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The pollution of *polychlorinated biphenyls* (PCBs) waste from PLN electrical activities

Ni Putu Wulan Romianingsih [1*]

[1] School of Environmentalist, Universitas Indonesia; Jl. Salemba Raya, Central Jakarta, 10430, Indonesia.
* Correspondence: wulanromia@gmail.com

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Abstract
PCB waste pollution from PLN (State Electricity Company) electrical activities is a serious problem that affects the environment and public health. This article discusses the sources and impacts of PCB waste pollution, as well as the steps that can be taken to address it. PCB waste originates from transformers, capacitors, and other electrical equipment used by PLN, and it can contaminate the soil, water, air, and surrounding living organisms. The consequences include ecosystem damage, disturbance of ecological balance, health risks, and even economic implications. To tackle this issue, effective waste management technologies such as retrofilling, thermal processes, and sodium processes need to be implemented. Additionally, strict waste management policies and regulations should be established, and public awareness of the dangers of PCB waste should be raised. By adopting these measures, we can mitigate the negative impacts of PCB waste pollution and work towards a cleaner and healthier environment.
Keywords: PCB; PLN electrical activities; waste pollution; waste management

1. Introduction

Polychlorinated biphenyls (PCBs) are synthetic organochlorine compounds, having 209 congeners according to the number and location of the chlorine atoms in the biphenyl ring. Figure 1 shows the general structure of the PCB. This compound is in the form of oil, pale yellow to clear, odorless, does not crystallize at low temperatures, and is dielectric (Reddy et al., 2019; United Nations Environment Programme, 2016; Zhu et al., 2021). In terms of its chemical properties, this compound is stable (not easily decomposed, even with light), and is resistant to heating even above 1000 °C (Reddy et al., 2019; United Nations Environment Programme, 2016; Zhu et al., 2021). Due to their physicochemical properties, PCBs are produced globally for use in a variety of applications, such as dielectric oils in transformers and capacitors, hydraulic fluids, adhesives, and applications in paints, sealants, and carbon paper (Reddy et al., 2019; United Nations Environment Programme, 2016; Zhu et al., 2021). Due to growing concern about the risks posed by their use, PCBs were classified as persistent organic pollutants (POPs) by the Stockholm Convention on 22 May 2001 (Stockholm Convention, 2001).

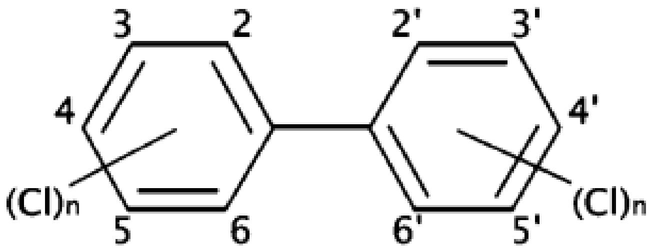

Figure 1. PCB chemical structure
(Source: Wikoff et al., 2012)

Global PCB production from 1930 to 1993 has been estimated at 1.3 million metric tons (Zhu et al., 2021), dan sekitar 10% of which about 10% remains in the environment today (Reddy et al., 2019; Wolska et al., 2012). In the past, PCBs were commercialized under the names arochlor (USA), chlophen (Germany), kanechlor (Japan) and fenclor (Italy) (Hu et al., 2011). Although the production and use of PCBs was banned in most countries in the late 1970s and early 1980s, PCBs continue to be released into the environment from old equipment and waste disposal into the environment (Hu et al., 2011; Jones et al., 2003; Wolska et al., 2012; Zhu et al., 2021).

Many studies have found PCB pollution to have a significant impact on ecosystems and human health (Chiesa et al., 2016; Erdmann et al., 2013; Gupta et al., 2018; Hu et al., 2011; Ilyas et al., 2011; Megson et al., 2021; Shoiful, 2010; Zaynab et al., 2021). In 2001 the Indonesian government issued PP No. 74/2001, which states that PCBs are categorized as B3 which is prohibited. To improve PCB management in Indonesia, in 2020, the Ministry of Environment and Forestry issued Ministerial Regulation Number P.29/MENLHK/SETJEN/PLB.3/12/2020 concerning the Management of Polychlorinated Biphenyls. This article will examine PCB pollution that occurs in Indonesia along with PCB pollution control concepts and technologies.

Although PCBs have not been used in Indonesia since 2001, due to their persistent nature, they are still found in the environment. PCBs can be distributed through air, soil, and water resulting in PCB contamination occurring in areas that are even far from the center of pollution (Lauby-Secretan et al., 2013; Reddy et al., 2019; Wolska et al., 2012). Approximately 10% of PCBs produced in 1930 – 1929 are still present in the environment today (Reddy et al., 2019; Wolska et al., 2012).

The research findings of Shoiful et al. (2010) found a unique pattern in Ciliwung river water in Pluit, Jakarta, where decachlorinated biphenyl (PCB IUPAC #209) and dichlorinated biphenyl (PCB IUPAC #11) were detected at relatively high concentrations, each of 406.77 ng/ L and 6.38 ng/L. In addition, sediment and river water in Surabaya have been contaminated with PCBs (Ilyas et al., 2011). They also reported that PCB levels in river sediments were higher than in coastal sediments and even exceeded sediment quality guideline standards, indicating a possible detrimental effect on aquatic biota. Not only in water, PCBs have also been found in breast milk in Bogor, Purwakarta, Jakarta, Lampung with PCB concentrations > 33 ppb (Sudaryanto et al., 2006; UNIDO, 2021). From the explanation above, it is necessary to understand (1) how the path of PCB contamination to the environment and its impact on ecosystems, health and the economy; (2) PCB pollution control mechanism; and (3) PCB pollution control technology. By understanding this, it is hoped that PCB waste can be controlled in electrical activities at PLN.

2. Methods

This research is focused on PLN's electricity activities because it considers that the main source of electricity in Indonesia is managed by PLN. The method used is quantitative using data collected from literature studies. To analyze pollution and PCB waste control efforts, descriptive statistics were used.

3. Results and Discussion

3.1. Environmental Pollution Analysis

Despite its wide application in industry, most PCBs in the environment are believed to originate from electrical activities, especially capacitors and electrical transformers (Jones et al., 2003; Reddy et al., 2019; Shin & Kim, 2006). In Indonesia, PLN's electrical activities are the main PCB contributor. UNIDO (2021) emphasizes that 60% of PCBs in Indonesia are used in electric transformers and capacitors. PCB-based power transformers are used for old power transformers installed before 1996 (PLN, 2020). From an inventory conducted by the Ministry of Environment and Forestry (KLHK) and UNIDO on 4,524 transformers in Java & Sumatra in 2015 – 2020, it was found that 91.25% of transformers were contaminated with PCBs with a concentration of < 50 ppm and the remaining 8.75% were contaminated with PCBs ≥ 50 ppm with a total total PCBs reached 2,336 tonnes (UNIDO, 2021). Indonesia does not experience pure PCB pollution but cross-contamination. As much as 6% of the transformers conformed to the profile of the original PCB transformer while 94% of the transformers were victims of PCB cross-contamination during treatment (UNIDO, 2021).

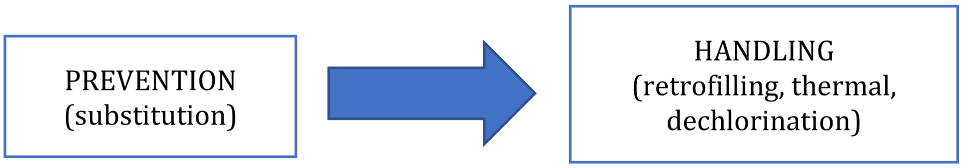

Figure 2. Principles of PCB Pollution Control
(Adopted from (Deif, 2011; Helmer & Hespanhol, 1997; Permen LHK No. P.29/MENLHK/SETJEN/PLB.3/12/2020)

PCB distribution channels to the environment also vary. If in the past, the tendency for PCB exposure was more oriented towards occupational contamination, such as during the production of PCBs, transformers and capacitors, but currently, exposure can come from disassembly, dysfunction or uncontrolled recycling of equipment contaminated with PCBs (Lauby-Secretan et al., 2013). PCBs can be released into the air, water and soil during use, distribution or disposal. The following are possible PCB pollution pathways in the Ciliwung and Surabaya rivers:

- Spills and leaks from distribution, storage and maintenance of transformers, capacitors and other products that use PCBs;
- PCBs can evaporate from polluted waters and then fall in the form of rain which then contaminates ground and surface water;
- Improper and unlawful disposal of PCB waste or disposal of old electrical equipment and used dielectric oil containing PCBs to domestic, industrial or other landfills;
- Improper and inefficient disposal technology; And
- Hazardous and Toxic (B3) waste disposal sites containing PCBs that are not properly maintained.

PCBs are lipophilic compounds and therefore PCBs are found in hydrophobic environments such as soil and riverbeds, and eventually accumulate in the adipose tissue of organisms, including humans (Lauby-Secretan et al., 2013). This is why breast milk in several regions in Indonesia contains PCBs. PCB pollution is multidimensional, as illustrated in Figure 2. The direct impact of PCBs is seen on ecosystems and human health. PCB pollution if not managed properly will also have a derivative impact on the economy.

3.1.1. Ecosystem

Erdmann et al. (2013) examined PCB pollution in Arctic fauna. They report that PCBs are found in the blood of species at the top of the food chain, such as polar bears and birds of prey. These compounds are known to disrupt endocrine (hormonal) processes, including reproductive processes. This study demonstrates the presence of PCBs in areas far from the main sources of these contaminants, ensuring that PCBs can be distributed via oceanic and atmospheric currents and are persistent in the environment. Chiesa et al. (2016) measured PCBs in bluefin tuna (Thunnus thynnus) worldwide. The results showed that PCBs were found in tuna samples from the Indian Ocean, Atlantic Ocean and Mediterranean Sea. Many other studies have also found PCB initiation in marine ecosystems (Wolska et al., 2012) and surface water (Hu et al., 2011; Ilyas et al., 2011; Shoiful, 2010). In China, PCBs were also detected in various plant samples, such as rice, corn, vegetables, taro and sugar cane, from areas near emission sources to remote areas far from emission sources (Zhu et al., 2021). This proves that PCBs are bioaccumulative and have a direct impact on food webs that carry massive ecological risks.

3.1.2. Health

Historically, human exposure to PCBs was through work or accidents, but the most relevant route of PCB exposure today is through ingestion of PCB-contaminated food and water. PCBs are easily absorbed and distributed in the body, and accumulated in adipose tissue are directly genotoxic and mutagenic (Ludewig & Robertson, 2012).

Furthermore, health problems associated with PCB exposure can be acute or chronic depending on the dose, duration of exposure, and the type of congener (Gupta et al., 2018). The acute disturbance occurs as a result of accidental exposure or occupational exposure to high doses and lasts a short time. Acute disturbances have been reported in accidental PCB poisoning such as Yusho's disease in 1968 which affected about 14,000 people in Japan and Yu-cheng's disease in 1979 which affected about 2,000 people in Taiwan (Hsu et al., 1985; Kuratsune et al., 1981). During the incident, mass poisoning occurred in people who consumed rice bran oil previously contaminated with PCBs. Common symptoms of the poisoning are dermal and ocular effects such as chloracne, skin rashes and ocular lesions, irregular menstrual cycles and carcinogenesis (Hsu et al., 1985; Kuratsune at al., 1981). Chronic or long-term exposure to PCBs in humans can cause disorders of the liver system, cardiovascular complications, endocrine dysfunction, reproductive and developmental abnormalities, neurological defects and effects on the immune system (Gupta et al., 2018; Klaren et al., 2015; Lauby-Secretan et al., 2013; Ludewig & Robertson, 2012).

Jacobson & Jacobson (1996) investigated children born to women who ate PCB-contaminated Lake Michigan fish. The study shows that prenatal exposure to PCBs causes low IQ, memory and verbal abilities. Exposed children were three times more likely to have low average IQ scores and twice as likely to be behind at least two years in reading comprehension.

3.1.3. Economy

The persistent and toxic nature of PBT contaminants means that they have potentially significant economic implications over the long term. PBT contamination leads to increased public health costs, losses in the commercial fishing sector, disruption to recreational and tourism activities, and monitoring and management costs. Usually manufacturers and companies that use PCBs do not take into account the externalities of PCB contamination caused by them.

Continuing the research conducted by Jacobson dan Jacobson (1996) in the previous explanation, if women's exposure to PCB contamination occurs on a large enough scale, the economic costs for society will be high considering that a decrease in average IQ has the potential to cause loss of income and decrease in productivity. patient's economy.

The commercial and recreational fishing sector due to PCB contamination can also have significant economic consequences. Willson & Kazmierczack Jr., (2007) report that the waters of New Bedford Harbor and the Buzzards Bay area in Massachusetts have been closed to lobster harvest since 1979 as a result of PCB contamination, forcing local fishers to travel further or stop harvesting. This can also happen in Indonesia considering that PCBs have been found in the coastal areas of Surabaya and Jakarta and there is potential for PCB exposure in other areas. As a maritime country, PCB pollution will have a major impact on the country's economy where millions of people in Indonesia depend on marine products for their lives.

3.2. Pollution Control Concept

Considering that PCB (1) is a B3 material classified as prohibited from being used; (2) still found in transformers, capacitors, and dielectric oil; (3) have significant environmental, health and economic impacts, it is necessary to carry out efforts to control pollution. The Indonesian government has issued a series of regulations as the basis and guidelines for industries to manage their PCB waste. Thus PCB pollution management is a mandate not an option. Current PCB-Related Regulations include:

- PP No. 74/2001, which states that PCBs are categorized as B3 which is prohibited. PLN also prohibits the use of PCBs;
- PP No. 18/1999- PP GR No. 85/1999 concerning Management of Hazardous and Toxic Materials;
- Ministerial Regulation No. 18/2009 regarding the procedure for obtaining a permit for the management of B3 includes a ban on the use of PCBs.
- Minister of Environment and Forestry No. P.29/MENLHK/SETJEN/PLB.3/12/2020 which regulates PCB management for transformers, capacitors, and dielectric oil.

Pollution control is the effort of prevention and mitigation of environmental component pollution, as well as the restoration of the quality of environmental components in accordance with prevailing regulations. The concept of pollution control for PCBs can adopt the principles of green manufacturing (Deif, 2011). Basically the concept of waste control is from upstream to downstream, namely (1) prevention, (2) reduction, and (3) handling (Deif, 2011; Helmer & Hespanhol, 1997). However, because PCB is a prohibited material, reduction is not a control option. Figure 2 describes the PCB pollution control concept.

Prevention is the highest hierarchy in pollution control because it eliminates pollutants upstream. PCBs are no longer needed because replacement materials are available which have physical properties similar to PCBs, as described in Table 1. In cases where the installed transformer or capacitor already contains PCBs or where PCB contamination has already occurred, special technology is needed which will be discussed later in Pollution Control Technology section.

Table 1. More Environmentally Friendly PCB Replacement Compounds

	PCB	**Mineral oil**	**Silicon oil**	**High molecular hydrocarbon**	**Synthetic ester**	**Natural ester**
Flash Point (°C)	170	160	300	275	275	315
Fire Point (°C)	380	170	340	310	300	350

(Source: UNIDO, 2021)

PLN as the largest PCB contributor in Indonesia also prohibits the use of PCBs throughout its activity chain. This is stated in the Environmental Management Plan for the Development of Group II Substations (PLN, 2016). The form of mitigation of PLN PCB pollution is presented in Table 2.

Table 2. PLN's Environmental Management Plan Related to PCBs

Activity Phase	Mitigation Measures
Pre-construction	The procurement document will require the procurement of equipment that does not contain PCBs
Construction	• The contractor submits a statement that the material is free from PCB. • Used transformer oil waste will be managed in accordance with applicable laws and regulations.
Operation	• No PCB will be used in any transformer oil change. • Waste oil will be handled, stored and disposed of in accordance with applicable regulations.

(Source: PLN, 2016)

3.3. Pollution Control Technology

PCB pollution control technology in transformers, capacitors and dielectric oil is fully regulated in Permen LHK No. P.29/MENLHK/SETJEN/PLB.3/12/2020. According to these regulations, broadly speaking this technology is divided into two, namely:

a. On transformers that are still in use
The most appropriate technology for decontamination of transformers that are still in use is retrofilling which is carried out in-situ. Retrofilling is a method to reduce the concentration of PCBs in a transformer by replacing dielectric oil containing PCBs with dielectric oil that does not contain PCBs so that the concentration of PCBs falls below the lowest PCBs concentration limit. The dielectric oil options that can be used are listed in Table 1.

b. On unused transformers and capacitors, as well as dielectric oil
There are two possible technologies for this case, namely thermal and non-thermal. In order to enter the thermal process, waste must have a combustion efficiency of at least 99.99% and a combustion temperature of at least 850°. Thermal processing of PCBs is carried out on dielectric oils with high concentration values (above 10,000 ppm) and porous dense materials.

PCB processing by non-thermal means includes decontamination and dechlorination. Decontamination is done by cleaning the surface of the non-porous material using a solvent. If the swab test on the decontamination results has a PCB concentration of <10 μg/cm2, then this material can then be used as raw material for production or managed according to regulations in the non-B3 waste sector.

Dechlorination of dielectric oil from transformers and capacitors is carried out by using alkaline metals bound to organic or inorganic compounds to remove one or more chlorine atoms from PCB compounds. If a quick test or laboratory test shows that the PCB contamination value is less than the PCB concentration limit, then the dielectric oil can be reused in the transformer or managed according to regulations in the B3 waste sector.

In addition to the above technological forms, PCBs can also be managed using chemical processes such as the sodium process (Johnston, 1985). This process is used on dielectric grease. Sodium, in the form of elements or compounds (such as sodium napthalide, sodium alcoholate) reacts with chlorine in the PCB molecule to produce sodium chloride and an aromatic polymer based on the biphenyl structure. The polymer material and sodium chloride produced are then removed, leaving behind the decontaminated oil.

4. Conclusions

PCBs have been banned for use in Indonesia since 2001, but because of their persistent nature, these compounds are still found in the environment. PCBs can be distributed through air, soil and water resulting in contamination. This compound is found in Ciliwung river water, sediment and river water in Surabaya, as well as in breast milk. Most PCB pollution in Indonesia comes from cross-contamination from PLN's electrical activities, such as transformers, capacitors and dielectric oil. The impact of this pollution varies, ranging from the environment, health, to the economy. To control pollution, the government has issued various regulations, which regulate the PCB ban and PCB waste management processes. From the industrial sector, especially PLN, the principles of PCB waste control include prevention (substitution) and treatment using technologies such as retrofilling, thermal, decontamination, dechlorination, and sodium processes.

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Conflicts of Interest
The authors declare no conflict of interest.

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