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ASSESSING THE EFFECTIVENESS OF OIL PALM PLANTATION MANAGEMENT PRACTICES FOR CONSERVING AQUATIC ENVIRONMENT USING BIOLOGICAL AND PHYSICOCHEMICAL APPROACHES

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ABSTRACT

Oil palm plantations on peatlands present challenges for water quality and biodiversity, impacting ecosystem health. Management practices in these plantations, herewith referred as buffer, modified buffer and main drain management, are essential in regulating water quality and supporting aquatic biodiversity while sustaining high yields. This study evaluates these practices within the Sabaju Oil Palm Plantation in Bintulu, Sarawak, Malaysia, using water quality parameters and aquatic insect diversity as indicators. Physicochemical parameters, including temperature, dissolved oxygen (DO), biochemical oxygen demand over 5 days (BOD_5), nutrients, chlorophyll-a, and total dissolved solids (TDS), were measured concurrently with aquatic insect sampling in April and September 2023. Malaysian biological indices Biological Monitoring Working Party Malaysia (BMWP-My) and Malaysian Family Biotic Index (MFBI) were calculated and compared with water quality data. A Generalised Linear Model (GLM) assessed the relationships between aquatic insect abundance and water quality. Results showed that buffer-managed sites maintained higher water quality, with lower temperatures, higher DO, lower nutrient levels, and a greater diversity of sensitive insect families, such as Hydropsychidae and Baetidae. In contrast, tolerant taxa like Chironomidae dominated modified buffer and main drain areas. Findings underscore the importance of native riparian buffer zones in safeguarding water quality and supporting aquatic diversity. The study suggests maintaining forest strips along waterways to mitigate the impact of oil palm plantations, illustrating the value of integrating biological and physicochemical measures in sustainable peatland management.

Keywords: aquatic insects, bioindicator, Borneo, oil palm plantation, water quality.

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INTRODUCTION

The rapid conversion of land for oil palm plantations in Sarawak, Malaysia has had a profound impact on local aquatic ecosystems. Between 1993 and 2003, land conversion rates in Sarawak surged by about 87%, leading to significant environmental changes, including the destruction of riparian vegetation, soil erosion, and pollution from agrochemicals (Mielke & Mielke, 2003). A study done by Wan Mohd Jaafar et al. (2020)

found that over the 28-year period, forest cover in Sarawak and Sabah declined by 12.6% and 16.3%, respectively, while peatland areas shrank by 20.5% and 19.1%. These trends underscore the significant and ongoing loss of vital ecosystems in both regions (Wan Mohd Jaafar et al., 2020). These changes have degraded water quality and biodiversity within and beyond plantation waterways. Assessing the effects of oil palm plantations is complex due to the intricate relationships between biological variables, prompting the use of multiple approaches to gauge aquatic ecosystem health, including bioindicators like aquatic insects. Aquatic insects serve as effective indicators due to their sensitivity to both current and historical environmental stressors, and their sedentary nature reflects both immediate water quality and past disturbances (Jumaat & Hamid, 2021). For example, Odonata (dragonflies and damselflies) are widely used as bioindicators of freshwater ecosystem health due to their high species richness and varied ecological requirements (Carvalho et al., 2013; Oliveira-Junior et al., 2015). The Ephemeroptera, Plecoptera, Trichoptera (EPT) families are particularly sensitive as they have gills and sedimentation might smother their gills or filtering devices, being clogged by the increase in sand or silts that often accompanies bank erosion (Wantzen, 2006).

Oil palm plantations rely heavily on pesticides and herbicides to sustain high yields. Consequently, chemical residuals frequently leach into nearby waterways, and some toxic residuals can harm aquatic biodiversity. A study shows that pesticide contamination can reduce aquatic invertebrate diversity and alter community structures (Suhling et al., 2000). Other studies have found that streams within oil palm plantations tend to have lower species richness and abundance compared to undisturbed control streams, with notable declines in aquatic insects like the orders Coleoptera and Hemiptera (Mercer et al., 2014). Loss of biodiversity has broader ecological implications, disrupting the natural balance of aquatic communities such as the collaps of Functional Feeding Guilds (FFGs) as different groups served different roles in the aquatic ecosystems (Talaga et al., 2017). Besides that, riparian buffer strips are essential in oil palm plantations because they protect waterways, maintain habitat quality, and support biodiversity. A study conducted by Williamson et al. (2020) found that wider and well-vegetated buffers were shown to create cooler and more humid microclimates, helping streams retain more natural environmental conditions. High-quality buffers also improve stream structure by reducing sedimentation and maintaining deeper, cooler channels (Luke et al., 2017). Biodiversity benefits are clear as well, as riparian set-asides in Bornean plantations were found to support higher bird richness (Amit et al., 2023), and diverse native fish communities in Sarawak plantation streams suggest that protected riparian zones help sustain freshwater fauna (Adha et al., 2021). Additionally, studies have shown that aquatic insect diversity and abundance are greater in streams with intact riparian buffers, highlighting their role in maintaining water quality and ecosystem health in oil palm landscapes (Williamson et al., 2020).

How do physicochemical parameters contribute to evaluating stream health in oil palm plantations, and what complementary metrics can strengthen the accuracy of these assessments? To address this ecological question, this study utilised two Malaysian biological indices, which are the Biological Monitoring Working Party Malaysia (BMWP-My) and Malaysian Family Biotic Index (MFBI), alongside physicochemical parameters, to assess the effectiveness of management practices in oil palm plantations for conserving aquatic ecosystems.

MATERIALS AND METHODS

Study Area and Sampling Sites

The study was conducted at the Sabaju Oil Palm Plantation (*Figure 1*), managed by Sarawak Oil Palms Berhad (SOPB) in Bintulu, Sarawak, Malaysia. Spanning approximately 8,041 ha, the plantation primarily consists of peatland with some mineral soil areas. Sungai Ngiat and all main drainage systems (MD 10/28 and MD 11/13) are on peatland soils, while Sungai Belungai, Sungai Sabaju, and Sungai Sujan flow through areas with mineral soils. Although the broader Sabaju Oil Palm Plantation is predominantly a peat-domed landscape, it also contains small pockets of elevated mineral soils (Cook et al., 2018). Therefore, surface water samples collected for physicochemical analysis reflect the integrated drainage water rather than isolated groundwater from small mineral hills. Its waterways include a managed drainage system (main, collection, and field drains) and natural streams and rivers (Sungai Ngiat, Sungai Belungai, Sungai Sujan and Sungai Sabaju) that flow into the Sungai Kemena. These water systems are vital to the local communities' livelihoods. SOPB oversees the plantation's operations, including waterway management within and beyond its boundaries.

The plantation employs three management strategies to balance palm oil production with biodiversity conservation: buffer management, modified buffer management, and main drain management. In buffer and modified buffer zones, no chemical inputs (fertilisers, herbicides, or pesticides) are applied, and pruned fronds are prohibited from entering waterways. The primary difference between these two approaches lies in vegetation: buffer management retains native forest cover, while modified buffer management is dominated by grasses, exposing waterways to more runoff.

Main drain management focuses on flood prevention by maintaining water levels through periodic excavation of drain channels to remove debris or vegetation from the drain using excavators to re-establish the original depth and channel profile. These areas are lined with oil palm trees and grasses and lack riparian forest vegetation.

The three management practices represent distinct strategies required under the Malaysian Sustainable Palm Oil (MSPO) Certification 2.0 (Cheah, 2023). They aim to mitigate environmental impacts by conserving riparian buffer zones and leaving unsuitable areas uncultivated, ensuring sustainable plantation management.

Sampling Design

Between April and September 2023, sampling was carried out during both wet and dry seasons. Within each site, sampling points were selected randomly using random distances or coordinates to avoid favouring any particular microhabitat. Sampling covered buffer management sites (Sungai Ngiat, Sungai Sujan and Sungai Belungai), the modified buffer management site (Sungai Sabaju), and main drain management sites (MD 11/13 and MD 10/28), with 50 m stretches sampled per stream. The modified buffer only has one site because of logistical constraints, as it remained flooded and inaccessible during both sampling periods, preventing safe access and reliable data collection. Nevertheless, the single modified buffer site included in this study remains valid and representative because it consistently reflects the environmental conditions characteristic of modified buffer zones within the plantation, allowing for meaningful comparison with the buffer and drain management practices. Two sessions per station, held in the afternoon and evening, ensured coverage of aquatic insect activity variations as many taxa show changes in behaviour drift, and emergence across different times.

In situ water quality measurements were taken using a YSI multiparameter probe to record temperature, dissolved oxygen (DO), pH, conductivity, and turbidity, while a FlowWatch flowmeter measured water flow. *Ex situ* water samples were collected for laboratory analysis, assessing parameters such as chemical oxygen demand (COD), ammoniacal nitrogen (NH_3-N), total phosphorus (TP), chlorophyll-*a* (Chl-*a*), total dissolved solids (TDS), and biochemical oxygen demand over 5 days (BOD_5). A 500 mL sample of the surface water below 10 cm (Gupta, 2009) was collected from each sampling point using sterilised polypropylene bottles. A total of three replicates of water samples were taken at each site in all management practices. COD indicated pollution levels, NH_3-N reflected ammonia contamination, TP highlighted eutrophication risks, and Chl-*a* measured algal productivity. BOD_5 samples were stored in sterilised, light-protected bottles to prevent photosynthesis and ensure accurate measurements. Reading for BOD analysis was taken after five days upon collection using a DO meter.

Aquatic insects were collected from the same transects where water quality was performed. The 3 min kick net method was used by placing the net facing upstream, while the area in front of the net was agitated for about 3 min (Blakely et al., 2014). Hand-net methods were used to collect surface-dwelling insects. Collected samples were then preserved in 70% ethanol, and identified to the family level under a stereomicroscope. Standard identification keys by Orr (2003) and Yule and Yong (2004) were used. Adult Odonata were also collected along the same transects with sweep nets and preserved using the papering method (Cezário et al., 2021).

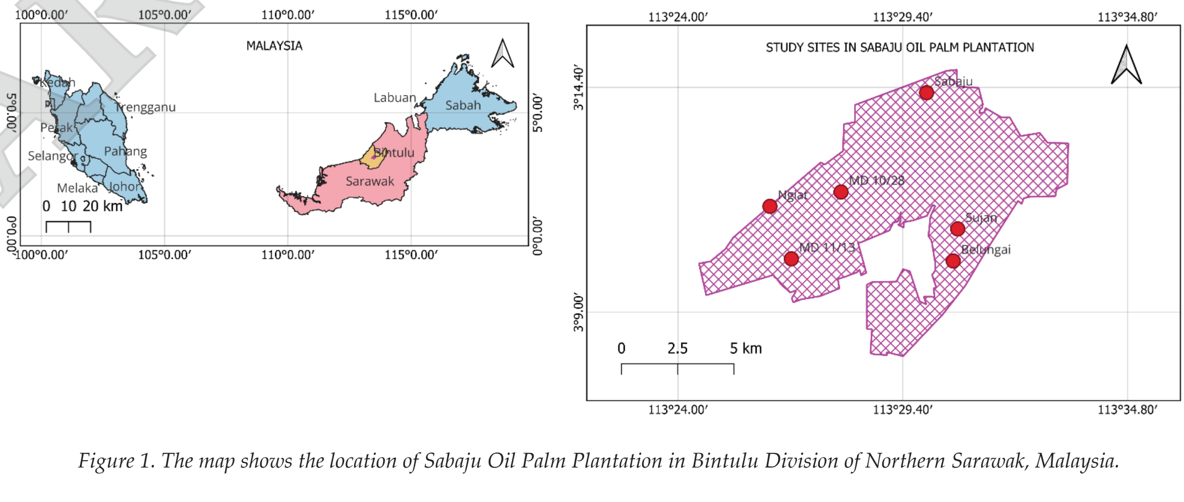


Figure 1. The map shows the location of Sabaju Oil Palm Plantation in Bintulu Division of Northern Sarawak, Malaysia.

Data Analysis

Principal component analysis (PCA) was applied to 13 water quality parameters to simplify the data and identify key factors affecting aquatic conditions under different management practices. The water quality index (WQI) was calculated based on the Interim National Water Quality Standards (INWQS) (Department of Environment [DOE], 2001) to classify water quality. PCA was used to examine the variation in aquatic insect family composition across management practices without being constrained by specific environmental variables. The PCA was performed using Paleontological Statistics (PAST) software (version 4.03) (Hammer et al., 2001).

Aquatic insect abundance was summarised in a boxplot using JAMOVI software (version 2.3.28), while Shannon's diversity index (H') was calculated using PAST software and the Jaccard similarity index assessed family diversity. Significant differences in diversity across management practices were evaluated using a Hutcheson's Student's T-test because diversity indices like Shannon H' have special statistical properties that do not fit normal t-test assumptions. Hutcheson's method is specifically designed for comparing diversity indices, properly handling their unique variance structure and ensuring reliable statistical conclusions about biodiversity differences. A rarefaction curve, estimating family richness with 50 bootstraps and 95% confidence intervals, was generated using iNEXT Online (version March 2024) (Chao et al., 2016).

Two Malaysian biological indices, BMWP-My and MFBI (Wan Abdul Ghani, 2016), were used to assess biological water quality. The BMWP-My score (*Table 1*) classifies water quality based on taxon-specific tolerance values (1 = high tolerance, 10 = low tolerance) and was calculated using the equation from Wan Abdul Ghani (2016) in Equation (1).

$$\text{BMWP-My} = \Sigma t_i \tag{1}$$

where t_i is the tolerance value of the family i.

The MFBI scores are derived by weighting family abundance by tolerance scores, providing a similar classification for each site. The MFBI was calculated using the following equation from Wan Abdul Ghani (2016) in Equation (2):

$$\text{MFBI} = \frac{\Sigma(t_i \times n_i)}{N} \tag{2}$$

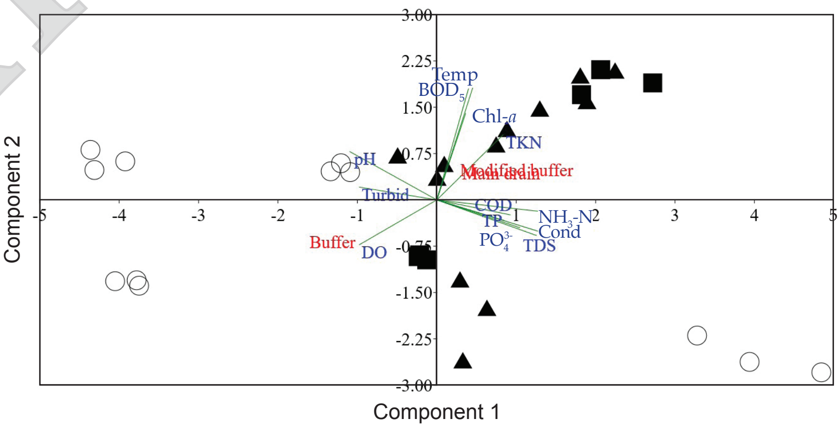
where n_i is the number of individuals in the family i, t_i is the tolerance value of family i, and N is the total number of individuals in the sample, calculated as $N = \Sigma n_i$.

A generalised linear model (GLM) with a Poisson link was used to assess the relationship between water parameters and insect abundance using JASP (version 0.18; JASP Team, 2024). To address multicollinearity in the dataset, variance inflation factor (VIF) diagnostics were performed on all water quality variables before modelling. Variables with VIF values above the recommended threshold (VIF > 10) were excluded from subsequent analyses to improve model performance and interpretability.

RESULTS AND DISCUSSION

Variation of Water Quality Parameters Across Management Activities

The 13 water quality parameters varied across the three management activities, as illustrated in the PCA biplot (*Figure 2*), reflecting the effectiveness of each management practice in the Sabaju Oil Palm Plantation. The analysis simplifies the dataset while



Note: Circles - buffer management; squares - modified buffer management; and triangles - main drain management.

Figure 2. The PCA plot shows the variation in 13 water quality parameters across management practices.

highlighting key differences, with Components 1 and 2 explaining 48% and 18% of the total variance, respectively. *Table 1* shows a summary of water quality parameters across management practices.

Component 1 is influenced by conductivity (0.370), TDS (0.366), and NH_3-N (0.370), highlighting nutrient-level differences among management practices. Modified buffer and main drain management are positively associated with this component, indicating higher nutrient levels. Modified buffer management showed the highest TDS (89.38 ± 3.99 mg/L) and NH_3-N (1.21 ± 0.01 mg/L), followed by main drain management (TDS = 77.61 ± 0.86 mg/L, NH_3-N = 0.97 ± 0.03 mg/L), while buffer management had the lowest values (TDS = 60.11 ± 3.03 mg/L, NH_3-N = 0.75 ± 0.09 mg/L). Nutrient concentrations, especially NH_3-N, were higher in modified buffer and main drain areas, likely due to fertiliser runoff (Abidin et al., 2018). Buffer zones had the lowest NH_3-N levels, showcasing the filtration capacity of riparian vegetation (Mayer et al., 2007). Although buffer sections included minor mineral soil patches within the peat-dominated landscape, NH_3-N patterns were primarily driven by vegetation density and hydrological buffering rather than soil type. However, unexpectedly high TP levels in buffer zones may indicate vegetation reaching its nutrient absorption limits, resulting in phosphorus runoff (Correll, 1998; Frissel & Van Veen, 1981). Elevated NH_3-N and TP in modified buffer areas also correlated with higher Chl-*a* levels, a sign of eutrophication that stresses ecosystems by reducing water clarity and depleting oxygen during algal decomposition (Smith & Schindler, 2009). Lower TP concentrations in the main drain may be due to active phosphorus uptake by periphyton, which removes phosphorus from the water column (Pearce et al., 2023), supported by the higher Chl-*a* levels observed in this management area.

Component 2 is driven by temperature (0.527), BOD_5 (0.525), and Chl-*a* (0.408). Modified buffer and main drain management correlated strongly with this component, showing elevated BOD_5 and Chl-*a* levels. Modified buffer management recorded the highest BOD_5 (4.95 ± 0.49 mg/L) and Chl-*a* (9.11 ± 0.36 mg/L), followed by main drain management (BOD_5 = 4.66 ± 0.27 mg/L, Chl-*a* = 7.48 ± 0.83 mg/L). Buffer management showed the lowest values (BOD_5 = 2.79 ± 0.29 mg/L, Chl-*a* = 5.50 ± 0.40 mg/L). Water temperature was consistent across sites, though slightly higher in the main drain management (28.18 ± 0.10°C). The analysis of BOD_5 levels highlights organic pollution and its impact on ecosystem health. Higher BOD_5 levels in modified buffer and main drain areas suggest greater organic pollution from plant litter, agricultural runoff, and fertilisers. This increases microbial activity, depleting DO during organic matter decomposition. Similarly, Bajpai (2018) noted a direct link between BOD_5 and DO, where higher organic matter accelerates oxygen consumption. Lower BOD_5 levels in buffer zones indicate that riparian vegetation filters organic matter effectively, supporting better DO levels (Mayer et al., 2007). This is vital in peat swamps, where slow decomposition could otherwise lead to oxygen depletion (Page et al., 1999). In contrast, lower Chl-*a* levels in buffer zones emphasise the role of riparian vegetation in mitigating nutrient runoff and eutrophication (Burrell et al., 2014).

Temperature plays a crucial role in regulating DO, essential for aquatic life. In drain management areas, the lack of canopy cover exposes water to direct sunlight, increasing temperatures and lowering DO levels. While our study found no significant temperature differences between management practices, even small increases can substantially impact DO, as noted by Allan and Castillo (2007). Rosli et al. (2010) observed similar patterns in deforested areas, where higher temperatures reduced DO. This effect is particularly concerning in tropical peat swamps, which naturally have low DO levels (Rahim et al., 2009; Yule & Gomez, 2009).

TABLE 1. SUMMARY OF WATER QUALITY PARAMETERS ACROSS MANAGEMENT PRACTICES, MEASURED *IN SITU* USING YSI MULTIPARAMETER AND LABORATORY ANALYSIS

Parameters	Mean ± standard error		
	Buffer	Modified buffer	Main drain
TDS (mg/L)	60.11 ± 3.03	89.38 ± 4.00	77.61 ± 0.86
Temperature (°C)	27.67 ± 0.03	27.45 ± 0.05	28.18 ± 0.10
DO (mg/L)	4.31 ± 0.20	2.56 ± 0.21	1.73 ± 0.24
COD (mg/L)	63.92 ± 4.99	60.00 ± 1.94	79.96 ± 2.51
NH_3-N (mg/L)	0.75 ± 0.09	1.21 ± 0.01	0.97 ± 0.03
TP (mg/L)	1.36 ± 0.10	1.04 ± 0.08	1.20 ± 0.03
BOD_5 (mg/L)	2.79 ± 0.29	4.95 ± 0.49	4.66 ± 0.27
Chl-*a* (mg/L)	5.50 ± 0.40	7.48 ± 0.83	9.11 ± 0.36

Note: TDS - total dissolved solids; DO - dissolved oxygen; COD - chemical oxygen demand; NH_3-N - ammoniacal nitrogen; TP - total phosphorus; BOD_5 - biochemical oxygen demand over 5 days; Chl-*a* - chlorophyll-*a*.

In contrast, buffer management areas with riparian vegetation provide shade, stabilise temperatures, and help maintain higher DO levels. The cooling effect of riparian zones, as highlighted by Rojas-Castillo et al. (2023), plays a critical role in reducing environmental stress on aquatic ecosystems.

The COD and TDS provide further insight into pollution levels. Main drain areas had the highest COD, reflecting elevated pollutants from poor waste management (Yisa & Jimoh, 2010). In peat-dominated systems such as Sabaju, being waterlogged, they accumulate pollutants over time, worsening COD in unmanaged areas (Yule, 2010). Modified buffer areas showed the highest TDS levels, likely from erosion and sedimentation due to inadequate riparian cover, as noted by Chellaiah and Yule (2018), as riparian buffers help mitigate soil erosion because the vegetation stabilises the riverbanks, with root systems binding the soil together and reducing sediment loss. The riparian vegetation at the modified buffer is dominated by some grasses and little to none native forest cover compared to buffer management. Buffer zones, with lower COD and TDS, demonstrate the ability of riparian vegetation to trap sediments and pollutants before they enter waterways (Mayer et al., 2007).

Assemblages of Aquatic Insect Families Among Three Management Practices

This study identified 2,944 aquatic insect individuals from 19 families across eight orders in three management practices (buffer, modified buffer and main drain) within the Sabaju Oil Palm Plantation (*Table 2*). Hemiptera dominated with 43% of the total abundance sampled across all management, while Odonata was the most diverse, represented by eight families, which consist of Libellulidae, Coenagrionidae, Gomphidae, Platycnemididae, formerly placed under Protoneuridae (Dijkstra et al., 2014), Euphaeidae, Chlorocyphidae, Aeshnidae, and Lestidae. Other orders, including Coleoptera, Trichoptera, and Ephemeroptera, were represented by one or two families each.

Buffer management had the highest diversity with a total of 17 families, contributing 45.52% (1,340 individuals) of the total, with Micronectidae (Hemiptera) making up 15.00%. Modified buffer management accounted for 22.32% (657 individuals) from 14 families, with Notonectidae (Hemiptera) as the dominant family. Main drain management, the least diverse, comprised 32.17% (947 individuals) from 11 families, with Notonectidae again being the dominant group. The box plot (*Figure 3*) highlights that buffer sites supported the largest number of individuals, while main drain sites, despite a high median count, showed lower abundance, and modified buffer management had the fewest individuals.

The PCA was conducted to examine the variation in aquatic insect species composition across management practices (*Figure 4*). The first two components (PC1 and PC2) explained 94.1687% of the total variance, with PC1 accounting for 85.0100% and PC2 contributing 9.1500%. PC1 revealed significant differences among insect families, with Notonectidae (4.272) and

TABLE 2. AQUATIC INSECT FAMILY ABUNDANCE ACROSS THREE MANAGEMENT PRACTICES (BUFFER, MODIFIED BUFFER AND MAIN DRAIN)

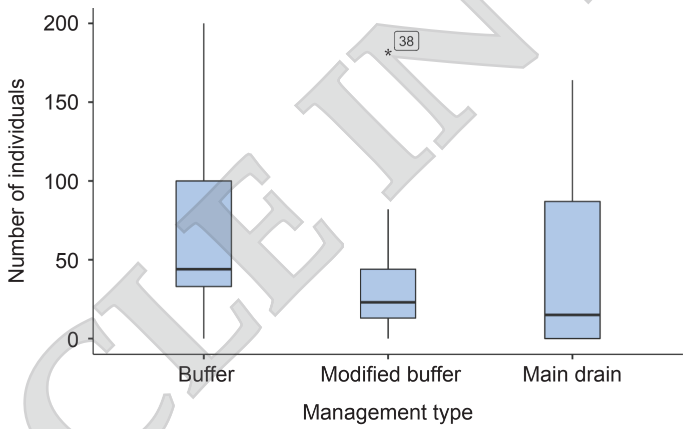
Order	Family	Malaysian tolerance value (TV)	Buffer	Modified buffer	Main drain
Odonata	Libellulidae	5	117	48	79
	Gomphidae	5	90	53	42
	Lestidae	0	48	23	42
	Coenagrionidae	5	81	44	58
	Euphaeidae	6	17	0	0
	Chlorocyphidae	5	32	0	0
	Platycnemididae	7	37	0	0
	Aeshnidae	8	51	0	0
Hemiptera	Notonectidae	5	178	182	164
	Micronectidae	0	200	82	154
	Gerridae	5	100	26	87
	Hydrometridae	0	35	51	0
Coleoptera	Dysticidae	6	110	38	103
	Gyrinidae	5	39	0	0
	Hydrophilidae	6	132	38	99
Trichoptera	Hydropsychidae	5	40	20	0
Diptera	Tipulidae	6	0	13	0
	Chironomidae	1	0	24	104
Ephemeroptera	Baetidae	6	33	15	15

Micronectidae (3.056) showing strong positive loadings, indicating that these families thrive in modified buffer and buffer management. In contrast, families such as Euphaeidae (–1.535) were negatively associated with PC1, highlighting their strong affiliation with buffer areas. PC2 revealed additional variation, with Notonectidae (1.296) and Hydrometridae (0.921) positively associated with modified buffer management. The proximity of the main drain and buffer on the PCA plot indicates that insect community composition in these two habitat types is similar.

Buffer zones, with intact riparian vegetation, supported higher aquatic insect family diversity (H’) compared to modified buffer and main drain areas (*Table 3*). This aligns with studies highlighting the role of riparian buffers in enhancing habitat complexity and reducing agricultural runoff impacts (Sweeney & Newbold, 2014; Yule, 2010). However, declines in sensitive taxa within buffer zones suggest that even these areas face ecological limits in high-intensity agricultural systems like oil palm plantations (Luke et al., 2020).

Sensitive taxa, such as Hydropsychidae and Baetidae, were more prevalent in buffer zones, likely benefiting from stable microhabitat conditions, including moderated temperatures, higher DO levels, and reduced eutrophication due to vegetative nutrient uptake (Azrina et al., 2006). In contrast, the modified buffer and main drain areas were dominated by pollution-tolerant taxa such as Chironomidae, indicating degraded conditions due to runoff and sedimentation (Al-Shami et al., 2011).

The dominance of resilient taxa such as Chironomidae, Notonectidae, and Micronectidae in disturbed areas reflects a shift to less diverse communities adapted to poor water quality (Wan Abdul Ghani, 2016). This pattern aligns with studies showing reduced EPT taxa in areas with high sedimentation, such as Baetidae and Hydropsychidae (Mercer et al., 2014; Wahizatul et al., 2011; Yule et al., 2010). The absence of sensitive taxa in modified buffer and main drain areas underscores the importance of native riparian buffers in maintaining biodiversity and mitigating environmental stress.



Note: The outlier, as indicated by an asterisk (*) 38, refers to the family Notonectidae with 182 individuals. Each management type consists of two replicates for the buffer, one replicate for the modified buffer and two replicates for the main drain.

Figure 3. The boxplot of the abundance of aquatic insect families from three management activities of the oil palm plantation.

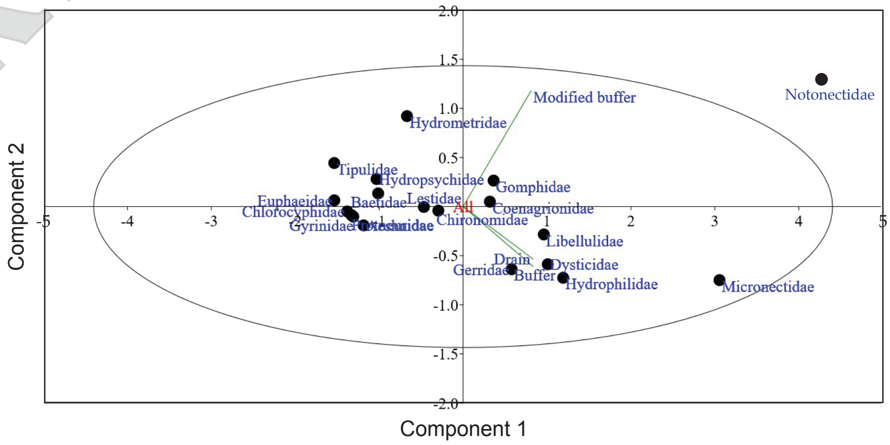


Figure 4. The plot of PCA shows the variation of aquatic insect abundance across three management activities at Sabaju Oil PalmPlantation.

TABLE 3. THE VALUES OF SHANNON'S DIVERSITY INDEX (H') AND JACCARD'S SIMILARITY INDEX FOR MEASURED FAMILY LEVEL AT THREE DIFFERENT MANAGEMENT ACTIVITIES OF OIL PALM PLANTATIONS

Management activity	Modified buffer (H' = 2.36)	Main drain (H' = 2.26)
Buffer (H' = 2.63)	Jaccard's Index = 0.63 *t = 7.716, $p < 0.0001$	Jaccard's Index = 0.56 *t = 16.017, $p < 0.0001$
Modified buffer		Jaccard's Index = 0.79 t = 62.809, $p = 0.0051$

Note: * - The means of Shannon's index are significantly different among the three management activities.

Jaccard similarity analysis (*Table 3*) showed moderate overlap between buffer and modified buffer areas, sharing 11 families. There were five families exclusive to buffer zones, emphasising their role in biodiversity conservation. The low similarity between buffer and main drain areas indicates significant species loss and environmental degradation in main drain management (Luke et al., 2020). These findings demonstrate the ecological value of riparian buffers in stabilising aquatic ecosystems through multiple mechanisms: Regulating water temperature and light penetration, stabilising stream banks to maintain benthic habitat, filtering agricultural runoff, and providing organic matter inputs that support aquatic food webs, collectively underpinning their importance for aquatic biodiversity conservation.

Generalist species, such as many members of the Odonata families, Libellulidae and Coenagrionidae, were more common across all management practices in the oil palm plantation. These species are more adaptable to altered environments, while forest specialists, which are more sensitive to habitat changes, declined. The presence of generalists indicates habitat homogeneity, where species with broad ecological tolerance thrive, but sensitive species are lost (Ferreira et al., 2014; Fitzherbert et al., 2008). A study by Elo et al. (2015) on Finnish peatlands reported that Odonata communities were negatively affected by drainage but showed rapid recovery following peatland restoration, with new water pools being recolonised within just three years.

In the context of oil palm plantations, it suggests strengthening management practices, particularly by enhancing and restoring buffer zones to mitigate the impacts of drainage and support the recovery of sensitive aquatic insect groups. Rarefaction curves (*Figure 5*) showed that buffer management supported higher family richness, while modified buffer and main drain management reached species saturation earlier, indicating lower richness. This highlights the role of buffer zones with intact riparian vegetation in maintaining higher biodiversity and providing more stable habitats for aquatic insects (Shafie et al., 2017). Modified buffer and main drain management, on the other hand, produced more homogenised communities dominated by fewer, more resilient taxa. Environmental factors such as rainfall and water flow fluctuate across seasons and can significantly affect nutrient levels, DO, and sedimentation. Seasonal studies in similar ecosystems have shown that certain taxa vary in abundance and diversity over time due to changes in water flow, vegetation cover, and nutrient input (Al-Shami et al., 2011).

Biological Indicator Versus Physicochemical Approaches

The BMWP-My scores (Wan Abdul Ghani, 2016) for buffer were classified as Class III, indicating moderately good water quality, with buffer management scoring 79, modified buffer management scoring 55, and main drain management receiving the lowest score of 44, both falling under Class IV, indicating very poor water quality (*Table 4*). The MFBI showed that all management practices had good water quality, with buffer management scoring 5.50 and modified buffer management scoring 5.02 (*Table 4*). Main drain management, with a score of 4.74, was also classified as having good water quality (Class II) (Wan Abdul Ghani et al., 2018).

The assessment of WQI (*Table 4*) using the INWQS shows buffer management was classified under Class III (polluted), which is only suitable for livestock drinking, while both modified buffer and main drain management areas fell under Class IV (very polluted), only suitable for irrigation (DOE, 2001). These classifications illustrate discrepancies between biological indices and physicochemical assessments. While biological indices, like BMWP-My and MFBI, indicated moderate to good water quality across the management practices, the physicochemical WQI classified buffer management as moderately polluted and both modified buffer and main drain management as heavily polluted. This divergence is common and can be explained by the different temporal responses of each method. The macroinvertebrate communities reflect ecological conditions integrated over weeks or months and may be dominated by pollution-tolerant species (e.g., Chironomids) that survive and reproduce

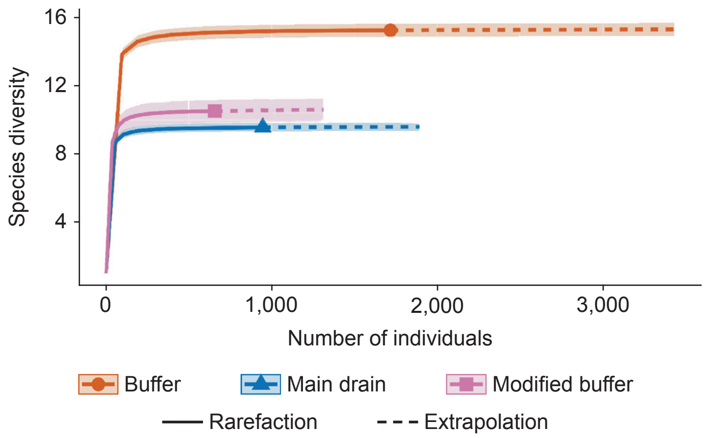


Figure 5. Rarefaction curve and extrapolation of family richness among three management practices based on 50 bootstraps and 95% confidence intervals.

TABLE 4. THE RANGE AND AVERAGE OF BIOLOGICAL INDICES AND THEIR WATER QUALITY CLASSIFICATION AT THREE MANAGEMENT PRACTICES

Biological indices	Management activities		
	Buffer	Modified buffer	Main drain
BMWP-My	79 Good Class II	55 Very poor Class IV	44 Very poor Class IV
MFBI	5.50 Good Class III	5.02 Good Class III	4.74 Good Class III
WQI	63.27 Class III	47.21 Class IV	51.46 Class IV

Note: BMWP-My - Biological Monitoring Working Party Malaysia; MFBI - Malaysian Family Biotic Index; WQI - water quality index.

in chronically disturbed habitats. In contrast, the physicochemical WQI captures acute, short-term pollution events that the resilient biological community has temporarily withstood (Nguyen et al., 2023; Tampo et al., 2021).

The GLM analysis revealed significant correlations between various water quality parameters and aquatic insect abundance (*Table 5*). Seven key water quality variables (temperature, DO, NH_3-N, BOD_5, TP, Chl-*a*, and COD) were analysed after excluding six highly intercorrelated variables. Temperature was found to have a negative relationship with insect abundance, with each unit increase in temperature decreasing insect abundance by 29.0% (Exp(B) = 0.706). Similarly, COD showed a small but significant negative effect, reducing insect abundance by 0.8% for each unit increase (Exp(B) = 0.992). In contrast, NH_3-N showed a positive correlation, increasing insect abundance by 63% with every unit increase (Exp(B) = 1.629). The DO negatively impacted insect abundance, with each increase in DO decreasing abundance by 7.0% (Exp(B) = 0.932), while BOD_5 had a positive effect, increasing insect abundance by 4.5% (Exp(B) = 1.045). Buffer management was consistently associated with higher insect abundance, as demonstrated by the GLM analysis, which found a 31.2% and 31.3% decrease in insect abundance in the main drain and modified buffer zones, respectively, compared to buffer zones. These results underscore the critical role of buffer zones in mitigating environmental stressors and maintaining biodiversity.

The absence of sensitive insect families such as Chlorocyphidae and Euphaeidae (Odonata) in modified buffer and main drain areas further emphasises the positive impact of conserving native riparian buffer zones instead of just grasses on biodiversity conservation (Oliveira-Junior & Juen, 2019). Buffer zones effectively reduce stressors such as elevated temperatures and increased organic pollution, which are prevalent in areas lacking riparian vegetation (Rosli et al., 2010). Interestingly, nutrient enrichment, especially the increase of NH_3-N concentration, appears to support higher insect populations, likely due to the prevalence of nutrient-tolerant taxa. This is supported by a study conducted by Li et al. (2023), which demonstrated that increased ammonia loading led to higher macroinvertebrate abundance, primarily driven

TABLE 5. RESULTS OF GENERALISED LINEAR MODEL (GLM) WITH POISSON LINK FUNCTION (LOG) FOR AQUATIC INSECT ABUNDANCE AND ENVIRONMENTAL PARAMETERS

Item	B	Exp(B)	Standard error	z-value	*p*-value
Intercept	15.687	6,497,968	1.854	8.463	<0.001
Temperature	–0.348	0.706	0.067	–5.164	<0.001
COD	–0.008	0.992	0.001	–5.242	<0.001
NH_3-N	0.488	1.629	0.103	4.744	<0.001
DO	–0.070	0.932	0.020	–3.511	<0.001
BOD_5	0.044	1.045	0.017	2.642	0.008
Main drain vs. buffer	–0.374	0.688	0.054	–6.931	<0.001
Modified buffer vs. buffer	–0.376	0.687	0.066	–5.713	<0.001
Main drain vs. modified buffer	0.002	1.002	0.071	0.024	0.981

Note: COD - chemical oxygen demand; NH_3-N - ammoniacal nitrogen; DO - dissolved oxygen; BOD_5 - biochemical oxygen demand over 5 days.

by gathering collectors and predators. This was attributed to enhanced phytoplankton growth promoted by the ammonia input and increased internal phosphorus release in the ponds. Additionally, the biomass of predators rose with increasing NH_3 levels, likely due to a bottom-up effect through greater prey availability. Their findings also indicated that the toxicity of ammonia to aquatic organisms depends on the ecological scale (Li et al., 2023). However, this trend may mask broader biodiversity losses, emphasising the need for multidimensional metrics that go beyond mere species presence or absence, including abundance patterns, functional feeding groups diversity, and shifts in community composition to capture ecological resilience (Resh & Rosenberg, 2008). These complex dynamics underscore the importance of integrated monitoring frameworks that combine biological and physicochemical data for a more accurate assessment of ecosystem conditions (Wan Abdul Ghani et al., 2018).

The discrepancy between biological and physicochemical indices in assessing water quality is evident. Biological indices such as BMWP-My and MFBI are effective in tracking the responses of sensitive taxa but may be limited by their regional specificity. Meanwhile, the MFBI (*Table 5*), which showed relatively stable values across all management practices, failed to capture subtle ecological changes in disturbed areas. This is due to the exclusion of resilient insect families such as Hydrometridae and Micronectidae from the MFBI calculations, leading to an overestimation of water quality in degraded habitats (Wan Abdul Ghani et al., 2018). Moreover, while the presence of tolerant families like Chironomids was noted, their inclusion did not sufficiently raise MFBI scores in disturbed areas, further diminishing the reliability of the index in assessing water quality (Hilsenhoff, 1998).

The WQI shows pollution levels but does not fully reflect the biological implications of these findings. For instance, while buffer management was classified as moderately polluted and modified buffer and main drain management as heavily polluted, the biological indices painted a more nuanced picture, highlighting ecological changes not immediately apparent from the chemical parameters alone (Metcalfe, 1989). This discrepancy between biological indices and WQI is common in agricultural ecosystems, where biological assessments often detect ecological shifts that chemical indices overlook (Suhaila & Che Salmah, 2017).

The study's limitations lie in the potential time-lagged effects of management practices on biological indices. The response of macroinvertebrate communities may take time to reflect changes in water quality, making it challenging to assess the immediate impact of management practices (Cousins & Vanhoenacker, 2011). Physicochemical assessments, in contrast, offer a more immediate measure of water quality, but they may not capture the complexity of tropical ecosystems like peat swamps, which could explain the discrepancies observed with biological indices (Metcalfe, 1989).

There is also a pressing need to adapt existing biological indices, such as the MFBI, to reflect the specific ecological conditions of Southeast Asian peat swamp ecosystems. Current indices fail to account for key taxa that are important indicators of disturbance, thus compromising their reliability in assessing the ecological health of these habitats (Wan Abdul Ghani et al., 2018).

CONCLUSION

In conclusion, this study highlights buffer management as the most effective strategy for maintaining ecological health and biodiversity in the Sabaju Oil Palm Plantation in Bintulu, Sarawak, Malaysia. Buffer zones showed the highest aquatic insect diversity, reflecting healthier ecosystems and better water quality than the modified buffer and main drain management practices. These zones serve as natural filters, reducing sedimentation, nutrient runoff, and pollutants while supporting habitat integrity and species diversity.

The results emphasise the importance of riparian buffers, particularly native buffers, for biodiversity conservation. Optimising buffer design, such as using multi-layered vegetation or wider zones, could enhance their ability to protect biodiversity. However, nutrient runoff from peatland substrates may limit the filtering capacity of even well-established buffer zones. Comparing buffer performance between peatland and mineral soil plantations could provide insights into whether peatland buffers need adapted practices.

Effective assessment of management practices requires combining biological and physicochemical monitoring. Biological monitoring using aquatic insect diversity indices (e.g., BMWP-My and MFBI) provides a long-term view of ecosystem health, while physicochemical monitoring offers immediate insights into water quality. Both methods complement each other in detecting both short-term pollution and long-term environmental stressors.

Early monitoring is crucial for establishing baseline data and tracking trends over time. Regular seasonal sampling, expanding buffer zones, and restoring riparian zones are essential for conserving aquatic life and managing water quality. Integrating these strategies into an adaptive management framework will support sustainable plantation practices that align with conservation goals, promoting biodiversity and ecosystem health throughout the plantation lifecycle.

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