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Comparative Critical Review of Microplastic Pollution and Greenhouse Gas Emissions from Industrial Wastewater: Evidence from Indonesian River and Palm Oil Mill Environments

Endaryanto Endaryanto[1], Hengki Wibowo[2], Encep Irawan[3], Reza Aditya[4], Astri Sulastri[5], Ahmad Badawi Saluy[6]
[1]Universitas Paramadina, Jakarta, Indonesia, endaryanto1207@gmail.com
[2]Universitas Paramadina, Jakarta, Indonesia, alhengki.wiboeo@gmail.com
[3]Universitas Paramadina, Jakarta, Indonesia, encepirawan646@gmail.com
[4]Universitas Paramadina, Jakarta, Indonesia, rzaditya@gmail.com
[5]Universitas Paramadina, Jakarta, Indonesia, astrisulastrispd@gmail.com
[6]Universitas Paramadina, Jakarta, Indonesia, ahmad.badawi@paramadina.ac.id

Corresponding Author: endaryanto1207@gmail.com[1]

Abstract: This review critically examines two peer-reviewed articles published in the Environment and Natural Resources Journal addressing distinct yet complementary dimensions of Indonesia's environmental pollution challenge. Paper 1 (Suparno et al., 2024) presents the first systematic investigation of microplastic (MP) abundance, morphology, and polymer composition in the Batang Anai River estuary, Padang Pariaman Regency, West Sumatera, reporting MP concentrations of 37–77 particles/L with fragments (49.44%) and black particles (48%) predominating. Paper 2 (Putro, 2022) quantifies greenhouse gas (GHG) emissions from anaerobic palm oil mill effluent (POME) treatment ponds in South Sumatera, recording mean CH4 and CO2 emission rates of 261.93 g/m2/day and 595.99 g/m2/day respectively, equivalent to 14,571.5 t CO2-eq/year, while demonstrating a renewable energy potential of 1.045 MWe. Both studies provide novel baseline data of high policy relevance, applying rigorous analytical methods including ATR-FTIR spectroscopy (Paper 1) and gas chromatography with closed static chamber methodology (Paper 2). This comparative review assesses the methodological soundness, originality, data quality, and practical implications of both papers, assigns scientific evaluation scores, and identifies areas for future research.

Keyword: Microplastics, Batang Anai River, POME, Greenhouse Gas Emissions, Palm Oil Mill, ATR-FTIR, Environmental Review.

INTRODUCTION

Environmental pollution arising from industrial and anthropogenic activities represents one of the foremost challenges confronting developing nations. In Indonesia, rapid industrial expansion — particularly in palm oil processing and urban residential development — has generated diverse forms of pollution that affect both aquatic ecosystems and the atmospheric environment. Two categories of pollution that have attracted growing scientific attention are microplastic (MP) contamination in riverine and estuarine systems, and greenhouse gas (GHG) emissions from agro-industrial wastewater treatment.

Microplastics, defined as plastic particles smaller than 5 mm (GESAMP, 2015), originate from either primary manufacturing sources or secondary fragmentation of larger plastic items. They are now ubiquitous in marine and freshwater environments globally (Du et al., 2021), posing ecotoxicological risks to aquatic organisms and entering human food chains through the ingestion of contaminated seafood (Da Costa et al., 2017). Rivers function as critical conduits transporting terrestrial plastic waste to marine environments (Ho et al., 2020), making riverine MP studies essential for understanding total marine plastic loading.

Simultaneously, the Indonesian palm oil industry — the world's largest producer with 33.23 million tons of crude palm oil (CPO) in 2016 — generates vast quantities of palm oil mill effluent (POME) during processing. The conventional open ponding system used to treat POME in Indonesia releases CH_4 and CO_2, the two dominant greenhouse gases, in uncontrolled and largely unquantified quantities (Wu et al., 2010). As GHG emissions from POME treatment constitute over 90% of total emissions from palm oil mills (Rahayu et al., 2015), addressing this emission pathway is critical for Indonesia's climate commitments under the Paris Agreement.

This review critically examines two research articles published in the Environment and Natural Resources Journal that address these two pollution categories in Indonesian contexts. Paper 1 (Suparno et al., 2024) investigates MP abundance and characteristics in the Batang Anai River estuary, while Paper 2 (Putro, 2022) quantifies GHG emissions from anaerobic POME treatment ponds and assesses renewable energy potential. By subjecting both papers to structured critical analysis, this review aims to: (1) evaluate methodological rigor and analytical soundness; (2) contextualize findings within broader environmental science literature; (3) identify research gaps and limitations; and (4) propose directions for future investigation.

METHOD

This review applies a structured critical appraisal framework adapted from established scientific article review protocols (Greenhalgh, 2019). Each article was evaluated across seven dimensions: (1) clarity of research objectives; (2) methodological rigor; (3) data presentation quality; (4) depth and accuracy of results discussion; (5) originality and scientific contribution; (6) validity of conclusions; and (7) quality and currency of references. Scores were assigned on a 1–5 scale per criterion, yielding a maximum total of 35 points per paper.

The review also includes a comparative thematic analysis of both papers to assess their collective contribution to understanding industrial pollution dynamics in Indonesia. Source documents were read in full and cross-referenced with relevant international literature cited in each paper. All bibliographic data, statistical findings, and quoted values are sourced directly from the original articles.

RESULTS AND DISCUSSION

Paper 1: Microplastics in the Water of Batang Anai Estuary

Table 1. Bibliographic Information

Title	Microplastics in the Water of Batang Anai Estuary, Padang Pariaman Regency, Indonesia: Assessing Effects on Riverine Plastic Load in the Marine Environment
Authors	Suparno Suparno, Deswati Deswati, Wiya Elsa Fitri, Hilfi Pardi, Adewirli Putra
Journal	Environment and Natural Resources Journal
Volume/Issue	Vol. 22, No. 1, pp. 55–64

Year	2024
DOI	10.32526/ennrj/22/20230191
Affiliations	Universitas Bung Hatta; Andalas University; Syedza Saintika College; Raja Ali Haji Maritime University

Abstract Summary

This study investigated the abundance, morphological characteristics (shape, color, size), and polymer types of microplastics (MP) in the water of Batang Anai River, Padang Pariaman Regency, West Sumatera. Water samples were collected from three sampling stations (upstream, tidal bridge, and river mouth) during January–February 2023. Analysis was performed using optical microscopy and ATR-FTIR spectroscopy. Microplastic abundance ranged from 37 to 77 particles/L, with fragments most dominant (49.44%), black coloration (48%), and particle sizes exceeding 1,000 um (33%). Polymer identification via FTIR confirmed the presence of cellulose, ethylene-propylene copolymer, neoprene, and polyester.

Research Objectives

- To systematically examine the incidence of MP pollution in the Batang Anai River
- To explain and analyze the distribution characteristics of MP particles
- To provide initial baseline data to support plastic waste pollution control

Methodology Review

Study Design & Sampling: The study employed a descriptive field-sampling design across three stations representing an upstream-to-estuary gradient. Samples were collected three times (January 1, January 30, February 28) using 5 L buckets filtered 20 times through a 300 um plankton net. This repeated temporal sampling strengthens reliability. However, the use of a 300 um net mesh is a limitation as particles smaller than this size were not captured, likely underestimating true MP abundance.

MP Extraction: Hydrogen peroxide (H_2O_2, 30%) was used for organic matter digestion, a widely accepted protocol (Cordova et al., 2019). Samples were filtered using Whatman No. 42 filter paper under vacuum. Quality control measures included non-plastic lab equipment, cotton lab clothing, and blank procedure checks — commendable contamination control practices.

Identification & Analysis: Visual identification was performed using a trinocular microscope with Moticplus 3.0 software. Polymer confirmation was conducted via PerkinElmer Spectrum Spotlight 400 micro-FTIR in ATR mode, with spectra matched to the SadItler database at a >70% match threshold. This dual approach is methodologically sound for MP characterization.

Key Findings

- MP abundance: 37–77 particles/L; highest at ST 2 (middle reach, high population density and sand mining activity)
- Dominant shape: Fragments (49.44%), followed by fibers (47.78%) and film (3.33%)
- Dominant color: Black (48%), attributed to breakdown of black plastic products with low recycling rates
- Dominant size: >1,000 um (33%), influenced by the 300 um mesh net used
- Polymers identified: Cellulose, ethylene-propylene copolymer, neoprene, and polyester via FTIR
- MP abundance lower than Yellow River Estuary, China (930 p/L) but higher than Ciwalengke River, Indonesia (5.85 p/L)

Critical Evaluation

Strengths:

- First documented MP study for Batang Anai River — fills an important knowledge gap
- Rigorous contamination control procedures throughout sampling and analysis
- Dual analytical approach (microscopy + FTIR) provides robust polymer identification
- Comparative analysis with international datasets contextualizes findings effectively
- Multi-parameter characterization (shape, color, size, polymer type) is comprehensive

Weaknesses & Limitations:

- 300 um net mesh size causes underestimation of smaller MP particles — a known but acknowledged limitation
- Limited number of sampling stations (n=3) and collection events may reduce spatial representativeness
- FTIR identification performed on only 9.5% of particles (63 out of total) — broader polymer characterization would strengthen conclusions
- No sediment sampling conducted; combined water–sediment analysis would provide a fuller picture of MP load
- No statistical tests reported for differences between stations; inferential statistics are absent
- Seasonal variation not captured — sampling limited to dry-wet season transition period

Recommendations:

- Expand sampling to include sediment and biota to assess ecosystem-wide MP burden
- Employ finer mesh sizes or manta trawl to capture sub-300 um particles
- Increase FTIR polymer identification coverage to at least 30% of particles

Apply statistical tests (ANOVA, Kruskal-Wallis) to assess inter-station differences

Scientific Evaluation Scorecard

Table 2. Scientific Evaluation Scorecard – Paper 1 (Microplastics)

Criterion	Score	Comment
Research Objective Clarity	**4/5**	Objectives clearly stated but could be more specific
Methodology Rigor	**3/5**	Good QC, but limited mesh size and small FTIR sample
Data Presentation	**4/5**	Figures and tables are clear and well-captioned
Results Discussion	**4/5**	Good comparative context with global literature
Originality & Contribution	**5/5**	First study in this location; high baseline value
Conclusion Validity	**4/5**	Conclusions supported by data; no overreach
Reference Quality	**4/5**	Recent and relevant citations, well-integrated
TOTAL SCORE	**28/35**	**Good (80%) — Suitable for publication with minor revisions**

Paper 2: GHG Emissions from Palm Oil Mill Wastewater (POME)

Table 3. Bibliographic Information

Title	Emissions of CH4 and CO2 from Wastewater of Palm Oil Mills: A Real Contribution to Increase the Greenhouse Gas and Its Potential as Renewable Energy Sources
Author	Ledis Heru Saryono Putro
Journal	Environment and Natural Resources Journal
Volume/Issue	Vol. 20, No. 1, pp. 61–72
Year	2022
DOI	10.32526/ennrj/20/202100149
Affiliation	Universitas Islam Negeri Raden Fatah Palembang, South Sumatra, Indonesia

Abstract Summary

This study quantified GHG emissions — specifically CH_4 and CO_2 — from anaerobic pond POME treatment at a palm oil mill in South Sumatra, Indonesia. Gas samples were collected using closed static chambers at three locations (inlet, middle, outlet) in anaerobic ponds AP2 and AP1 across three sampling days in May and June 2019. Gas concentrations were analyzed via gas chromatography (GC) with FID for CH_4 and TCD for CO_2. Mean emission rates were 261.93 g CH_4/m^2/day and 595.99 g CO_2/m^2/day, equivalent to 14,571.5 t CO_2-eq/year. The study also determined GHG conversion coefficients and calculated a maximum renewable energy potential of 1.045 MWe (8,603 MWh/year).

Research Objectives

- To estimate GHG emissions (CH_4 and CO_2) from anaerobic POME treatment ponds based on direct field measurements
- To determine GHG emission conversion coefficients per kg COD, per m^3 POME, and per ton CPO
- To assess the potential of POME as a renewable energy source through biogas-methane capture

Methodology Review

Study Site & Experimental Setup: The study was conducted at a 30-ton FFB/hour palm oil mill (PT SPOI) in Banyuasin Regency, South Sumatra. The WWTP facility comprises seven ponds. Measurements were focused on the functionally connected anaerobic ponds AP2-AP1 (combined volume 40,519 m^3, depth 6 m). This site selection is appropriate as it represents a typical Indonesian open ponding system.

Gas Sampling: Closed static polypropylene chambers (0.30 x 0.28 x 0.415 m; V = 0.02742 m^3) were deployed at pond inlet, middle, and outlet. Gas was sampled via syringe at 0, 10, 20, and 30-minute intervals during morning (08:00), afternoon (12:00), and evening (18:00). This temporal coverage over 3 sampling days yielded 36 samples per day — a robust dataset for emission rate calculation.

Analytical Methods: Gas concentration analysis was performed by Gas Chromatography (GC-Shimadzu 14A) with FID (CH_4) and TCD (CO_2) at an accredited agricultural research institute. Emission flux was calculated using the IAEA (1992) formula, corrected to standard temperature and pressure. Daily totals were obtained by Simpson numerical integration of hourly interpolated data using MATLAB R2017b — a rigorous and reproducible analytical pipeline.

Energy Conversion Calculation: Renewable energy potential was calculated using IPCC (2006) and Rahayu et al. (2015) formulas, incorporating COD loading, CH_4 conversion coefficient (0.2102 kg CH_4/kg COD), engine efficiency (40%), and availability factor (94%). This multi-step calculation is transparent and well-documented.

Key Findings

- Mean CH_4 emission: 261.93 +/- 11.026 g/m2/day (1,604.3 kg/day total); mean CO_2: 595.99 +/- 126.915 g/m2/day (3,650.4 kg/day)
- CO_2 emissions more than double CH_4 emissions, indicating suboptimal anaerobic conditions in the open pond
- Total GHG from POME: 48.572 t CO_2-eq/day or 14,571.5 t CO_2-eq/year
- CH_4 constitutes 92.48% of total GHG emissions in CO_2-equivalent terms
- GHG conversion coefficients: 6.266 kg CO_2-eq/kg COD; 0.163 t CO_2-eq/m3 POME; 0.556 t CO_2-eq/t CPO
- Maximum renewable energy potential: 1.045 MWe with power capacity 8,603 MWh/year
- Highest GHG emissions near AP2 inlet (highest COD), decreasing toward the outlet

Critical Evaluation

Strengths:

- First direct field measurement study for WWTP with multiple-feeding systems in Indonesia — novel contribution
- Rigorous multi-temporal gas sampling design (3 times/day, 3 days, 3 spatial locations)
- Transparent and well-documented calculation methodology using IAEA, IPCC, and Rahayu frameworks
- Provides practical conversion coefficients immediately applicable by industry practitioners
- Dual focus on environmental impact and energy recovery adds significant applied value

Weaknesses & Limitations:

- Single mill study site limits generalizability across different mill sizes and climatic zones
- Only three sampling days — insufficient to capture seasonal GHG emission variation given known harvest season influences
- Wastewater quality data from only 3 replicates may underrepresent true temporal variability
- Closed static chamber method is known to have potential flux underestimation under high-turbulence conditions

Recommendations:

- Replicate study across multiple mills with varying capacities (30, 45, 60, 90 t FFB/hour) and seasons
- Extend sampling to at least 12 months to capture seasonal harvest variation
- Compare open ponding with covered/HRAL systems at the same site to quantify GHG reduction potential
- Conduct economic analysis of POME-to-energy conversion to strengthen renewable energy policy recommendations

Scientific Evaluation Scorecard

Table 4. Scientific Evaluation Scorecard – Paper 2 (GHG Emissions / POME)

Criterion	Score	Comment
Research Objective Clarity	**5/5**	Objectives are specific, measurable, and well-defined
Methodology Rigor	**4/5**	Robust design; limited by few sampling days and one site
Data Presentation	**5/5**	Tables and figures are detailed, clearly labeled, and complete
Results Discussion	**5/5**	Excellent integration of mechanisms and comparative analysis
Originality & Contribution	**5/5**	Novel direct measurements; new conversion coefficients
Conclusion Validity	**4/5**	Well-supported; some generalization caution warranted
Reference Quality	**4/5**	Broad, relevant references; a few older sources used
TOTAL SCORE	**32/35**	**Excellent (91%) — Suitable for publication; minor revisions recommended**

Comparative Analysis of Both Papers

1. Thematic Relationship

Both papers address environmental contamination in Indonesian aquatic systems, specifically in the context of anthropogenic activities. Paper 1 deals with physical plastic pollution (microplastics) in a riverine-estuarine system, while Paper 2 addresses gaseous chemical pollution (GHG emissions) from agro-industrial wastewater. Together, they represent two critical yet distinct dimensions of Indonesia's environmental pollution challenge linked to land-use and industrial activity. Both studies provide baseline data of high policy relevance for their respective pollution pathways, and both advocate for stronger regulatory frameworks to mitigate their identified environmental impacts.

2. Side-by-Side Comparison

Table 5. Comparative Analysis of Both Papers

Aspect	Paper 1 (Microplastics)	Paper 2 (GHG / POME)
Pollutant Type	Physical (microplastic particles)	Chemical/gaseous (CH4, CO2)
Location	Batang Anai River, W. Sumatera	Palm oil mill WWTP, S. Sumatera
Sampling Design	3 stations, 3 timepoints	3 chamber locations, 3 days
Analytical Method	Microscopy + ATR-FTIR	GC-FID + GC-TCD
Primary Finding	37–77 MP particles/L; fragments dominant	261.93 g CH4/m2/day; 14,571 t CO2-eq/year
Key Impact	Ecotoxicological threat to aquatic biota	GHG contribution to climate change
Applied Value	Baseline for pollution management	Energy recovery potential (1.045 MWe)
Overall Score	28/35 — Good (80%)	32/35 — Excellent (91%)

Overall Assessment

Both papers make genuine contributions to environmental science in Indonesia. Paper 2 demonstrates slightly higher scientific rigor through its more sophisticated analytical pipeline, transparent multi-formula calculation framework, and stronger quantitative outputs with direct policy relevance. Paper 1 earns its value primarily through its baseline contribution in a previously unstudied location, though it would benefit from expanded methodology and statistical analysis in future work. Both papers are appropriate for their target journal and represent sound, publishable science.

CONCLUSION

This comparative critical review has evaluated two peer-reviewed articles addressing distinct but complementary environmental pollution challenges in Indonesia. Paper 1 (Suparno et al., 2024) provides the first systematic documentation of microplastic contamination in the Batang Anai River estuary, establishing important baseline data on MP abundance (37–77 particles/L), morphology, and polymer composition. Despite some methodological limitations related to net mesh size and incomplete polymer identification coverage, the study represents a meaningful contribution to the growing body of Indonesian MP research and provides actionable data for local waste management policy.

Paper 2 (Putro, 2022) delivers a rigorous, first-of-its-kind direct field measurement of GHG emissions from POME anaerobic treatment ponds, demonstrating that the open ponding system releases substantial quantities of CH4 and CO2 (total 14,571.5 t CO2-eq/year). The study's derivation of novel GHG conversion coefficients and quantification of 1.045 MWe renewable energy potential from biogas capture constitute highly valuable outputs for both the scientific community and industry practitioners seeking to reduce the carbon footprint of palm oil processing.

Together, these papers underscore the urgent need for integrated environmental governance in Indonesia that addresses both solid waste management — to reduce plastic leakage into river systems — and industrial GHG management, particularly in the palm oil sector. Future research should prioritize multi-seasonal, multi-site studies with enhanced statistical rigor to build upon the foundations established by both articles.

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