Jurnal Serambi Engineering
Volume XI, No.2, April 2026 Hal 18521 - 18528
p-ISSN : 2528-3561
e-ISSN : 2541-1934

Monitoring of PCBs in Transformer Oils in Indonesia and Policy Implications for Hazardous Waste Management

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Received: January 22, 2026 Approved: January 28, 2026

Abstract

Polychlorinated biphenyls (PCBs) are toxic, persistent organic pollutants (POPs) that have been historically used in electrical equipment, such as transformers. Despite global bans, residual PCBs remain a concern due to legacy equipment found in developing countries. This study proposes to evaluate the presence of PCBs in six transformer oil samples. Samples of PCBs in six transformer oils were collected from transformers operated by Indonesia's state-owned electricity company (PLN). The analysis was conducted using Gas Chromatography–Electron Capture Detection (GC-ECD) following US EPA Method 8082A. The results confirm that Aroclor 1254 is the predominant PCB congener, with concentrations varying from non-detectable levels to 20.35 ppm. According to Government Regulation No. 101/2014, two samples fall within the "not clearly defined" category (5–50 ppm), which requires monitoring, while the other four samples are classified as non-PCB oils (less than 5 ppm). None of the samples exceeded the 50-ppm threshold for hazardous waste; however, the mid-range contamination levels indicate environmental risks and regulatory gaps.

Keywords: *polychlorinated biphenyls (pcbs), transformer oil, gc-ecd, utility sector, hazardous waste*

Abstrak

Polychlorinated biphenyls (PCB) merupakan polutan organik persisten *(persistent organic pollutants/POPs)* yang bersifat toksik dan secara historis banyak digunakan dalam peralatan listrik, seperti transformator. Meskipun telah diberlakukan pelarangan secara global, keberadaan PCB residu masih menjadi perhatian, terutama akibat penggunaan peralatan lama (*legacy equipment*) yang masih digunakan dan beroperasi di negara berkembang. Penelitian ini bertujuan untuk mengevaluasi keberadaan PCB pada enam sampel minyak transformator. Sampel minyak transformator dikumpulkan dari transformator yang dioperasikan oleh PLN (Perusahaan Listrik Negara). Analisis dilakukan menggunakan metode Gas Chromatography–Electron Capture Detection (GC-ECD) dengan mengacu pada US EPA Method 8082A. Hasil penelitian menunjukkan bahwa Aroclor 1254 merupakan kongener PCB yang dominan, dengan konsentrasi berkisar antara tidak terdeteksi hingga 20,35 ppm. Berdasarkan Peraturan Pemerintah Nomor 101 Tahun 2014, dua sampel termasuk dalam kategori "tidak terdefinisi secara jelas" (5–50 ppm) yang memerlukan pemantauan lebih lanjut, sedangkan empat sampel lainnya diklasifikasikan sebagai minyak non-PCB (kurang dari 5 ppm). Tidak terdapat sampel yang melebihi ambang batas 50 ppm untuk limbah B3; namun demikian, tingkat kontaminasi pada kisaran menengah tersebut menunjukkan adanya potensi risiko lingkungan serta mengindikasikan masih adanya kesenjangan dalam penerapan regulasi.

Kata Kunci: *polychlorinated biphenyls (pcb), minyak transformator, gc-ecd, sektor utilitas, limbah b3*

1. Introduction

Polychlorinated biphenyls (PCBs) are a group of synthetic chlorinated hydrocarbons composed of two benzene rings substituted with one to ten chlorine atoms, resulting in 209 possible congeners [1]. Owing to their high thermal stability, non-flammability, and excellent insulating properties, PCBs were extensively used in industrial applications for several decades, most notably as dielectric fluids in transformers and capacitors [2][3]. These same physicochemical characteristics, however, have also contributed to their long-term persistence in the environment. Combined with their strong tendency to bioaccumulate and a wide range of documented toxic effects, including carcinogenicity, endocrine disruption, and adverse neurodevelopmental outcomes, PCBs are now internationally recognised as Persistent Organic Pollutants (POPs) [4][1].

At the global level, the Stockholm Convention requires the elimination of PCB use by 2025 and the achievement of environmentally sound management of PCB-containing waste by 2028. Indonesia, as a party to the Stockholm, Basel, and Rotterdam Conventions, has incorporated these commitments into its national regulatory framework, including Government Regulation No. 101/2014. Under this regulation, transformer oil containing PCB concentrations exceeding 50 ppm is classified as hazardous waste and must be managed through controlled treatment and disposal pathways [5]. Despite the prohibition of PCB production and importation, equipment containing PCBs particularly oil-filled transformers manufactured prior to the 1990s continues to operate across various industrial and utility sectors. Efforts to identify and monitor PCB contamination in Indonesia remain fragmented, constrained by incomplete national inventories, uneven testing practices, and limited technical and financial resources [6][7][8].

Reliable identification and quantification of PCBs in transformer oils are therefore critical, not only to ensure regulatory compliance but also to inform risk management decisions and prioritise equipment replacement. Among available analytical techniques, Gas Chromatography–Electron Capture Detection (GC-ECD) is widely employed for PCB analysis due to its high sensitivity toward halogenated compounds [8]. When supported by appropriate sample preparation and clean-up procedures such as multilayer silica gel column treatment GC-ECD can produce robust and reproducible results, even in complex oil matrices [9].

Based on this background, the present study aims to: (1) quantify PCB concentrations in selected transformer oil samples obtained from industrial and utility sectors in Indonesia using GC-ECD in accordance with US EPA Method 8082A; (2) classify the samples based on applicable Indonesian regulatory thresholds; (3) contextualize the results through comparison with national inventory data and international standards; and (4) discuss the policy implications of the findings, particularly in relation to accelerating Indonesia's compliance with the PCB phase-out targets mandated under the Stockholm Convention.

2. Material and Methods

Sample Collection

Transformer oil samples were collected from selected transformer units located at the Bogor Baru Main Substation in West Java, under the operational jurisdiction of PT PLN (Persero), Indonesia's state-owned electricity company responsible for generating, transmitting, and distributing electricity nationwide. The sampling involved six transformer units; each rated at 20 kV. The sampling was conducted from December 2024 to January 2025, with laboratory analysis performed at the Central Certification Unit (Pusertif), Chemical and Environmental Testing Laboratory, a division of PT PLN (Persero) specializing in environmental and electrical testing.

The sampling and analysis procedures followed national and international standards, particularly Indonesia's Regulation on Hazardous Waste Management (Permen LHK No. 29/2020) and US EPA Method 8082A for the detection of polychlorinated biphenyls (PCBs) in transformer oil [10]. Prior to sampling, each transformer was identified and verified on-site. Each sample was labeled with the transformer ID, sampling date, and location, then immediately stored in an ice-cooled container at 4 °C. Samples were transported to the laboratory and analyzed within 24 hours, ensuring the integrity of the material for accurate PCB quantification via Gas Chromatography–Electron Capture Detection (GC-ECD) in accordance with IEC 61619.

Instrumentation and Analytical Procedure

PCB quantification was conducted using an Agilent 8890 Gas Chromatograph coupled with an Electron Capture Detector (ECD). The GC had a DB-5ms capillary column (30 m × 0.25 mm ID, 0.25 µm film thickness). Helium served as the carrier gas, with nitrogen as the makeup gas. Injector and detector temperatures were set at 250 °C and 300–350 °C, respectively. The oven temperature program and flow rates were optimized according to IEC 61619 guidelines. Before analysis, the GC was conditioned for 2 hours using a PCB-specific heating protocol. The system was operated in splitless mode to enhance sensitivity, particularly for low-level PCB detection. The Aroclor standard mixtures (1242, 1254, and 1260) were used to calibrate retention times and peak identification.

PCB identification was based on retention time matching against certified standard mixtures. Quantitative determination was performed using external calibration with PCB congener mixes. Calibration curves were prepared across a concentration range relevant to regulatory thresholds (e.g., 0.1–25 ppm). The final PCB concentration in each sample was calculated using the peak area method, adjusted for the blank, following the formula:

$$\text{Final Concentration (ppm)} = \frac{(Sample\ Peak - Blank\ Peak)}{100}$$

3. Results and Discussion

Identification and Quantification of PCBs

Chromatographic analysis of the insulating oil samples was performed using GC-ECD, which is highly sensitive to chlorinated compounds, such as PCBs. **Figure 1** illustrates the chromatogram output for one of the samples.

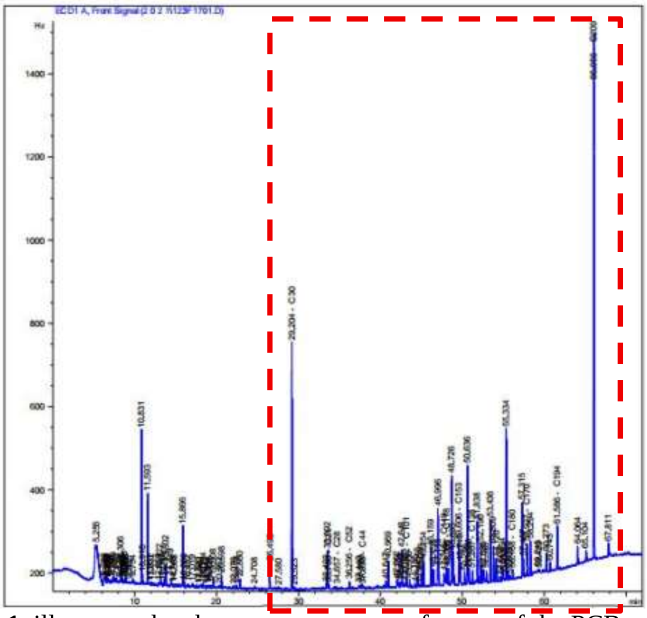

Figure 1. illustrates the chromatogram output for one of the PCB samples.

The retention times for PCB peaks were recorded between 29 and 66 minutes, which aligns with the expected elution windows for multi-chlorinated biphenyls (Aroclors) [11][12].

RetTime [min]	Type	ISTD used	Area [Hz*s]	Amt/Area ratio	Amount [ppb]	Grp	Name
29.204	BB I	1	2454.23242	1.00000	20.00000		C30
30.762		1	-	-	-		C18
33.700	VB	1	44.04548	1.44124	5.17311e-1		C31
34.657	BB	1	37.72087	0.00000	0.00000		C28
36.256	BB	1	71.96004	0.00000	0.00000		C52
37.898	VB	1	23.38107	0.00000	0.00000		C44
43.162	VB	1	96.45358	1.20279	9.45413e-1		C101
47.748	BB	1	171.57599	0.00000	0.00000		C149
48.096	BB	1	162.69206	2.80520e-1	3.71916e-1		C118
49.606	BV	1	432.13632	2.73647e-1	9.63664e-1		C153
51.267	BB	1	150.30054	0.00000	0.00000		C138
56.168	BB	1	107.85882	7.09045e-1	6.23223e-1		C180
57.927	BB	1	349.39960	4.22078e-1	1.20179		C170
61.586	BB	1	485.45306	4.05331e-1	1.60351		C194
66.056	BB	1	5728.55811	4.10137e-1	19.14645		C209

Totals without ISTD(s) : 25.37327

Figure 2. Sample Analysis Data

The resulting peaks represent different PCB congeners with varying numbers and positions of chlorine atoms. **Figure 2** shows that these peaks were processed to calculate each detected congener's area and corresponding concentration (in ppb). The total PCB content was calculated by summing the values in the "Amount" column, resulting in a *Total without ISTD* value of 25.37327 ppm, indicating detectable yet sub-threshold PCB levels in this sample.

This chromatographic profile further corroborates the identification of Aroclor 1254 as the dominant type, consistent with the peak distribution observed in other studies [12][13]. The high peak intensity around 29–35 min and a cluster of peaks from 45–65 min are typical for hexa- and hepta-chlorinated biphenyls, which dominate Aroclor 1254 formulations [9][2].

Furthermore, the additive function of PCBs in transformer oils, especially their role as chemical inhibitors that stabilise oil under high thermal stress, explains their widespread historical use. However, their environmental persistence and toxicity necessitate careful monitoring—even at low concentrations [14][15]

PCB Concentration and Classification Based on National Standards

The analysis of six transformer oil samples using GC-ECD according to IEC 61619 revealed a wide range of PCB concentrations, from non-detectable to over 20 ppm. **Table 1** summarises the measured PCB content and classification based on the Indonesian Government Regulation No. 101/2014, which defines three categories:

- Non-PCB oil: <5 ppm (or <5 mg/kg)
- Not Clearly Defined PCB oil: 5–50 ppm
- PCB waste: >50 ppm

Table 1. PCB Levels and Classification in Transformer Oils

No	Sample ID	PCB Concentration (ppm)	Classification
1	BGR 009	20,346	Not clearly defined PCBs
2	BGR 025	7,366	Not clearly defined PCBs
3	BGR 013	0,182	Non-PCBs
4	BGR 022	0,065	Non-PCBs
5	BGR 029	0,2607	Non-PCBs
6	BGR UP3	0,196	Non-PCBs

Two samples (BGR 009 and BGR 025) fell into the "not clearly defined" category, indicating measurable PCB levels that do not meet hazardous waste criteria but still require management attention. The remaining four samples were classified as non-PCB oils (<5 ppm), consistent with findings from similar studies in other Southeast Asian countries, where legacy equipment remained in use decades after PCB bans [12][18]

This variation may stem from differences in transformer age, maintenance history, manufacturer origin, or prior oil replacement. According to UNIDO [6], transformer equipment manufactured before the 1990s in Indonesia may still contain Aroclor-based PCBs due to a lack of systematic inventory during import and use.

Indonesia PCB Distribution Map and Inventory Data Gap Analysis

As part of Indonesia's national commitment to the Stockholm Convention, the Ministry of Environment and Forestry (KLHK), in collaboration with the United Nations Industrial Development Organization (UNIDO) and supported by the Global Environment Facility (GEF), developed a PCBs Inventory Database Management System. This digital GIS-based platform enables real-time storage, processing, and visualization of PCB inventory data. The system is vital in supporting Indonesia's target of eliminating PCB use and contamination by 2028.

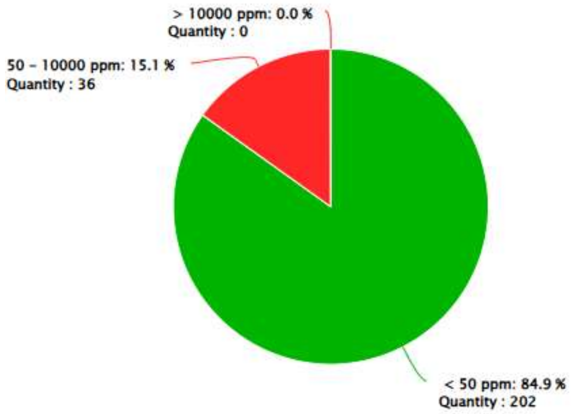

Figure 3. GC-ECD Analytical Results
Source: https://sitkb3.menlhk.go.id/pcbs/site/index

Figure 3 presents the Gas Chromatography–Electron Capture Detection (GC-ECD) results for 238 transformer oil samples. Two hundred samples (84.9%) exhibited PCB concentrations below 50 ppm, while 36 samples (15.1%) fell within the 50–10,000 ppm range. No samples exceeded 10,000 ppm. Although most samples are within the non-hazardous range, mid-level contamination remains a concern, as it requires proactive management under the precautionary principle and may signal incomplete oil replacement or residual legacy contamination. A study conducted by Ododo and Wabalo [16] emphasizes that even low to moderate concentrations of PCBs can have long-term toxicological impacts due to their lipophilic properties and resistance to degradation.

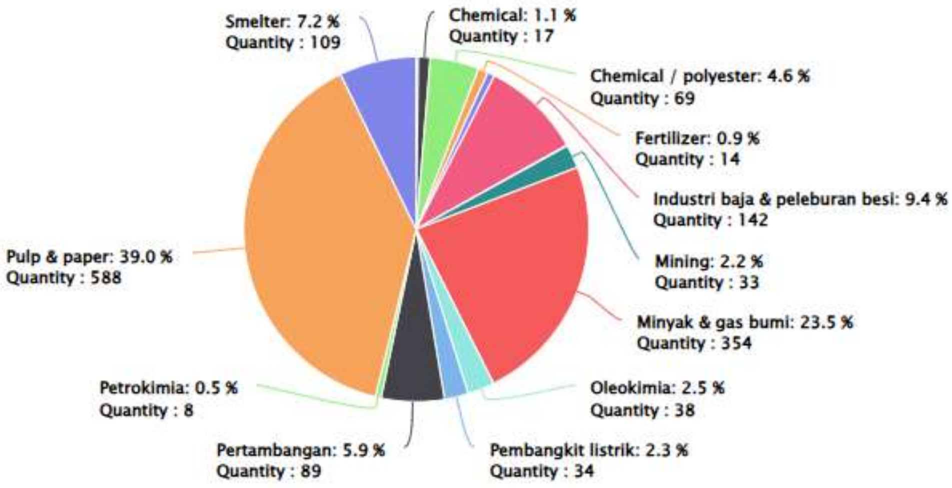

Figure 4. Industrial Sector Distribution

As shown in **Figure 4**, while the Indonesian inventory (2015–2020) provides valuable insights into domestic PCB distribution highlighting the pulp and paper (39.0%) and oil and gas (23.5%) industries as the main users of PCB-containing transformers, it may not fully reflect the broader international context. The dataset, although substantial, is limited in scope to selected regions (Java and Sumatra) and industries with accessible records. This raises questions about its representativeness and generalizability across the national industrial landscape, particularly in regions such as Kalimantan, Sulawesi, and Eastern Indonesia that remain largely unmonitored.

Global studies often identify power generation, electrical equipment manufacturing, and waste incineration as major historical contributors to PCB emissions [4], whereas these sectors are underrepresented in Indonesian data. This discrepancy may be attributed not only to differences in industrial structure but also to limitations in sampling coverage and reporting systems. In countries with longstanding bans, PCBs persist in transformers and capacitors, often undetected due to fragmented inventories. Thus, Indonesia's PCB data should be interpreted cautiously and considered a partial representation rather than a definitive national or global model [7].

Comparison with International Thresholds and Environmental Risk Assessment

Although none of the samples exceeded the 50-ppm limit for hazardous waste classification, PCB concentrations between 7 and 20 ppm should not be considered negligible. PCBs, especially in mixtures such as Aroclor 1254, exhibit high environmental persistence and bioaccumulative properties [4]. Even low-level exposures may contribute to cumulative environmental loading, especially when transformer oils are spilled, leaked, or burned without proper treatment.

Studies in Taiwan and Tanzania have found similar intermediate levels of PCBs in active equipment, suggesting that partial degradation or dilution through oil replacement could account for residual concentrations [15][8]. In Indonesia, these intermediate concentrations represent a regulatory gray area, highlighting the importance of precautionary management even when hazardous waste thresholds are not exceeded.

Moreover, poorly incinerated PCB-contaminated soils may generate dioxins and furans, compounds significantly more toxic than PCBs [10][17]. The risk of secondary contamination is high because transformer maintenance or disposal may occur in areas with insufficient hazardous-waste infrastructure.

Policy Recommendations and Implications for Transformer Management

Indonesia's ratification of the Stockholm Convention in 2009 formalised its commitment to phasing out PCBs by 2025 and ensuring the complete elimination of PCB-containing equipment by 2028 [10]. However, this study's results and national inventory data demonstrate that transformers with *mid-level contamination* (5–50 ppm) remain in active operation across the industrial and utility sectors. Although this concentration range does not meet the hazardous waste classification threshold under Government Regulation No. 101/2014, it nevertheless represents a regulatory grey zone that carries long-term environmental and human health risks, particularly given the persistence and bioaccumulative nature of PCBs [4][15]. This situation underscores the need for more proactive measures to close the management gap for mid-level contamination, as failure to address it may compromise national compliance with the 2025 and 2028 targets.

To address this gap, a mandatory and standardised inventory system should be implemented nationwide, requiring all operational transformers to undergo certified PCB testing in accordance with established protocols such as IEC 61619. The results must be accompanied by a uniform labelling system that clearly indicates PCB concentration bands and prescribes appropriate handling procedures. Such measures would not only improve data reliability but also facilitate more effective planning for phased equipment replacement.

Given that this study identified units within the *not clearly defined* category such as BGR 009 (20.346 ppm) and BGR 025 (7.366 ppm) a targeted phase-out programme is warranted. This initiative should prioritise the replacement or decontamination of mid-level contaminated transformers, particularly those located in high-risk or densely populated areas. Government-supported financial incentives, including subsidies or cost-sharing schemes, could accelerate industry participation, especially for entities facing high capital replacement costs.

Furthermore, the geographical concentration of PCB treatment facilities in Java presents a logistical challenge for equipment located in other regions. Developing decentralised infrastructure either through regional fixed plants or mobile dechlorination units would reduce transportation risks, lower disposal costs, and ensure equitable access to environmentally sound treatment options. Such facilities should comply with Best Available Techniques and Best Environmental Practices (BAT/BEP) to prevent the unintentional formation of dioxins and furans during PCB destruction.

Finally, long-term sustainability of PCB management requires an integrated monitoring and public disclosure mechanism. Embedding PCB reporting into the national hazardous waste information system would enable consistent data flows between provincial environmental agencies and central regulators. Annual publication of aggregated PCB statistics, verified by accredited laboratories, would enhance transparency, encourage compliance, and raise public awareness further aligning Indonesia's efforts with global best practices.

By adopting these measures, Indonesia can close existing policy and operational gaps, mitigate the risks associated with residual PCB contamination, and strengthen its trajectory towards full compliance with the Stockholm Convention's phase-out and elimination timelines.

4. Conclusion

This study quantified polychlorinated biphenyl (PCB) concentrations in six transformer oil samples from industrial electrical equipment in Indonesia using US EPA Method 8082A with Gas Chromatography–Electron Capture Detection (GC-ECD). The analytical method achieved a method detection limit of 0.05 ppm, with calibration linearity exceeding $R^2 = 0.999$ and quality control parameters meeting international performance criteria.

Chromatographic analysis confirmed Aroclor 1254 as the dominant PCB formulation, with peak retention times ranging from 29 to 66 minutes. Total PCB concentrations varied from non-detectable to 20.35 ppm, placing two samples within the "not clearly defined PCBs" category (5–50 ppm) under Indonesian Government Regulation No. 101/2014, while the remaining four samples were classified as non-PCB oils (<5 ppm). No samples exceeded the 50-ppm hazardous waste threshold the Stockholm Convention and Basel POPs Guideline.

Detecting intermediate PCB levels indicates potential residual contamination from historical use or partial oil replacement. Although below hazardous waste limits, these concentrations remain environmentally significant due to the persistence, bioaccumulation potential, and risk of secondary contamination associated with PCBs. The presence of complex Aroclor mixtures reflects the continued operational use of legacy equipment in certain sectors.

The findings reinforce the urgency of implementing a comprehensive national PCB inventory, prioritising the phase-out of mid-contaminated transformers, and expanding decentralised treatment infrastructure. Such measures are essential for ensuring that Indonesia meets its 2025 phase-out and 2028 elimination targets under the Stockholm Convention and reducing long-term environmental and public health risks.

5. Acknowledgment

The authors gratefully acknowledge colleagues from Universitas Sahid Jakarta for their valuable insights, technical discussions, and academic support that greatly assisted this research, although they may not necessarily agree with all interpretations or conclusions presented in this paper. The authors also express their appreciation to the Central Certification Unit (Pusertif), Chemical and Environmental Testing Laboratory of PT PLN (Persero), for providing laboratory facilities and technical assistance during sample analysis. Any remaining errors or interpretations are the sole responsibility of the authors.

6. Abbreviations

Abbreviation	Description
BAT/BEP	Best Available Techniques / Best Environmental Practices
ECD	Electron Capture Detector
GC	Gas Chromatography
GC-ECD	Gas Chromatography–Electron Capture Detection
GEF	Global Environment Facility
GIS	Geographic Information System
IEC	International Electrotechnical Commission
ISTD	Internal Standard
KLHK	Ministry of Environment and Forestry of the Republic of Indonesia
MoEF	Ministry of Environment and Forestry
PCB(s)	Polychlorinated Biphenyl(s)
POPs	Persistent Organic Pollutants
PT PLN (Persero)	Perusahaan Listrik Negara (State Electricity Company of Indonesia)
QC	Quality Control
R^2	Coefficient of Determination
SCX	Strong Cation Exchange
SPE	Solid Phase Extraction
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
US EPA	United States Environmental Protection Agency

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