUMMARY OF WATER QUALITY PARAMETERS IN WATERWAYS OF OIL PALM PLANTATION

Parameters	Mean $\pm$ SE (95% CI)			<i>p</i> -value	Effect size
	Buffer zones	Modified buffer zones	Drainage systems		
Temp ($^{\circ}$ C)	27.67 $\pm$ 0.05 (95% CI: 27.56–27.77)	27.45 $\pm$ 0.01 (95% CI: 27.26–27.64)	28.18 $\pm$ 0.19 (95% CI: 27.81–28.56)	*0.04	$\epsilon^2 = 0.16$
pH	4.42 $\pm$ 0.06 (95% CI: 4.31–4.54)	4.25 $\pm$ 0.18 (95% CI: 3.89–4.61)	4.23 $\pm$ 0.03 (95% CI: 4.18–4.27)	0.06	$\epsilon^2 = 0.13$
DO (mg/L)	4.30 ^a $\pm$ 0.39 (95% CI: 3.55–5.06), Class III	4.25 ^{ab} $\pm$ 0.18 (95% CI: 1.77–3.31), Class III	1.73 ^b $\pm$ 0.45 (95% CI: 0.86–2.60), Class III	*<0.001	$\epsilon^2 = 0.49$
Conductivity (μ S/cm)	97.23 $\pm$ 9.31 (95% CI: 78.97–115.48)	144.05 $\pm$ 12.41 (95% CI: 119.76–168.37)	127.17 $\pm$ 2.51 (95% CI: 122.24–132.09)	0.07	$\epsilon^2 = 0.12$
TDS (mg/L)	65.48 ^a $\pm$ 8.13 (95% CI: 49.55–81.42)	81.81 $\pm$ 1.32 ^b (95% CI: 79.22–84.40)	76.29 $\pm$ 1.51 ^{ab} (95% CI: 73.33–79.25)	*0.04	$\epsilon^2 = 0.17$
TSS (mg/L)	23.50 $\pm$ 8.47 (95% CI: 6.90–40.10), Class I	7.167 $\pm$ 3.31 (95% CI: 0.87–13.46), Class I	3.88 $\pm$ 1.32 (95% CI: 1.29–6.46), Class I	0.41	$\epsilon^2 = 0.00$
Chl-a (μ g/L)	5.50 $\pm$ 0.77 (95% CI: 3.99–7.00)	9.11 $\pm$ 0.95 (95% CI: 7.25–10.96)	7.48 $\pm$ 1.7 (95% CI: 4.10–10.86)	0.24	$\eta^2 = 0.10$
BOD ₅ (mg/L)	2.79 $\pm$ 0.54 (95% CI: 1.73–3.86), Class II	4.95 $\pm$ 0.96 (95% CI: 3.07–6.84), Class III	4.66 $\pm$ 0.51 (95% CI: 3.66–5.67), Class III	0.116	$\epsilon^2 = 0.09$
COD (mg/L)	63.92 $\pm$ 9.53 (95% CI: 45.24–82.60), Class IV	60.00 $\pm$ 6.43 (95% CI: 47.40–72.60), Class IV	79.92 $\pm$ 6.58 (95% CI: 67.01–92.82), Class IV	*0.04	$\epsilon^2 = 0.16$
NH ₃ -N (mg/L)	0.75 $\pm$ 0.17 (95% CI: 0.43–1.08), Class III	1.21 $\pm$ 0.03 (95% CI: 1.16–1.26), Class IV	0.97 $\pm$ 0.06 (95% CI: 0.85–1.09), Class IV	0.05	$\epsilon^2 = 0.15$
TKN (mg/L)	0.79 $\pm$ 0.04 (95% CI: 0.71–0.88)	0.83 $\pm$ 0.05 (95% CI: 0.73–0.92)	0.91 $\pm$ 0.06 (95% CI: 0.80–1.02)	0.33	$\epsilon^2 = 0.01$
PO ₄ ³⁻ (mg/L)	0.23 $\pm$ 0.10 ^a (95% CI: 0.03–0.42)	0.41 $\pm$ 0.08 ^b (95% CI: 0.26–0.56)	0.31 $\pm$ 0.03 ^b (95% CI: 0.25–0.37)	*0.01	$\epsilon^2 = 0.29$
TP (mg/L)	1.36 $\pm$ 0.19 (95% CI: 0.99–1.73)	1.04 $\pm$ 0.16 (95% CI: 0.73–1.35)	1.20 $\pm$ 0.08 (95% CI: 1.04–1.37)	0.73	$\epsilon^2 = 0.00$
WQI Index	61.35	58.84	48.85		
Class	III	III	IV		
Category	Slightly polluted	Polluted	Polluted		

Note: Different superscript letters within the same row indicate significant differences ($p < 0.05$) based on Tukey's test (for ANOVA) or Dunn's test with Bonferroni correction (for Kruskal-Wallis test). * indicates a significant difference among groups at $p < 0.05$; Temp - temperature; DO - dissolved oxygen; TDS - total dissolved solids; TSS - total suspended solids; Chl-a - chlorophyll-a; BOD₅ - biochemical oxygen demand; COD - chemical oxygen demand; NH₃-N - ammonia nitrogen; TKN - total Kjeldahl nitrogen; PO₄³⁻ - orthophosphate; TP - total phosphorus; WQI - water quality index.

management systems. Buffer zones, positioned on the negative space of PC1, were associated with higher dissolved oxygen levels. In contrast, drainage systems and modified buffer zones, located on the positive space of PC1, were strongly influenced by elevated nutrient concentration and organic matter.

PC2 was primarily associated with temperature (loading = 0.32), pH (loading = 0.43), TSS (loading = 0.42), BOD₅ (loading = 0.48), TKN (loading = 0.34) and TP (loading = 0.30), suggesting PC2 represents variations related to physicochemical, organic and nutrient inputs. Buffer and drainage systems, positioned on the positive side of PC2, were associated with higher temperature, pH and organic input, which may influence water clarity and habitat conditions. Chl-a contributes a little to the variance in the principal components. TDS and

conductivity show a correlation as they were closely parallel to each other.

Higher temperatures in drainage systems are likely due to less canopy cover, shallow waterways, stagnant conditions, and increased exposure to direct sunlight (Gandaseca et al., 2015). Canopy cover of buffer and modified buffer is partly shaded, while drainage is mostly open. Elevated temperature, with lower pH and dissolved oxygen, may reflect the influence of agricultural activities within oil palm plantations, consistent with findings from the MAAH oil palm plantation in Selangor (Azizan et al., 2021). Increased temperature reduces oxygen solubility, lowering DO concentrations, a pattern similarly reported by Irvine et al. (2013). In contrast, buffer zones with native riparian vegetation provide canopy, shading and thermal regulation, helping to maintain lower

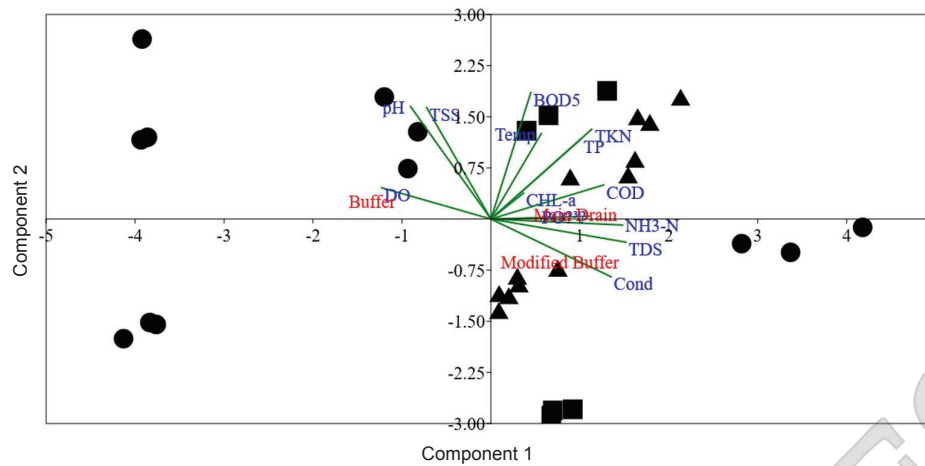


Figure 2. Biplot of principal component analysis (PCA) shows the variation of 13 water quality parameters among three management sites. Circle (●) – buffer zones; square (■) – modified buffer zones; triangle (▲) – drainage systems.

water temperature and higher DO levels, reducing environmental stress in aquatic ecosystems (Rojas-Castillo et al., 2023).

The relatively higher TSS and TP observed in buffer zones may indicate that the buffering capacity of vegetation has reached its limit for nutrient absorption and sediment retention (Wang et al., 2024). Accumulation of fine sediments and nutrients over time can lead to saturation, thereby reducing the effectiveness of buffer zones in filtering pollutants (Valkama et al., 2019). In contrast, lower TP concentrations in drainage systems may be attributed to uptake by periphyton that assimilate phosphorus from the water column (Pearce et al., 2023). Elevated TP levels can stimulate phytoplankton growth (Guimarães et al., 2023), potentially leading to eutrophication, hypoxia and disruption of food web structure (Ma et al., 2015), while high TSS can further reduce DO and contribute to oxygen depletion, particularly under low-flow conditions (Rubel et al., 2019).

Significantly higher TDS and PO_4^{3-} , together with relatively elevated $\text{NH}_3\text{-N}$, conductivity, Chl-a and BOD_5 in modified buffer zones compared to buffer zones, suggest that grass- and shrub-dominated riparian strips are less effective at filtering surface runoff and retaining nutrients. This is consistent with findings by the Ministry of Natural Resources and Environment (NRE, 2008), which reported that forested buffer zones are more effective in reducing pollutant loads and soil erosion due to deeper and more extensive root systems (Chellaiah & Yule, 2018).

The higher concentrations of these parameters in modified buffer zones relative to drainage systems may be explained by increased decomposition of grass and organic matter. The decomposition of plant material releases dissolved ions, organic substances

and nutrients such as phosphorus (Wetzel, 2001), thereby increasing conductivity, TDS and PO_4^{3-} concentrations. These nutrient inputs can stimulate microbial activity and algal growth, leading to elevated Chl-a concentrations, while microbial decomposition increases oxygen demand, reflected in higher BOD_5 . Elevated levels of these parameters can negatively impact aquatic biodiversity; for example, high conductivity increases energetic costs for osmoregulation in fish (Armstead et al., 2016), high TDS excludes sensitive species (Weber-Scannell & Duffy, 2007) and elevated $\text{NH}_3\text{-N}$ can cause toxicity and immune impairment (Xu et al., 2021).

Despite this, conductivity, TDS, Chl-a, BOD_5 and PO_4^{3-} remained higher in the main drain compared to buffer zones, indicating that intact forest buffers are still effective in mitigating runoff. The higher COD observed in the main drain may be attributed to the absence of dense riparian vegetation. Vegetated buffer zones have been shown to reduce COD concentrations (Hou et al., 2019), while elevated COD can lead to oxygen depletion, toxicity, and overall ecosystem degradation (Bar, 2025). Lower concentrations of sediments and pollutants in buffer zones further demonstrate the capacity of riparian vegetation to intercept and retain runoff before it enters waterways, consistent with findings by Saleh et al. (2018), who reported high efficiency of vegetative buffers in controlling pollutant loads.

Based on the National Water Quality Standards and Water Quality Index (DOE, 2022), the WQI values (Table 1) indicate that buffer zones were classified as slightly polluted. In contrast, both modified buffer zones and drainage systems were classified as polluted. These results suggest that intact buffer zones with native riparian vegetation

are more effective in maintaining water quality compared to modified buffers and drainage systems. Nutrient enrichment and declining water quality may reduce the availability of high-quality food resources for aquatic consumers, ultimately simplifying riverine food webs (Yan et al., 2024).

A total of 20 fish species representing 11 families were recorded across the three management types in the SOPE. Standard length and wet weight were measured for 19 species, with *Kryptopterus lais* excluded due to poor specimen condition (Table 2). Four non-native species were also recorded, namely *C. gariepinus*, *Chitala chitala*, *H. Temminckii* and *Trichopodus pectoralis*; however, the history and pathways of their introduction to the area remain unknown. *C. gariepinus* and *Desmopuntius johorensis* were recorded across all management types; however, they were excluded from further analysis due to poor stomach condition.

The consistent occurrence of *C. leiakanthus* and *H. temminckii* across all management types indicates high tolerance to habitat disturbance and limited food resources from oil palm cultivation. Nevertheless, further investigation is required to establish a direct causal relationship between habitat modification and species distribution. Predominantly nocturnal *Clarias* species hide in burrows by day to avoid predation and maintain moisture until dissolved oxygen levels improve.

Their elongated bodies and robust pectoral spines facilitate overland movement, enabling them to traverse between water bodies and escape unfavourable conditions (Ponzoni & Nguyen, 2008).

Both *C. leiakanthus* and *H. temminckii* are commonly associated with stagnant or slow-flowing waters (low oxygen) (Abdul Rahim et al., 2009). These species have specialised air-breathing adaptations: *C. leiakanthus* uses a suprabranchial chamber, while *H. temminckii* a labyrinth organ (Müller et al., 2022), allowing them to persist in oxygen-depleted habitats. Besides, *Clarias* is particularly tolerant of extreme peatland conditions (low pH and DO) (Barus, 2022). Additionally, *H. temminckii* exhibits behavioural adaptations by occupying surface waters where oxygen concentrations are relatively higher.

In addition to physiological and behavioural adaptations, trophic plasticity likely plays an important role in the persistence of these species across disturbed habitats. Both *C. leiakanthus* and *H. temminckii* exhibited flexible feeding strategies, enabling them to exploit available food resources under varying environmental conditions. FO% analysis further revealed variations in diet composition across management types. For *C. leiakanthus*, plant material, arthropods and fish parts were most frequently recorded in buffer

TABLE 2. THE SUMMARY OF MORPHOMETRICS OF THE FISH IN THREE MANAGEMENT TYPES

Species	SL (cm) (Mean ± SE)	WW (g) (Mean ± SE)	Occurrence
<i>Anabas testudineus</i> (Bloch, 1792)	16.90 ± 0.24	164.04 ± 6.45	BZ, MBZ, DS
<i>Betta</i> sp.	3.80 ± 0.60	1.10 ± 0.60	BZ
<i>Channa lucius</i> (Cuvier, 1831)	19.24 ± 1.10	107.26 ± 12.00	BZ, DS
<i>Channa striata</i> (Bloch, 1793)	29.25 ± 7.79	444.84 ± 237.78	MBZ, DS
<i>Chitala chitala</i> (Hamilton, 1822)*	29.50 ± 1.00	211.90 ± 36.00	MBZ
<i>Clarias gariepinus</i> (Burchell, 1822)*	32.88 ± 1.02	422.57 ± 49.60	BZ, MBZ, DS
<i>Clarias leiakanthus</i> (Bleeker, 1851)	33.74 ± 1.69	396.67 ± 37.98	BZ, MBZ, DS
<i>Clarias nieuhofii</i> (Valenciennes, 1840)	42.53 ± 0.98	545.73 ± 90.02	MBZ
<i>Cyclocheilichthys apogon</i> (Valenciennes, 1842)	10.53 ± 0.41	35.03 ± 4.99	BZ
<i>Desmopuntius johorensis</i> (Duncker, 1904)	8.14 ± 0.34	14.72 ± 1.63	BZ, MBZ, DS
<i>Helostoma temminckii</i> (Cuvier, 1829)*	14.38 ± 0.46	119.32 ± 10.79	BZ, MBZ, DS
<i>Hemibagrus planiceps</i> (Valenciennes, 1840)	21.24 ± 0.83	184.10 ± 16.38	BZ, MBZ
<i>Osteochilus vittatus</i> (Valenciennes, 1842)	7.93 ± 0.83	13.71 ± 3.46	BZ
<i>Oxygaster anomalura</i> (Van Hasselt, 1823)	12.50	21.20	BZ
<i>Pristolepis fasciata</i> (Bleeker, 1851)	7.17 ± 0.67	17.63 ± 5.49	BZ
<i>Pristolepis grootii</i> (Bleeker, 1852)	12.33 ± 0.40	94.38 ± 7.74	BZ, MBZ
<i>Trichopodus pectoralis</i> (Regan, 1910)*	14.90	93.90	BZ
<i>Trichopodus trichopterus</i> (Pallas, 1770)	7.09 ± 0.09	10.77 ± 0.38	MBZ, DS
<i>Wallago leerii</i> (Bleeker, 1851)	22.53 ± 3.54	219.00 ± 64.69	BZ, MBZ

Note: SL – standard length (cm), WW – wet weight (g), BZ – buffer zones, MBZ – modified buffer zones, DS – drainage systems,

* – non-native species.

zones (Table 3). In modified buffer zones, plant material dominated the diet, while in drainage systems, both plant material and arthropods were prevalent. Similarly, *H. temminckii* exhibited high occurrences of detritus, plant material and arthropods in both buffer and modified buffer zones.

PCA revealed that prey composition in the stomach contents of *C. leiacanthus* varied across management types, with the first and second components explaining 55% and 45% of the total variation, respectively (Figure 3). PC1 was strongly positively associated with plant matter (loading = 0.55), arthropods (loading = 0.55) and fish parts (loading = 0.52), indicating that this axis represents a gradient of active feeding on higher-quality prey resources. In contrast, PC2 was primarily associated with debris (loading = 0.63), suggesting a detritus-based feeding gradient.

Individuals from the drainage systems were positioned in the negative space of PC1 and the positive space of PC2, indicating a stronger association with debris consumption. In contrast, individuals from the buffer zones clustered in the positive space of PC1 and the negative space of PC2, suggesting greater reliance on plant matter, arthropods and fish parts. Meanwhile, individuals from the modified buffer zones occupied the

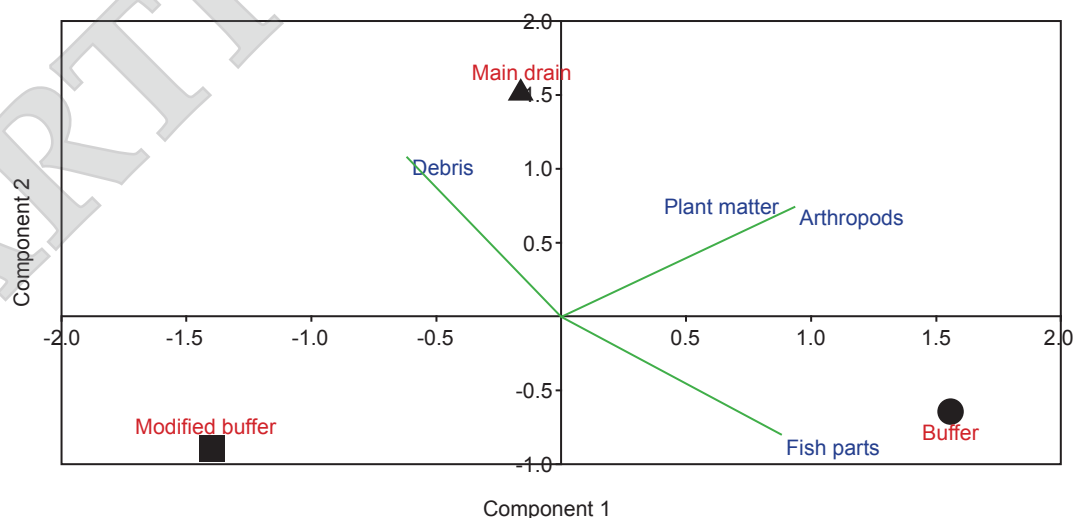
negative space of both PC1 and PC2, indicating a comparatively weaker association with both high-quality prey items and detrital resources.

For *H. temminckii*, PCA showed that the first two principal components together explained 100% of the total variance (Figure 4). PC1 accounted for the vast majority of variation (99%) and was strongly associated with debris, plant matter and arthropods, indicating a gradient representing benthic-derived food resources and active foraging behaviour. PC2 was of less importance, explaining only 1% of the total variation and was primarily associated with zooplankton, indicating a weak dietary gradient related to zooplanktivory.

In the biplot, individuals from the buffer zones were positioned in the positive space of PC1 and the upper space of PC2, indicating a strong association with debris, plant matter, arthropods and zooplankton. In contrast, individuals from the modified buffer zones were clustered in the negative space of PC1 and the lower side of PC2, reflecting a weaker association with these prey categories. Specimens from the drainage systems were positioned in the positive space of PC1 but the lower space of PC2, suggesting a diet primarily associated with debris, plant matter and arthropods, with minimal contribution from zooplankton.

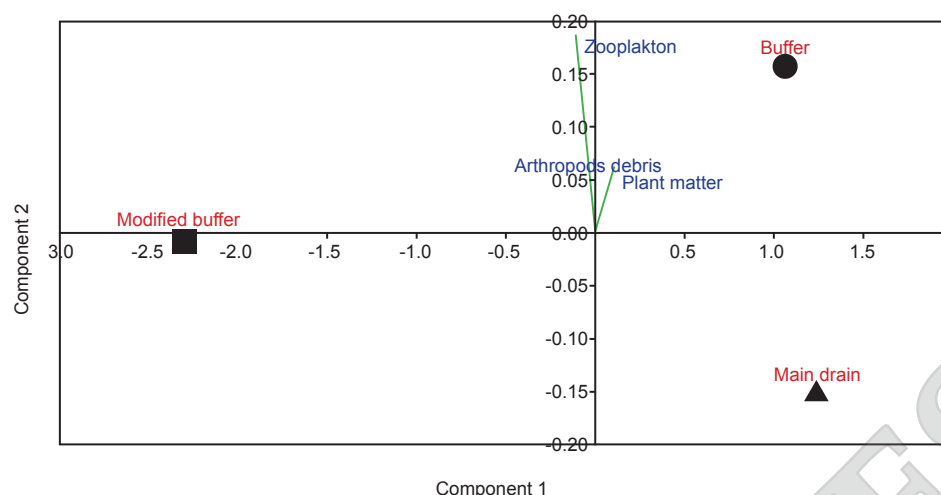
TABLE 3. PREY ITEMS AND FREQUENCY OF OCCURRENCE (FO%) OF TWO FISH SPECIES AT THREE MANAGEMENT SYSTEMS

Species	Buffer zones	Modified buffer zones	Drainage systems
<i>Clarias leiacanthus</i>	All plant matter, arthropods and fish parts are 100%	Debris 18%, plant matter 73%, arthropods 45% and fish parts 27%	Both plant matter and arthropods are 100%; debris 40%
<i>Helostoma temminckii</i>	All debris, plant matter and arthropods are 100%; zooplankton 13%	All debris, plant matter and arthropods are 83%; zooplankton, 67%	All debris, plant matter and arthropods are 100%



Note: Circle (●) – buffer zones; square (■) – modified buffer zones; triangle (▲) – drainage systems.

Figure 3. Biplot of principal component analysis (PCA) shows the variation of diets of *Clarias leiacanthus* at three management systems.



Note: Circle (●) – buffer zones; square (■) – modified buffer zones; triangle (▲) – drainage systems.

Figure 4. Biplot of principal component analysis (PCA) shows the variation of diets of *Helostoma temminckii* at three management systems.

The diet composition of both *C. leiacanthus* and *H. temminckii* across the three management types highlights substantial feeding guild plasticity. In its natural habitat, *C. leiacanthus* is omnivorous, primarily consuming aquatic macroinvertebrates (Low et al., 2022), although it also tends towards carnivory, similar to other *Clarias* species. In buffer zones, the high frequency of plant matter, arthropods, and fish remains indicates that this species maintained its natural omnivorous feeding strategy. While cannibalism may occur opportunistically, the presence of fish prey likely reflects natural piscivory, consistent with previous findings in adult *Clarias* species (Tekle-Giorgis et al., 2016).

Similarly, *H. temminckii* is naturally omnivorous, feeding on detritus, palm oil, insects, clams, caterpillars, fish scales and plankton. The occurrence of debris, plant matter, zooplankton and arthropods in individuals from buffer and modified buffer zones suggests that this species largely retained its natural diet under these conditions. In contrast, individuals from the drainage systems lacked zooplankton in their diet, while *C. leiacanthus* showed no evidence of fish prey consumption. This pattern indicates a marked shift from their typical feeding guilds, reflecting dietary plasticity under altered environmental conditions.

In buffer and modified buffer zones, both species follow optimal foraging theory by selecting energetically profitable prey such as fish and zooplankton. Conversely, in the drainage systems, the high occurrence of debris and plant matter suggests opportunistic feeding behaviour (Winemiller, 1989), where individuals consume the most readily available resources despite their

relatively low nutritional value (Neves et al., 2021). This shift may indicate fish diet plasticity in oil palm management.

In general, fish in the drainage systems exhibited greater dietary shifts, indicating higher reliance on feeding flexibility, whereas diets in buffer and modified buffer zones remained more stable. Similar patterns have been reported, where the benthopelagic freshwater South American silver croaker, *Plagioscion squamosissimus*, altered its diet under disturbed conditions (Costa & Angelini, 2020). The presence of more diverse and higher-quality resources in buffer habitats likely supports dietary stability, highlighting the importance of effective habitat management for maintaining ecological integrity and biodiversity (Tran Ngoc & Phan, 2025).

Beyond conventional diet analysis, examining feeding guild plasticity provides deeper ecological insight into how fish communities respond to environmental variation. Rather than simply describing diet composition, this approach captures adaptive shifts in resource use across environmental gradients. Seasonal influences should also be considered, as sampling was conducted during the inter-monsoon (April 2023) and northeast monsoon (September 2023) periods. Seasonal variation may have influenced feeding behaviour, with fish often exhibiting broader and more diverse diets during the monsoon season (Idrus et al., 2021), potentially due to increased availability of prey such as aquatic insects under wetter conditions (Ridzuan et al., 2020). Although seasonal effects were not explicitly quantified in this study, they may have contributed to the observed dietary patterns.

Several limitations of this study should be acknowledged. Freshwater fish ecological studies in this region remain limited, constraining broader ecological interpretation. In addition, sampling was conducted only twice within the study period, resulting in relatively low sample sizes. The limited number of individuals and the highly digested condition of many prey items restricted the application of quantitative diet indices such as percentage composition and the IRI (Hyslop, 1980). Future studies should increase sampling frequency and duration, or incorporate replicated sampling gear, to improve sample size and dietary resolution. Incorporating vegetation assessment would also be valuable, as habitat structure can influence nutrient dynamics and trophic interactions. Finally, minimising post-capture digestion through rapid dissection and preservation would improve the accuracy and resolution of diet analysis.

Effect of Oil Palm Management on Fish Ecology

Oil palm management often degrades water quality and negatively affects fish ecology. Riparian and native forests function as natural filters by having dense vegetation and complex root systems to trap excess nutrients and pollutants. However, the removal or modification of these buffer zones facilitates the runoff of fertiliser and pesticide into adjacent aquatic systems. Elevated nutrient inputs can subsequently trigger eutrophication and algae blooms, leading to oxygen depletion and increased stress on fish communities.

Additionally, the absence of riparian zones, native forests and excavation, such as drainage systems, reduces the natural habitat complexity. Aquatic plant matter provides more complex habitats and is supported by more diverse fish and aquatic insect populations for fish diets (Guru et al., 2025). Without these terrestrial and aquatic plants, water quality declines, and the once-thriving habitat that fish rely on becomes more simplified and degraded. Periodic excavation in drain waterways reduces habitat complexity by removing shelters like aquatic plants, leaves and twigs that protect fish and insects (O'Keefe, 2015). Clearing of natural vegetation provides no habitat for nymphs of mayflies, caddisflies and stoneflies, causing a decrease in fish's food. Shown by dietary shifts of *C. leiacanthus* and *H. temminckii* in drains where the lack of buffer vegetation and native forests makes them unable to consume diverse prey found in healthier habitats. Through this observation, the negative impacts of oil palm management on fish ecology highlight the need for restoring riparian buffers and increasing native forests to mitigate effects on aquatic ecosystems.

CONCLUSION

This study evaluated the plasticity of fish feeding guilds in response to environmental disturbances associated with oil palm management. Buffer zone sites with higher DO and pH, lower concentrations of nutrient-related indicators (e.g., $\text{NH}_3\text{-N}$, PO_4^{3-} and Chl-a), organic pollution, conductivity and TDS, indicating comparatively better water quality conditions. Supported by the WQI, buffer zones were classified as slightly polluted, while modified buffer zones and drainage systems were categorised as polluted. Fish communities in the buffer and modified buffer zones exhibited diets more consistent with their natural feeding strategies, suggesting relatively stable ecosystem conditions and greater prey availability. In contrast, the reduced occurrence of key prey items in fish from the drainage systems indicated dietary shifts toward lower-energy food resources, highlighting feeding guild plasticity in response to environmental stress and habitat degradation. These findings demonstrate that trophic structure is highly sensitive to changes in habitat quality and that fish may adjust their feeding behaviour to cope with reduced resource availability and altered environmental conditions. Overall, the results emphasise the ecological importance of riparian buffers and native vegetation in mitigating agricultural impacts, maintaining water quality and supporting trophic stability in freshwater ecosystems within oil palm landscapes. Strengthening buffer zone implementation, alongside sustainability initiatives promoted by RSPO and government policies, will be essential for improving the ecological sustainability of oil palm management. Future study should incorporate year-round sampling to better capture seasonal variability, particularly the interactions among feeding dynamics, reproductive cycles and rainfall patterns, which may further influence trophic responses in freshwater fish communities.

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