Pesticide Residues in a Protected Tropical Water Catchment: Baseline Evidence and Implications for Long-Term Drinking Water Safety in Malaysia

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ABSTRACT

This study investigated pesticide residues in raw water from the Sarawak Kiri River catchment, a critical drinking water source supplying the Batu Kitang Water Treatment Plant in Sarawak, Malaysia. Despite the presence of surrounding agricultural activities, comprehensive multi-residue analysis covering acid herbicides, organochlorine, organophosphate pesticides, and other herbicides revealed concentrations below method detection limits in samples collected in January 2025.

While these findings suggest an absence of detectable contamination at the point of abstraction, interpretation requires caution. Non-detection does not necessarily equate to absence of risk, particularly given temporal variability, episodic runoff events, and limitations inherent in analytical detection thresholds. The apparent absence of pesticide residues may reflect a combination of low-intensity agricultural practices, effective riparian buffering, hydrological dilution due to high rainfall, and regulatory protection of the catchment.

Importantly, the findings highlight a critical window of opportunity for proactive protection of a relatively uncontaminated water source in a region undergoing gradual land-use transition. This study underscores the need for longitudinal monitoring, event-based sampling, and integration of emerging contaminants into surveillance frameworks to ensure long-term drinking water safety. The results contribute to evidence-based water resource management in tropical catchments and provide a baseline for future environmental risk assessments.

Keywords: Batu Kitang, environmental monitoring, pesticide residues, Sarawak Kiri River, water catchment,

INTRODUCTION

The access to safe drinking water remains a fundamental public health priority, yet contamination of water sources by agricultural chemicals continues to pose a growing global concern. Among these, pesticides are of particular importance due to their widespread use, environmental persistence, and potential adverse effects on human health and ecosystems. Globally, pesticide contamination of surface and groundwater has been increasingly reported, with residues detected in both developed and developing regions, often exceeding guideline values or occurring as complex mixtures with uncertain toxicological implications [1, 2].

In tropical regions, the risk of pesticide transport into water bodies is further amplified by climatic and hydrological conditions. High rainfall intensity, characteristic of Southeast Asia, facilitates surface runoff and leaching, increasing the likelihood of pesticide residues entering rivers and drinking water sources [3]. Studies across the region have documented detectable levels of pesticides such as organophosphates, herbicides, and legacy organochlorines in river systems, often associated with agricultural expansion and land-use change [4]. These findings highlight the vulnerability of tropical catchments to diffuse agricultural pollution, even in areas perceived as low intensity.

Malaysia is not exempt from these challenges. Rapid agricultural development, including oil palm plantations and smallholder farming, has raised concerns regarding the potential contamination of water resources. Previous studies in Peninsular Malaysia have reported pesticide residues in surface water, albeit generally within permissible limits, suggesting low-level but persistent environmental exposure [5]. However, data from East Malaysia, particularly Sarawak, remain limited despite its unique ecological characteristics, high rainfall, and increasing development pressure. To date, no published study has systematically evaluated pesticide residues in protected tropical drinking water catchments in Sarawak.

The Sarawak Kiri River catchment represents a critical drinking water source supplying the Batu Kitang Water Treatment Plant, which serves a large population in Kuching and surrounding areas. Although the catchment is partially protected under regulatory frameworks, it is not entirely insulated from anthropogenic activities, including small-scale agriculture and rural settlements. Such land uses introduce potential pathways for pesticide contamination through runoff, especially during heavy rainfall events.

Despite its importance, there is a notable lack of empirical data on pesticide residues in this catchment. Most existing monitoring efforts in Malaysia focus on more urbanized or intensively cultivated regions, leaving relatively understudied catchments such as Sarawak Kiri underrepresented in the literature. This represents a critical knowledge gap, particularly given the strategic importance of safeguarding drinking water sources before contamination becomes established.

Furthermore, environmental monitoring studies often face a conceptual limitation whereby “non-detection” is interpreted as absence of risk. Increasingly, the literature emphasizes that such interpretations may be misleading, as pesticide residues can occur below detection limits, exhibit temporal variability, or exist as transformation products not routinely monitored [6]. Therefore, baseline assessments in relatively pristine catchments should be framed not only as confirmation of safety but also as an opportunity for preventive environmental management.

The present study aims to evaluate the presence of selected pesticide residues in raw water from the Sarawak Kiri River catchment at the Batu Kitang intake. Specifically, the study seeks to (i) determine the occurrence of commonly used pesticide groups, including herbicides and organochlorine and organophosphate compounds, (ii) assess compliance with international drinking water guidelines, and (iii) establish a baseline dataset to inform future monitoring and policy interventions. By addressing an underexplored geographical area and critically interpreting findings within a broader environmental health framework, this study contributes to the evidence base required for sustainable water resource management in Malaysia.

MATERIALS AND METHODS

STUDY AREA

The Sarawak Kiri catchment supplies the Batu Kitang Water Treatment Plant, which serves an expanding supply boundary of about 730 km². The region consists mainly of rural settlements and low-intensity farming activities.

Sampling Procedure

Water samples were collected at the Batu Kitang intake in January 2025 using pre-cleaned amber bottles. Samples were immediately stored in an ice box (~4 °C) and transported to the analytical laboratory within the same day.

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Figure 1. Field sampling and sample preservation (Sarawak Kiri catchment).

Figure 2. Sampling team at Batu Kitang WTP (Kuching Water Board).

Figure 3. On-site sample collection at water intake outlet.

Analytical Methods

Laboratory analyses were conducted using EPA-validated and American Laboratory methods. All results were expressed in mg L^{-1}. All analytical methods and detection limits were as shown in Table 1.

RESULTS

A total of 17 pesticide-related parameters representing four major groups, including acid herbicides, organochlorine pesticides, organophosphate pesticides, and other commonly used herbicides were analysed in raw water samples collected from the Batu Kitang intake of the Sarawak Kiri River catchment (Table 1).

Overall, all analysed compounds were reported below their respective method detection limits (MDLs), indicating that no measurable pesticide residues were detected at the point of sampling. However, a more detailed examination of the analytical outputs reveals important insights into detection thresholds, compliance margins, and relative environmental risk.

Table 1. Analytical methods and detection limits

Group	Parameter	Detection Limit (mg/L)	Method	Instrument
Acid herbicides	2,4-D	<0.01	Method 0599 (American Lab 36154)	GC-MS
	2,4,5-T	<0.01		
	2,4,5-TP (Silvex)	<0.004		
Organochlorine pesticides	Aldrin	<0.00002	USEPA 608 & 8270E [7]	GC-MS
	Dieldrin	<0.00002		
	Chlordane	<0.00005		
	4,4′-DDT	<0.00005		
	Heptachlor	<0.00003		
	Heptachlor Epoxide	<0.00003		
	Lindane (BHC)	<0.00005		
	Methoxychlor	<0.00002		
	Endosulfan	<0.001		
	Hexachlorobenzene	<0.001		
Organophosphate	Chlorpyrifos	<0.001	QuEChERS + GC-MS	GC-MS

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Other herbicides	Paraquat	<0.01	Method 0598 (DFG Vol II 134-A)	HPLC
	Glyphosate	<0.01	Method 0566 (Agilent 5091-3621E) [8]	HPLC
	Aminomethylphosphonic acid (AMPA)	<0.01		

Acid Herbicides

Three acid herbicides, 2,4-D, 2,4,5-T, and 2,4,5-TP (Silvex) were analysed using validated laboratory methods with detection limits ranging from <0.004 to <0.01 mg/L. All compounds were reported below detection limits across the sampling event (Table 2).

When compared with the World Health Organization (WHO) guideline values for drinking water (0.03–0.1 mg/L), the analytical detection limits were substantially lower, indicating a wide margin of compliance. This suggests that even if residues were present at concentrations just below detection thresholds, they would remain well within internationally accepted safety limits.

Organochlorine Pesticides

A total of ten organochlorine pesticides, including aldrin, dieldrin, chlordane, 4,4′-DDT, heptachlor, heptachlor epoxide, lindane (BHC), methoxychlor, endosulfan, and hexachlorobenzene, were analysed using USEPA-approved GC-MS methods.

Detection limits for this group ranged from <0.00002 to <0.001 mg/L, reflecting high analytical sensitivity (Table 2). All compounds were below detection limits in the collected samples. Given that organochlorines are persistent organic pollutants with strong environmental stability and bioaccumulation potential, their non-detection is notable.

Comparison with WHO guideline values (0.001–0.03 mg/L) indicates that the analytical methods employed were sufficiently sensitive to detect concentrations well below regulatory thresholds. The absence of detectable residues suggests minimal recent or historical input of these compounds into the catchment at the time of sampling.

Organophosphate Pesticides

Chlorpyrifos was the only organophosphate pesticide included in the analysis, with a detection limit of <0.001 mg/L (Table 1). The compound was not detected in the water sample.

Relative to the WHO guideline value of 0.03 mg/L [9], the detection limit again provides a substantial safety margin. However, given the relatively rapid degradation of organophosphates in environmental conditions, non-detection at a single time point does not preclude episodic presence following recent application events.

Other Herbicides

Three additional herbicides are paraquat, glyphosate, and aminomethylphosphonic acid (AMPA), a primary degradation product of glyphosate, were analysed using HPLC-based methods with detection limits of <0.01 mg/L (Table 1).

All compounds were below detection limits. Notably, glyphosate and AMPA are among the most widely used herbicides globally, and their absence in detectable concentrations suggests limited transport into the water intake at the time of sampling.

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The detection limits for these compounds were substantially lower than WHO guideline values (up to 0.5 mg/L), indicating strong compliance with drinking water standards.

Overall Compliance and Analytical Sensitivity

Across all pesticide groups, the results demonstrate full compliance with WHO drinking water guideline values. Importantly, the analytical detection limits for all parameters were consistently lower, often by one to two orders of magnitude than the corresponding guideline thresholds (Table 2).

This indicates that the analytical methods employed were sufficiently sensitive to detect even low-level contamination, thereby increasing confidence in the observed non-detection results. Nevertheless, it is important to note that all values were reported as "less than" detection limits rather than absolute zero concentrations.

Table 2. Summary of pesticide analysis results

Pesticide Group	No. of Parameters	Result Range (mg/L)	WHO Guideline Limit (mg/L)	Compliance
Acid herbicides	3	<0.004–0.01	0.03–0.1	Compliant
Organochlorine	10	<0.00002–0.001	0.001–0.03	Compliant
Organophosphate	1	<0.001	0.03	Compliant
Other herbicides	3	<0.01	0.5	Compliant

DISCUSSION

The present study demonstrates that all targeted pesticide residues in the Sarawak Kiri River catchment were below analytical detection limits at the time of sampling. At face value, this suggests that the raw water source remains uncontaminated and suitable for downstream treatment. However, such findings warrant a more nuanced interpretation, particularly within the broader context of environmental monitoring and pesticide risk assessment.

First, it is essential to emphasise that non-detection does not equate to absence of contamination. Analytical detection limits, although sensitive, still represent a threshold below which residues may remain present but undetected. Previous studies have demonstrated that low-level pesticide residues, even below conventional detection limits, may exert chronic ecological and human health effects, particularly through long-term exposure and mixture toxicity [1]. Therefore, the absence of detectable residues in a single sampling event should not be interpreted as definitive evidence of zero risk.

Second, the temporal limitation of the study must be acknowledged. Sampling was conducted at a single time point (January 2025), which may not capture episodic contamination events. In tropical environments such as Sarawak, pesticide transport is highly influenced by rainfall patterns, with peak runoff events often occurring during heavy precipitation [3]. Given the region's high annual rainfall (~4000 mm), it is plausible that pesticide pulses may occur intermittently, particularly following agricultural application cycles. Studies in Southeast Asia have shown that pesticide concentrations in surface water can vary significantly across seasons, with peak levels often detected during monsoon periods [4]. As such, the current findings should be interpreted as a baseline rather than a comprehensive risk assessment.

Third, the absence of detectable residues may reflect specific characteristics of the Sarawak Kiri catchment. The relatively low intensity of agricultural activity, coupled with the presence of vegetated riparian buffers, likely contributes to reduced pesticide transport into surface water. Riparian vegetation has been widely recognised as an effective natural barrier, reducing pesticide runoff through filtration, adsorption, and microbial degradation [10]. Additionally, high rainfall may enhance dilution, further lowering detectable concentrations. However, dilution should not be misconstrued as mitigation, as it may mask underlying contamination while still contributing to cumulative environmental loading.

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From a regulatory perspective, the findings may suggest that current catchment protection measures, including the Sarawak Water Catchment Protection Ordinance, are functioning effectively. Nevertheless, regulatory success should not lead to complacency. International experience indicates that pesticide contamination often emerges gradually with intensification of agriculture and land-use change [2]. The Sarawak Kiri catchment is not immune to such transitions, particularly with ongoing rural development and potential expansion of agro-based activities.

A critical issue that remains unaddressed in the current study is the scope of analytes. While the study included several conventional pesticides, emerging contaminants such as neonicotinoids and degradation products were not assessed. These compounds have been increasingly detected in aquatic systems globally and are associated with ecological risks even at low concentrations [6]. The exclusion of such compounds limits the comprehensiveness of the risk assessment and highlights an important gap for future research.

The uniformly “positive” findings (i.e., all parameters compliant) should also be interpreted cautiously. While reassuring, such results may reflect limitations in sampling design, analytical scope, or temporal coverage rather than true environmental absence. In high-impact journals, overly “perfect” datasets often raise questions regarding robustness and representativeness. A more critical stance acknowledges that environmental systems are dynamic and that zero-detection findings require validation through repeated and diversified sampling strategies.

From a policy standpoint, the study offers both reassurance and warning. The current state of the Sarawak Kiri catchment represents a valuable opportunity for preventive governance. Unlike heavily contaminated systems where remediation is costly and complex, maintaining a low-contamination status is more feasible and cost-effective. This aligns with the precautionary principle in environmental health, which advocates for early intervention before risks become established.

However, sustaining this status requires a shift from reactive to proactive monitoring. Routine surveillance should incorporate longitudinal sampling, event-based monitoring during rainfall, and expansion of analyte panels. Furthermore, integrating community-based monitoring and stakeholder engagement could enhance early detection and compliance with environmental regulations.

Limitation

First, the study was based on a single sampling event conducted in January 2025. While this provides a useful snapshot of water quality, it does not capture temporal variability, particularly in tropical environments where pesticide transport is highly influenced by rainfall patterns and agricultural cycles. Episodic runoff events following pesticide application may result in transient spikes in concentration that would not be detected through single time-point sampling.

Second, the analytical scope was limited to selected pesticide groups, including acid herbicides, organochlorines, organophosphates, and a small number of commonly used herbicides. Emerging contaminants such as neonicotinoids, pyrethroids, and pesticide degradation products were not included. Increasing evidence suggests that such compounds are frequently detected in aquatic environments and may pose ecological and human health risks even at low concentrations [6]. The exclusion of these analytes may therefore underestimate the overall contamination burden.

Third, the interpretation of “non-detectable” results is inherently constrained by the detection limits of the analytical methods used. Residues present below these thresholds may still exist and contribute to chronic exposure, particularly when considering mixture effects. As highlighted in previous studies, low-level pesticide mixtures may exert additive or synergistic toxicity despite individual concentrations being below guideline values [1].

Fourth, the study did not incorporate ecological or human health risk assessment modelling. While compliance with guideline values provides a useful benchmark, it does not fully account for long-term exposure, bioaccumulation, or combined effects of multiple contaminants.

Finally, spatial coverage was limited to the intake point at the Batu Kitang Water Treatment Plant. Upstream variations in land use and potential localised contamination sources were not assessed, which may limit the ability to identify specific pollution pathways. Taken together, these limitations highlight the need for more comprehensive, longitudinal, and risk-based monitoring approaches to fully characterise pesticide dynamics in the Sarawak Kiri catchment.

CONCLUSION

This study provides important baseline evidence indicating that pesticide residues in the Sarawak Kiri River catchment were below analytical detection limits at the time of sampling. While these findings are encouraging, they should not be interpreted as definitive evidence of absence of risk. Instead, they highlight a critical window of opportunity to preserve a relatively uncontaminated drinking water source in the face of ongoing environmental and land-use changes.

The study underscores the limitations of single time-point monitoring and the need for more robust surveillance strategies that capture temporal variability and emerging contaminants. Future monitoring frameworks should incorporate longitudinal designs, expanded analyte coverage, and risk-based sampling approaches to ensure comprehensive assessment of water quality.

From a policy perspective, the findings support the continued enforcement of catchment protection measures while emphasising the importance of proactive, rather than reactive, environmental governance. Safeguarding water resources in tropical regions such as Sarawak requires sustained commitment, interdisciplinary collaboration, and adaptive monitoring systems capable of responding to evolving environmental pressures.

RECOMMENDATION

The findings of this study, while reassuring, should be interpreted as an opportunity to strengthen proactive environmental management rather than a justification for complacency. Several key recommendations can be proposed.

First, routine monitoring programmes should be expanded beyond single time-point assessments to include longitudinal and seasonal sampling. Given the strong influence of rainfall on pesticide transport in tropical regions, event-based sampling following heavy precipitation should be incorporated to capture potential peak contamination periods.

Second, the scope of analytical monitoring should be broadened to include emerging pesticide classes such as neonicotinoids, pyrethroids, and relevant degradation products. Advances in analytical techniques, including high-resolution mass spectrometry, should be leveraged to improve detection sensitivity and coverage.

Third, a risk-based monitoring framework should be adopted, integrating chemical analysis with ecological and human health risk assessment. This would enable a more comprehensive evaluation of potential impacts, particularly in relation to chronic low-level exposure and mixture toxicity.

Fourth, catchment management strategies should be strengthened through the preservation and enhancement of riparian buffer zones, which play a critical role in mitigating pesticide runoff. Evidence from global studies demonstrates that vegetated buffers can significantly reduce contaminant transport into surface water systems [10].

Fifth, regulatory enforcement under existing frameworks, including the Sarawak Water Catchment Protection Ordinance, should be continuously reviewed and strengthened in response to evolving land-use pressures. Preventive governance is particularly important in relatively low-contamination systems, where maintaining water quality is more cost-effective than remediation.

Finally, community engagement and awareness programmes should be integrated into catchment management efforts. Local agricultural practices, even at small scale, can cumulatively impact water quality. Promoting best practices in pesticide use and encouraging community participation in environmental monitoring may enhance long-term sustainability.

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Ethics Approval And Consent To Participate

Ethical approval was not required for this study as it involved environmental water sampling and did not include human participants, human data, or animal subjects. All sampling procedures were conducted in collaboration with the relevant authorities and in accordance with institutional and environmental regulations.

Consent For Publication

Not applicable.

Availability Of Data And Materials

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request. Supporting laboratory reports and raw analytical data can be provided to facilitate transparency and reproducibility.

Competing Interests

The authors declare that they have no competing interests.

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Authors' Contributions

LSH conceptualised and designed the study, collect the data, supervised the project, and drafted the manuscript. SFJ involved in data collection and data analysis. AST and HH involved in conceptualization and supervision of the project. NRS involved in data analysis. RN and TAJJ involved in manuscript preparation. DSAM involved in proofreading of the manuscript.

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