Analysis of mercury and soil physical properties post gold mining: A case study of illegal gold mining

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Abstract

Kuantan Singingi District in Riau Province holds significant gold deposits covering approximately 12.413.37 hectares. However, illegal gold mining has persisted in Kenegerian Kari, Kuantan Tengah Subdistrict, for about seventeen years, utilizing both traditional and modern methods. This area, originally a forested landscape, underwent extensive deforestation and subsequent illegal logging, resulting in the accumulation of tailings, sediment deposits, and the overgrowth of Cyperus species. This study aimed to determine the mercury content and assess the physical properties of the soil within this post-gold mining area. A quantitative descriptive method was employed to analyze soil pH, texture, permeability, porosity, bulk density, and mercury levels. The results revealed severe mercury contamination across all mining sites, with an average concentration of 4.001 ppm. Soil pH (H_2O) ranged from moderately to strongly acidic (3.92–4.66). Furthermore, soil porosity varied from 65% to 87%, bulk density ranged from 0.84 to 1.29 g/cm3, and soil permeability fluctuated from moderately slow to rapid (0.72–8.35 cm/h). Soil texture also exhibited variation: tailing sites were dominated by clay, Cyperus and sediment sites showed high sand content, whereas undisturbed forest areas retained a silty clay loam texture. These findings imply that long-term illegal mining has critically degraded soil structure and introduced toxic levels of heavy metals, highlighting an urgent need for targeted soil remediation and land rehabilitation strategies to restore the ecosystem.

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1. Introduction

Riau Province is characterized by gold mining potential but remains poorly managed. According to the Department of Energy and Mineral Resources of Kuantan Singingi District, land containing alluvial gold spans approximately 142.000413.37 hectares (Ministry Energy and Mineral Resources of Indonesia., 2023). Many residents engage in illegal mining activities, which are defined as unlicensed operations violating government regulations.

Illegal gold mining has severely degraded the Kuantan River ecosystem, causing pronounced water discoloration, foul odors, and widespread pollution. This persistent activity documented in the area for nearly two decades (Rahmayani et al., 2014) has caused extensive mercury (Hg) contamination, as formally validated by official laboratory analysis (Report of Test Results No. 0624/0359-0361/LHU/LKL-PR/II/2013). Consequently, the study area, which originally thrived as a pristine natural forest adjacent to the Petapahan River, has undergone drastic environmental regression characterized by severe soil degradation and systemic toxic pollution. For miners, the immediate benefits of income and livelihood come at the cost of long-term health risks that are often poorly understood or underestimated. For surrounding communities, mercury use contaminates soil, water, and food systems, creating an invisible but persistent threat to collective wellbeing (Gbeli et al., 2026).

Artisanal and small-scale gold mining (ASM) remains a major driver of water pollution in many tropical developing economies (Amidu et al., 2026). Due to prolonged illegal mining, the landscapes and soil quality have been altered. The post-mining land is now characterized by sandy, nutrient-poor soil with high acidity, loss of topsoil, and mercury contamination averaging 2.4–4.17 ppm. Mercury pollution poses severe risks, as it bioaccumulates in ecosystems and affects human health, causing neurological disorders, poisoning, and reproductive issues (Duruibe et al.. 2007; Basu 2023). Mercury concentrations remain elevated more than a century after mining ceased, and methylmercury (MeHg) continues to form within contaminated sediments. The strong association between Hg and fine-grained material indicates that sediment mobilisation is the primary

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mechanism driving downstream Hg transport (Schneider et al., 2026). It has no known positive functionality in the human body, and even at low concentrations, it can have harmful long-term health effects, seriously affecting the healthcare system as well as posing a serious public health threat (Charkiewicz., 2025).

While prior research has widely documented heavy metal distribution in volcanic and mountainous artisanal mining areas like Gorontalo (Arifin et al., 2025), the contamination dynamics in flat, alluvial river terrains such as Riau remain poorly understood. The mining sectors in Riau are characterized by low-lying, highly acidic alluvial soils that suffer from severe soil matrix degradation after years of unregulated activities. This study bridges this knowledge gap, rather than merely tracking macro-environmental pollutant pathways, we analyze at a micro-level how degraded physical properties of alluvial soil impact mercury (Hg) retention. Consequently, this work offers indispensable baseline data necessary for developing specific land remediation frameworks for alluvial ecosystems in Sumatra.

2. Method

This descriptive quantitative study was conducted from February to April 2017. Field sampling was carried out across an artisanal gold mining area (Unlicensed Gold Mining/PETI) in Kenegerian Kari, Kuantan Tengah District, Kuantan Singingi Regency, Riau, Indonesia (Figure 1). Laboratory fabrications and sample analyses were performed at the Laboratory of Agrostology, Feed Industry, and Soil Science (Sultan Syarif Kasim State Islamic University Riau), the Laboratory of Soil Science (University of Riau), and the Environmental Engineering Water Laboratory (Andalas University).

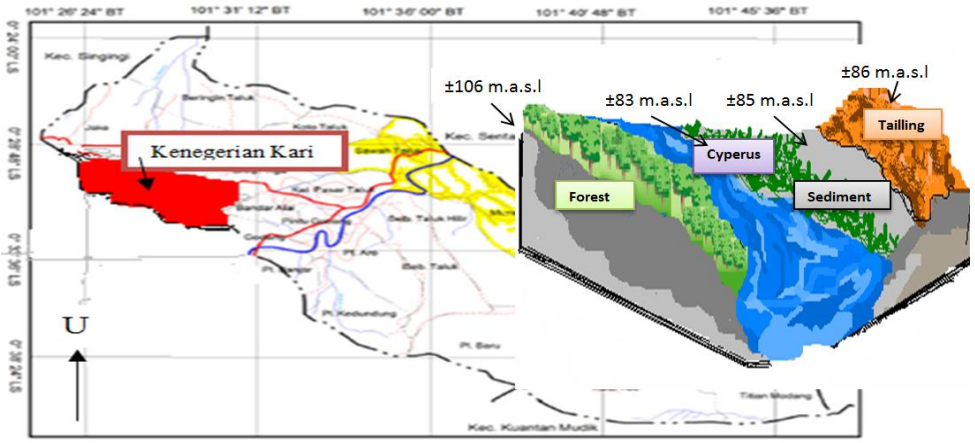

Figure 1. Location of the study area in Kenegerian Kari, Kuantan Singingi District, Riau Province, Indonesia

2.1. Sampling Collection

Field sampling was executed using a purposive sampling method across a heterogeneous 50-hectare mining perimeter. To capture environmental variability, four distinct land-use characteristics were established as sampling zones: natural forest (control), Cyperus kynglia vegetation zones, open sediment areas, and tailing mud zones. Soil samples were collected at a uniform depth of 30 cm and classified into two distinct experimental groups:

a. Undisturbed Soil Samples: Collected using standard core rings (3 rings x 5 replications x 4 locations = 60 samples) dedicated to the assessment of physical parameters including bulk density, porosity, and hydraulic permeability.

b. Disturbed Soil Samples: Obtained from core and peripheral sub-points (zones A, B, C, D, and E) at each location, which were subsequently homogenized into composite samples for the determination of soil pH, particle size distribution (texture), and total mercury (Hg) concentrations (Figure 2).

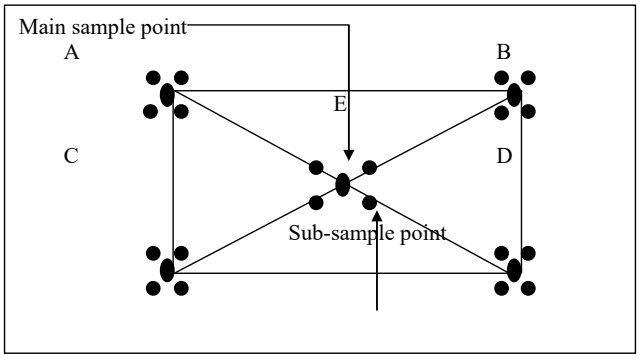

Figure 2. Sample Point Selection

2.2. Laboratory Analysis

a. Total Mercury (Hg) Concentration: Total mercury concentrations in soil matrices were determined using Cold Vapor Atomic Absorption Spectrophotometry (CV-AAS) at a wavelength of 253.7 nm. Finely ground soil samples (<0.5mm, 2.5 g) underwent sequential wet digestion using concentrated nitric acid (HNO_3 p.a.) and perchloric acid ($HclO_4$ p.a.) under a step-regulated thermal profile (100C to 200C) until a clear analyte or white precipitate remained. Digested samples were diluted with deionized water to 25 mL. Chemical reduction of Hg^{2+} to volatile elemental mercury (Hg0) vapor was induced using stannous chloride ($SnCl_2$) in an acidic medium prior to spectrophotometric measurement.

b. Soil pH: Determined electrometrically using a calibrated pH meter in a 1:2.5 (w/v) soil-to-distilled water (H2O) suspension after mechanical agitation at 250 rpm for 30 minutes.

c. Bulk Density: Determined using the core method via oven-drying undisturbed core samples at 105C for 24 hours until a constant dry weight was achieved.

d. Total Porosity: Computed from the relationship between bulk density (BD) and particle density (PD), measured via the pycnometer method

e. Soil Permeability: Saturated hydraulic conductivity (K) was measured in the laboratory using a constant-head permeabilitameter according to Darcy's Law.

f. Soil Textural Classifications: Soil particle size distribution (sand, silt, and clay fractions) was determined using the standard pipette method based on Stokes' sedimentation law. Finely ground soil samples (<2mm, 10 g) were initially treated with hydrogen peroxide (H_2O_2, 10% and 30% v/v) under thermal conditions to digest organic matter, followed by chemical dispersion using 2N hydrochloric acid (HCl) and 4% sodium pyrophosphate ($Na_4P_2O_7$).The sand fraction was separated mechanically using a 50 μm mesh sieve, while silt and clay fractions were quantified spectrophotometrically by sampling the soil-deionized water suspension at specific settling time intervals and depths.

2.3. Data Analysis

Statistical computations were performed using SPSS version 16.0. Variations in physical and chemical properties across different post-mining zones were validated using one-way Analysis of Variance (ANOVA). Statistically significant differences ($p<0.05$) were further analyzed using Duncan's Multiple Range Test (DMRT) at a $\alpha = 5\%$ significance level.

To determine pollution indexes and soil classification, experimental datasets were cross-examined with international and institutional regulatory frameworks:

a. Soil Hg Pollution: Benchmarked against the Science Report SC050021 / Mercury SGV (Environment Protection Agency, 2009).

b. Soil Texture: Categorized using the United States Department of Agriculture (USDA) soil texture triangle.

pH and Permeability: Evaluated according to the standard classification criteria established by the Indonesian Soil Research Institute (Soil Research Institute).

3. Results and Discussion

The physicochemical characteristics of soils from the tailing, sediment, Cyperus-dominated, and forest areas were evaluated using several parameters, including Hg concentration, pH, bulk density, porosity, permeability, and soil texture. A summary of the results is presented in Table 1.

Table 1. Results of All Study Parameters

No	Parameter	Tailing	Sediment	Cyperus	Forest
1	Hg (ppm)	3.977 Critical	3.972 Critical	4.115 Critical	3.940 Critical
2	pH (H_20)	3.918^a Strongly Acid	4.552^b Acid	4.006^a Strongly Acid	4.662^b Acid
3	Bulk Density (g/cm^3)	1.170^b	1.280^c	1.290^c	0.844^a
4	Porosity (%)	66.20^a	69.80^b	64.80^a	86.80^c
5	Permeability (cm/hours)	0.720^a Rather Slowly	4.300^b Moderately	6.740^c Rather Fastly	8.350^d Rather Fastly
6	Texture (%)	S.9.68 D.27.69 C.62.64 Clay	S.83.46 D.8.38 C.8.16 Clay Sand	S.84.38 D.7.00 C.8.16 Clay Sand	S.63.24 D.21.38 C.15.38 Clay of Clay Dusty

Note: Values followed by different superscripts (a, b, c, d) in the same row are significantly different (Duncan's test, $p < 0.05$).

3.1. Hg Concentration

The concentration of Hg across mining area was found to range between 3.940 and 4.115 mg/kg (ppm). The lowest Hg was recorded at the forest site (3.940 ppm), while the highest concentration was observed at the Cyperus-dominated site, reaching 4.115 ppm. The difference in Hg concentration between the sediment and tailing areas was minimal, with only a 0.005 ppm variation (3.972 ppm and 3.977 ppm, respectively). Despite these numerical differences, statistical analysis showed no significant variation among areas (Table 1). .

The analysis of Hg concentration showed that all areas fell into the critical contamination category, based on the threshold guidelines established by the Science Report SC050021/Mercury SGV from the UK Soil and Herbage Survey (Environment Agency., 2009). According to this reference, normal Hg levels in soil range from 0.01 to 0.3 ppm, and levels between 0.3 and 0.5 ppm are considered critical. In this study, the average Hg concentration ranged from 3.940 to 4.115 ppm, which was significantly above the critical threshold and showed severe heavy metal pollution. The maximum concentration was found in the Cyperus 121 area (4.115 ppm), showing that the wetland vegetation could play a role in metal retention as well as bioaccumulation (Yu et al., 2021; Phillips et al., 2015; Marcu et al., 2020). The increased concentrations of Hg could be due to emissions by illegal gold mining. Specifically, Hg was extensively used for amalgamation of gold and released to the environment (Gerson et al., 2022). Reports show that Hg contamination in mining soil can last for decades with the subsequent bioaccumulation of the element in plants and aquatic systems (Bernhardt., 2022; Ryzhenko et al., 2021).

Wetland plants often draw Hg from the surrounding sediment via transpiration, trapping it within the rhizosphere (root zone) or translocating it to their shoots. This explains why the sediment beneath the Cyperus canopy retains more Hg, as the vegetation effectively prevents the mercury from leaching or volatilizing back into the atmosphere compared to more open or differently vegetated sites (Ma., 2021).

3.2. Soil pH

In the study area, soil pH varied between a minimum value of 3.918 and a maximum of 4.662, suggesting a strongly acidic environment. These pH values were statistically different ($p < 0.05$) as shown by the analysis of variance (ANOVA). Tailing and the Cyperus-dominated areas were classified into a single homogenous group, with slightly lower pH values than the forest and sediment areas. The results showed the heterogeneity of soil acidity levels that could be attributed to the influence of specific land cover types and the history of exposure to mining-related disturbances (Table 1).

Acidic conditions are commonly observed in post-mining landscapes due to sulfide oxidation and acid mine drainage (Barroso et al., 2025; Festin et al., 2019). The tailing and Cyperus-dominated areas showed very strongly acidic pH levels, while the sediment and forest were categorized as strongly acidic. These variations suggest that mining activities, particularly in tailing area, have led to substantial chemical degradation of soil. The extremely low pH at tailing and Cyperus areas may be attributed to acid-generating reactions associated with sulfide minerals commonly found in mine waste. Generally, minerals exposed to air and water form sulfuric acid, lowering soil pH in a process called acid mine drainage. In this study, forest area had the highest pH, showing that natural vegetation and organic matter buffer against acidification. Organic matter increases cation

exchange capacity and supplies basic cations like Ca^{2+} and Mg^{2+} to neutralize acidity. Acidic soil increases mercury mobility, raising the risk of leaching and bioavailability to plants (Liu et al., 2020; Raj et al., 2020). In environmental geochemistry, soil pH acts as the master variable regulating heavy metal solubility, speciation, and bioavailability. When combined with total mercury concentrations exceeding standard safety limits, these variations illustrate how specific land uses and historical mining disturbances dictate the fate of environmental contaminants (Hou., 2019).

3.3. Bulk Density

Bulk density in mining area varied from 0.844 to 1.290 g/cm^3. Based on the results, forest area had the lowest bulk density (0.844 g/cm^3), which was statistically different from others. In comparison, the highest bulk densities were found at Cyperus (1.290 g/cm^3) and sediment areas (1.280 g/cm^3) (Table 1).

High bulk density at Cyperus and sediment area suggests compaction from mining, low organic matter, and limited soil biota. Despite the presence of Cyperus, soil structure has not improved. The low bulk density in forest area shows healthy, loose soil with high organic matter and active biological processes. This supports the idea that forest soil has lower bulk density due to organic matter and minimal disturbance. The tailing area shows moderate bulk density (1.170 g/cm^3), suggesting compaction. When overlaid with extreme soil acidity (pH 3.918–4.662) and severe mercury contamination (3.940–4.115 ppm), these parameters illustrate how land cover degradation dictates the spatial distribution and retention of toxic metalloids (Hurum, 2023).

3.4. Soil Porosity

Soil porosity across the mining area ranged from 64.80% to 86.40%, while permeability varied between 0.72 and 8.75 cm/hour. The highest porosity was recorded in forest area (86.40%), which was statistically different from others. In comparison, the lowest porosity values were observed at Cyperus-dominated (64.80%) and tailing (66.20%) areas, which fell under the same statistical group (Table 1).

Porosity is influenced by soil texture, structure, organic matter content, and biological activity. Generally, a decrease in porosity is associated with an increase in soil bulk density, showing compaction (Orzech et al., 2021; Chen et al., 2022; Nawaz et al., 2013). The high porosity in the natural forest shows an undisturbed soil condition, characterized by stable soil structure, abundant organic matter, and rich biological activity. These results were in line with Brady and Weil (2016), who stated that forest ecosystems showed high porosity due to minimal physical disturbance and continuous organic matter input from litter and root biomass. However, Cyperus and tailing areas showed lower porosity values, suggesting degraded soil structure, compaction, and reduced organic content primarily due to unregulated gold mining activities. According to Usharani et.al (2019), natural revegetation has occurred in Cyperus area, where the root systems of pioneer species showed limited capacity to restore soil porosity in the short term. When paired with high soil compaction (bulk density) and extreme mercury contamination, these hydrodynamic properties explain why specific land covers act either as passive pathways or as major geochemical sinks for heavy metals (Robles, 2025).

3.5. Soil Permeability

In this study, soil permeability in post-mining area varied widely, ranging from 0.720 to 8.350 cm/h, showing high variability among locations. The highest porosity was observed at the forest area, which showed a statistically significant difference compared to the other treatment sites (Table 1).

Forest area showed the highest average permeability, a characteristic of undisturbed natural soil with well-developed structure, abundant organic matter, and extensive root systems (Yi et al. 2019; François et al. 2024; Zangerle et al. 2021). Forest soil porosity and macropores allow for water infiltration and reduced runoff (Feng et al., 2025; Xu et al. 2017). Tailing area had the lowest permeability, classified as "very slow" (Soil Survey Staff, 2014), showing severe degradation from mining that compacted soil and removed vegetation (Feng et al., 2019; Singh et al., 2015; Bodner et al., 2023; Turgut., 2012; Putra et al., 2024).

Sediment area shows transitional conditions, with deposits containing various particle sizes and organic residues. Although more permeable than tailing, sediment area is less efficient than forest due to unstable aggregation and limited biological activity (Potter & Daniel., 1988; Feng et al., 2019). Cyperus-dominated area has moderate to high rates of early successional vegetation. The dense root networks of Cyperus plant facilitate macropore formation and enhance soil structure (Lalor et al., 2021; Soil Science Society of America., 2008). This suggests natural regeneration is a suitable rehabilitation strategy for post-mining landscapes when properly managed.

Poor drainage induces rapid oxygen depletion upon wetting, creating highly reducing, anoxic micro-environments within the soil matrix. Under these conditions, and in the presence of extreme acidity (pH 3.918–4.662), anaerobic microbes such as sulfate-reducing bacteria thrive. These bacteria utilize the trapped mercury to generate methylmercury (MeHg), a highly bioavailable and neurotoxic compound. Thus, the low-porosity

Cyperus and tailing corridors serve as both physical traps for total mercury and active chemical incubators for its most dangerous organic forms (Pezeshki., 2012).

3.6. Soil Textural Classifications

Soil textures varied across study areas, as shown by the analysis. Sediment and Cyperus areas were sandy loam with coarse texture due to high sand content. Tailing area was a fine-textured clay soil due to high clay content, while forest was a moderately fine-textured silty clay loam with a composition of 63.24% sand, 21.38% silt, and 15.38% clay (Table 1.).

Further analysis showed that tailing area was clay-dominated (62.64%), sediment and Cyperus sites had high sand content (83.46–84.38%), and forest had a balanced silty clay loam texture. High sand content in sediment and Cyperus areas reduces water and nutrient retention, leading to poor soil fertility (Richard et al., 2021). Clay-rich tailing has better water-holding capacity but is prone to compaction, reducing aeration and root penetration (Shen et al., 2020). The silty clay loam texture offers a balanced structure, supporting plant growth by retaining moisture while allowing adequate drainage (Yang et al., 2021).

The results show the severe impact of illegal gold mining on soil properties and Hg contamination. Acidic conditions and high porosity may facilitate Hg leaching into water bodies, posing risks to aquatic ecosystems and human health (Zhang et al., 2019). Therefore, restoration strategies are essential to neutralize acidity and reduce Hg mobility through soil amendments such as lime or bichar (Guo et al., 2022). Phytoremediation using mercury-accumulating plant species like Cyperus could aid in soil detoxification (Wei et al., 2021). Conversely, the natural physical architecture of the forest retains its high permeability and porosity, allowing the system to withstand severe mechanical degradation and resist the dense accumulation of mine tailings (Ghazaryan., 2024). Figure 3 shown a soil characteristics by location Tailings site, Sediment site, Cyperus site and, Forest site.

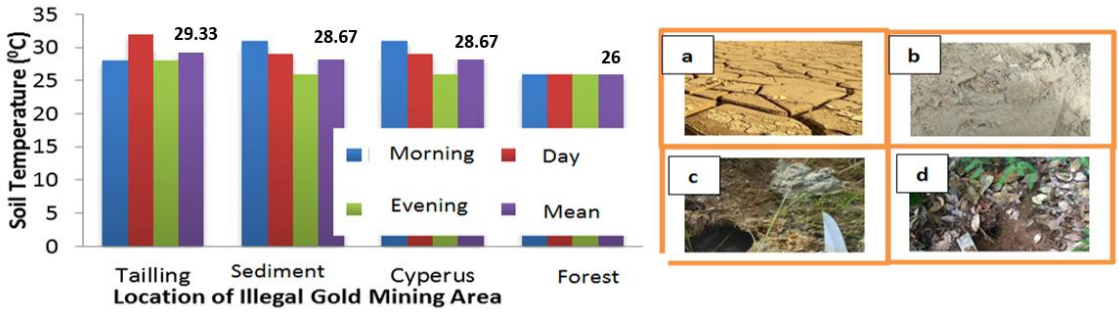

Figure 3. Soil characteristics by location: (a) Tailings site; (b) Sediment site; (c) Cyperus site; (d) Forest site

4. Conclusion

In conclusion, this study provides definitive evidence of severe ecological degradation driven by seventeen years of unregulated gold mining in Kuantan Singingi District. Beyond merely confirming critical mercury (Hg) contamination which averages an alarming 4.001 ppm across all active and legacy mining sites, this research synthesizes the profound coupling between heavy metal accumulation and the deterioration of soil physical architecture. The stark contrast between the resilient, structured silty clay loam of undisturbed forest soils and the highly disrupted, acidic (pH 3.92–4.66), and texturally altered tailing and sediment sites underscores how mining completely reshapes sub-surface hydrology and aeration.

The primary scientific contribution of this study lies in mapping the heterogeneous nature of post-mining landscapes, demonstrating how specific micro-environments such as Cyperus-dominated zones and sediment deposits alter bulk density, porosity, and permeability. These physical shifts directly influence how mercury is retained, leached, or mobilized within tropical agricultural ecosystems. Ultimately, these findings bridge the gap between heavy metal toxicology and soil physics, providing a vital baseline for engineers and policymakers. This data is essential for designing targeted, site-specific bioremediation protocols and enforcing stringent, sustainable mining regulations necessary to mitigate systemic mercury pollution in tropical regions.

Author Contributions

Irwan Taslapratama and Ervina Aryanti: Conceptualization, Methodology, Software. Oksana: Data curation, Writing - Original draft preparation. Fauziah Shahul Hamid: Writing - Reviewing and Editing All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

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Declaration of Conflicting Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Data Availability

The datasets generated during and/ or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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