

## Research Article

# Effectiveness of Charcoal Adsorbent in Flue Gas Filters for PCB Reduction in Smoke from Hospital Incinerators

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The release of gas-phase polychlorinated biphenyls (PCBs) as one of the persistent organic pollutants (POPs) is an unfortunate result of combustion, especially from medical waste incinerators. This tends to make incinerators unpopular. The idea of a cheaply available air pollution control device fitted to incinerator chimneys can justify the continued use of incinerators. A gas filter unit, consisting of 3 filter beds with activated charcoal as an adsorbent, was designed, constructed, and fitted onto an existing incinerator at a university hospital in Ghana. Flue gas from the incinerator was sampled before and after the filter beds, using cylindrically-shaped mini-polyurethane foam (mini-PUF) samplers, and the analytes in the samples were then Soxhlet-extracted, purified, and analyzed for certain PCBs using the gas chromatography-mass spectrometer (GC-MS) technique. Twelve of the 14 indicators PCBs analyzed in the smoke samples were present, and 11 of them saw mean reductions ranging from 3.67% to 54.9% by the charcoal filter beds. These were PCB 18, PCB 28, PCB 31, PCB 44, PCB 101, PCB 118, PCB 138, PCB 149, PCB 153, PCB 170, and PCB 180. The gaseous concentrations of PCBs before filtration ranged from 0.0000788 ng/m<sup>3</sup> for PCB 180 to 0.00129 ng/m<sup>3</sup> for PCB 153. After the filtration by the charcoal adsorbent, they ranged from 0.00003734 ng/m<sup>3</sup> for PCB 170 to 0.00112016 ng/m<sup>3</sup> for PCB 153. The highest mean reduction of 54.9% came from the homologue, PCB 180, whilst the homologue with a dioxin-like character (PCB 118) saw a 22.44% reduction. This suggests that dioxins and other dioxin-like compounds are most likely adsorbed by the charcoal adsorbent. This gas filter unit should further be investigated for its effectiveness at removing other dioxin-like PCBs, dioxins, and furanes and for testing the effectiveness of thermophilic bacterial strains that can further metabolize these POPs into less harmful products.

## 1. Introduction

Air pollution is currently a major problem in the developing world, and Ghana is no exception. A recent study suggests that at least 6.7 million deaths worldwide in 2019 were traceable to air pollution, with nearly 500,000 of them being neonatal deaths, mostly in Sub-Saharan Africa and India [1]. In Ghana, a WHO estimate of at least 28,000 annual premature deaths linked to air pollution means that dirty air is now a bigger killer than malaria and AIDS combined [2].

Air pollutants of particular concern have recently included a class of persistent organic pollutants (POPs) which include dioxins, furanes, and polychlorinated biphenyls (PCBs) among others. In particular, PCBs in the environment have resulted from both purposive production and unintended releases from combustion processes [3].

In the wake of the Stockholm Convention of 2001 on POPs unintentionally released from combustion processes, many countries in the advanced world began to close down a number of their incinerators for waste treatment [4]. The

trend in waste treatment has begun to shift towards non-incineration alternatives including central autoclaving, microwaving, alkaline hydrolyses, and mechanical treatment, among others. These alternatives are usually capital-intensive and require expertise in running them as well as effective waste segregation systems.

In a developing country like Ghana, incinerators are popularly used in hospitals for infectious waste treatment. Most of these hospitals have limited budgets which may not allow easy adoption of nonincineration treatment methods. Besides, the lack of thorough waste segregation in many hospitals in Ghana can hamper the integrity of these sets of equipment.

The idea of a cheaply available air pollution control device fitted to incinerator chimneys can justify the continued use of incinerators. According to Ghana's Ministry of Health, a locally-available incinerator that can function reliably must be preferred to sophisticated equipment which will break down frequently and whose spare parts are not easily procurable when it breaks down ([5]).

Kwawukume [6] developed a gas-based medical waste incinerator for treating medical waste in Ghana and other West African countries [6]. Other incinerators are also in use in Ghana such as the rectangular incinerators and the traditional De Montfort incinerators. Most of them are operating without air pollution control devices (APCDs). As a result, these incinerators release persistent organic pollutants (POPs) such as polychlorinated dibenzo-p-dioxins and furanes (PCDDs/Fs), polychlorinated biphenyls (PCBs), some of which are dioxin-like, and polycyclic aromatic hydrocarbons (PAHs) which are a concern, especially in the light of the Stockholm Convention of 2001 on POPs.

Legal limits for PCDD/Fs in flue gases are 0.1 ngTEQ/Nm<sup>3</sup> in the EU and 0.3 ngTEQ/Nm<sup>3</sup> in the U.S. Other jurisdictions have similar limits for these compounds. However, such a limit does not seem to exist for PCBs even in countries like China, even though they are common air pollutants, especially from the incineration of PVC materials found in infectious waste [7].

Filtration of exhaust gases is designed to reduce these pollutants and is popularly achieved by the adsorption process. The three materials usually deployed for adsorption are activated carbon, silica gel, and alumina. These materials have high micropore volumes and specific surface areas and are therefore good adsorbents particularly of trace organic compounds in industrial flue gas streams [8].

The pore size of the filter material should be big enough to allow steam and smoke in a size range of 0.01–1  $\mu\text{m}$  to pass through but small enough to prevent particulate matter, PM<sub>2.5</sub> (2–3  $\mu\text{m}$ ), and bigger dust as well as bacteria from passing through. Bacteria and dust have the same size ranges (1–100  $\mu\text{m}$ ).

Activated carbon is the universal standard for the purification and removal of trace organic contaminants from vapor and liquid streams. Many research findings have established activated carbon as the most effective adsorbent of volatile organic compounds [8], with activated

carbon fibers exhibiting higher adsorption capacity and faster adsorption kinetics than granular activated carbons [8].

For this study, a gas filter was designed which was fabricated and tested on a local incinerator in use at the University of Cape Coast Hospital in Ghana. This incinerator was chosen after a previous study involving 5 major hospitals in Ghana [9]. The gas filter was designed as a multibarrier filter having 3 beds of powdered activated charcoal supported on wire mesh. The powdered activated charcoal was commercially prepared from 3 tree species, namely *Mangifera indica*, *Zea mays*, and *Eucalyptus globulus*. This material is effective at removing particularly persistent organic pollutants (POPs) such as PCBs, dioxins, and furanes (PCDD/Fs) commonly formed from infectious hospital waste incineration.

Local incinerators in use in Ghana are small-scaled and operated intermittently as opposed to large-scale incinerators in advanced countries which are operated continuously [10]. Therefore, continuous injection of activated charcoal powder was not necessary. Rather, this filter system design has charcoal beds that can be used and replaced with fresh charcoal beds after a certain number of incineration cycles.

This study evaluated the efficiency of powdered activated charcoal in filter beds inside a smoke filter unit which was mounted on an incinerator for burning infectious waste.

## 2. Materials and Methods

**2.1. Geographical Location of the Incinerator.** The locally-made incinerator (Figure 1) chosen for the study was situated on latitude 5° 6' 15" N and longitude 1° 17' 5"W behind the Directorate of University Health Services (DUHS) at the campus of the University of Cape Coast in Ghana.

**2.2. Design and Manufacture of the Gas Filtration Unit.** The gas filter unit was designed and manufactured in a previous study by Adu et al. [9], based on the dimensions of the chimney stack of this incinerator (Figures 2 and 3). It was locally fabricated by a private company in Ghana called Richie K. Company Ltd. Its framework is made of galvanized metal. It has an inlet for the smoke, 3 filter bed supports made of steel wire mesh, a sampling point beneath the filters, and another sampling above the filters (Figure 2).

**2.3. Experimental Design.** The evaluation of the smoke filtration unit was designed as follows: duplicate samples of the flue gas were taken with the 2 foam samplers before contact with charcoal beds (to serve as the control [11]). Another pair of duplicate samples was taken above the 3 charcoal beds. After burning the waste, both sample pairs were brought to the Organic Chemistry Lab of the University of Cape Coast in Ghana for extraction and purification. Analysis was then carried out at the Pesticide Residue Lab of the Ghana Standards Authority. The experimental design was as follows:



FIGURE 1: Locally-made hospital incinerator.

- (1) Control (sampled flue gas before filtration)
- (2) Multibarrier filter with activated carbon powder
- (3) Sampled flue gas after filtration
- (4) Extracting and quantifying target pollutants from 2 sets of foam (PUF) samplers

Following a study by the authors in [15] on wood smoke filtration, already-made and commercially available powdered activated charcoal was chosen over locally-made activated charcoal for this study.

#### 2.4. Chemicals and Instrumentation

- (i) 4 mini-PUF passive sampling (PAS) foams (1.5 cm diameter  $\times$  5 cm length; Figure 4)
- (ii) Commercially-obtained activated charcoal powder as adsorbents on filter beds
- (iii) Methanol
- (iv) Soxhlet extractor
- (v) 1 L of GC-grade hexane as extraction solvent (from the Department of Chemistry, UCC, Ghana)
- (vi) Heating mantle
- (vii) Water circulator (water bath)
- (viii) Thimbles (to hold foam samples in the extractor)
- (ix) Rotary evaporator
- (x) Combined multilayer silica gel and activated carbon columns (for clean-up)

- (xi) Glass wool
- (xii) Gas Chromatograph–Agilent 7890 B GC Sampler 80, VF-5 ms GC Column (30 m  $\times$  0.25 mm I.D.  $\times$  0.25  $\mu$ m film thickness, 10 m EZ-Guard, 7 inch) fused silica capillary coated with VF-5 ms for separation of tri- to deca-CBs) from Ghana Standards Authority
- (xiii) Mass spectrometer (Agilent 7000°C Triple Quadrupole)
- (xiv) 10 ml of 20  $\mu$ g/L PCB calibration standard mix of 14 congeners (from Ghana Standards Authority).
- (xv) Anhydrous Na<sub>2</sub>SO<sub>4</sub>
- (xvi) Eppendorf pipettes with polypropylene tips
- (xvii) Helium 5.0 (carrier gas)
- (xviii) Acetonitrile (for reconstituting PCB extracts)

#### 2.5. Passive Sampling of Gas-Phase PCBs.

Cylindrically-shaped foam materials were fabricated to serve as mini-polyurethane foam (mini-PUF) samplers for personal deployment. They were chosen over disc samplers for stationary sampling (PUF-PAS discs) following an evaluation study carried out by Bohlin [13] for passive sampling of polycyclic aromatic hydrocarbons (PAHs) and other trace organics such as PCBs.

Prior to sampling, the foams were soaked in methanol for at least 12 hours in a beaker and then rinsed with distilled water to eliminate any PCBs accumulated in the PUF material.

On the gas filter designed and constructed, two pairs of pipes were provided which served as sampling points for the mini-PUF passive samplers used for taking smoke samples from the incinerator chimney stack. The flue gas was simultaneously sampled before and after the filter beds, following the sampling procedure adopted by [8].

Duplicate samples of smoke before and after filtration were taken with the modified PUF plugs during the time course of the study to assure reproducibility.

The sampling of smoke was carried out on the 6<sup>th</sup> of October, 2020 (Table 1).

The structures and nomenclatures of the 14 indicator PCBs tested are shown in Table 2, showing two biphenyl rings directly joined together and having different numbers of chlorine substituent atoms in either the ortho-, meta-, or para-positions of the biphenyl ring.

**2.6. PCB Extraction and Concentration.** Extraction and concentrating of PCBs from foam samples of smoke were adapted from Chen et al. [7]. Two duplicate samples of smoke were taken, before and after contact with the filters. Each of the 4 foam samples was cut into 4 parts and placed inside a cellulose thimble which, in turn, was placed inside the Soxhlet extractor. Each extraction was carried out over a minimum of 16 hours. After extraction, the analytes were dried over anhydrous Na<sub>2</sub>SO<sub>4</sub> and concentrated to 10 ml using a rotary evaporator.

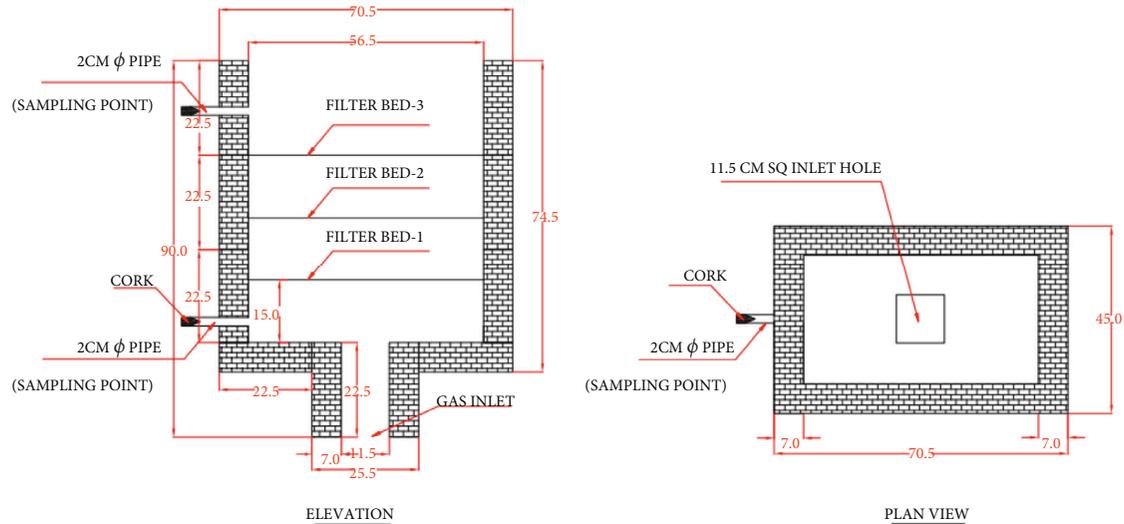


FIGURE 2: Elevation and plan views of smoke filter unit design.

**2.7. Postextraction Clean-Up.** The cleaning-up process was a manual silica gel clean-up using a two-layer column consisting of 2 adsorbents, namely silica gel and activated carbon. Prior to the clean-up process, the column containing glass wool was conditioned with 100 ml of the hexane solvent. Hexane and dichloromethane were then eluted through the system (50 ml: 50 ml) for washing. Prior to GC-MS analysis, the cleaned-up extracts were then concentrated to approximately 5 ml using the rotary evaporator into vials. They were then evaporated to dryness and then reconstituted in the acetonitrile phase, prior to the GC-MS analysis.

**2.8. GC-MS Analysis.** The analysis was performed using an Agilent 7890 B Gas Chromatograph with an Agilent Technologies GC sampler 80 which was coupled to an Agilent 7000°C Triple Quadrupole mass spectrometer. A VF-5 ms (30m + 10 m EZ-Guard × 0.25 mm internal diameter × 0.25 μm film thickness) capillary column was used for separation of the standard mixture of 14 PCB congeners and the sample analytes.

Helium gas at 189.75 kPa pressure was used as a carrier gas at a constant flow rate of 2.25 ml/min and N<sub>2</sub> as makeup or collision gas at a 1.5 ml/min flow rate. The injector was kept at 280°C, and the injection mode was the splitless mode. The positive EI ionization mode was used.

The GC temperature program was optimized as follows: the initial oven temperature was set at 70°C for 2 mins, then increased at 25°C/min to 150°C, then increased at 3°C/min to 200°C, and finally increased at 8°C/min to 280°C and held for 13.133 mins. The total run time per sample was thus 45 minutes.

**2.9. Instrument Accuracy.** The accuracy of the GC-MS instrument is given for each of the 14 PCB congeners, using the highest percentage accuracy and the corresponding concentration for each of the standard mixtures (Table 3).

**2.10. Laboratory Blanks Analysis.** For the laboratory blanks analysis, the polyurethane foams (PUFs) were soaked in methanol for 12 hours. Afterwards, pure hexane solvent was used in a Soxhlet extractor to extract any possible background PCBs, and the extract was concentrated in a rotary evaporator. The concentrate was analyzed for the 14 indicator PCBs using the GC-MS equipment, and the result showed no background PCB concentrations (Figure 5). Then, ethyl acetate (EA.D) was used for the solvent (reagent) check on the GC-MS instrument (Figure 6). The solvent run with ethyl acetate also gave zero values for all 14 indicator PCBs, indicating no background contamination with PCBs.

**2.11. Analytical Quality Control.** Firstly, internal quality control check was conducted using acetonitrile since the cleaned-up extracts were reconstituted in the acetonitrile phase. Secondly, 6 different concentrations (namely 5, 10, 20, 50, 100, and 200 μg/L) of the calibration standard (14 PCBs in a mixture, listed in Table 2) were prepared for calibrating the GC-MS instrument.

To evaluate the instrument's efficiency for the target compounds, recovery values were computed from the calibration runs (Table 4).

**2.12. Statistical Analysis.** The results of the GC-MS analyses on the 2 duplicate samples were entered into the Excel 2013 spreadsheet. An analysis of variance (ANOVA) at a 95% confidence interval for duplicates of smoke samples in foam was carried out using GraphPad Prism 5 software. The efficiency of the gas filter unit with respect to PCBs was calculated as follows:

$$\% \text{Reduction} = \frac{C_{\text{noch}} - C_{\text{char}}}{C_{\text{noch}}} \times 100\%, \quad (1)$$

where  $C_{\text{noch}}$  represents PCB amounts in foam samples before contact with filters and  $C_{\text{char}}$  represents PCB amounts in foam samples after contact with the charcoal filters.



FIGURE 3: Front and rear views of manufactured smoke filter unit.



FIGURE 4: Polyurethane foam materials (mini-PUF) are used for passive sampling.

### 3. Results and Discussion

**3.1. Quality Control Result.** The limit of detection (LOD) and limit of quantification (LOQ) for the 14 PCB congeners, as set by the GC-MS instrument, were  $1 \mu\text{g/L}$  and  $5 \mu\text{g/L}$ , respectively. Ethyl acetate was first used for the solvent run. The instrument was then calibrated with the standard

mixture of 14 PCBs, using 7 levels or concentrations of the standard mixture (5, 10, 20, 50, 100, 200, and  $500 \mu\text{g/L}$ ). The coefficients of determination ( $R^2$ ) over the seven-point concentration range of 5– $500 \mu\text{g/L}$  ranged from 0.9982 to 1.000 (Table 4) for the 14 PCB isomers in the calibration mixture which were very high values. The mean recoveries of the congeners with respect to the instrument were computed from the 7 levels of the calibration concentration for each of the 14 isomers (Table 4).

**3.2. Evaluation of the Charcoal Filter.** Out of 14 analytes in the PCB mixture tested in the evaluation of the smoke samples, two (2) were not present at all in the samples. These were the isomers (PCB 194 and PCB 209). Of the remaining 12 that were present, 11 of the isomers (PCBs 18, 28, 31, 44, 101, 118, 138, 149, 153, 170, and 180) saw reductions in mean levels by the charcoal bed filters. The mechanism of action by the activated charcoal was by the chemical adsorption process. The only exception was PCB 52 which had a higher

TABLE 1: Sampling conditions.

Sampling date	Exposed area of PUF (cm <sup>2</sup> )	Sampling time (min)	Environmental data			Humidity (%)	Likelihood of precipitation (%)
			Temp (°C)	Wind speed (m/s)	Wind pressure (mbar)		
6 <sup>th</sup> Oct 2020	23.6	6	25–27	7.3 mph	1014	92	41

TABLE 2: Structure and nomenclature of 14 PCB analytes tested for.

PCB analyte	Structure	IUPAC nomenclature	Chemical formula	Molecular weight (g/mol)
PCB-18		1,4-Dichloro-2-(2-chlorophenyl)benzene	<b>C<sub>12</sub>H<sub>7</sub>Cl<sub>3</sub></b>	<b>257.5</b>
PCB-28		2, 4, 4'—Trichlorobiphenyl	<b>C<sub>12</sub>H<sub>7</sub>Cl<sub>3</sub></b>	257.5
PCB-31		1,4-Dichloro-2-(4-chlorophenyl)benzene	<b>C<sub>12</sub>H<sub>7</sub>Cl<sub>3</sub></b>	<b>257.5</b>
PCB-44		2,2',3,5'—Tetrachlorobiphenyl	C <sub>12</sub> H <sub>6</sub> Cl <sub>4</sub>	291.99
PCB-52		1,4-Dichloro-2-(2,5-dichlorophenyl)benzene	<b>C<sub>12</sub>H<sub>6</sub>Cl<sub>4</sub></b>	<b>291.99</b>
PCB-101		2, 2',4,5,5'-Pentachlorobiphenyl	C <sub>12</sub> H <sub>5</sub> Cl <sub>5</sub>	326.43
PCB-118		2, 3', 4, 4',5 –Pentachlorobiphenyl (dioxin-like)	C <sub>12</sub> H <sub>5</sub> Cl <sub>5</sub>	326.43
PCB-138		- 2,2',3,4,4',5'-hexachlorobiphenyl	<b>C<sub>12</sub>H<sub>4</sub>Cl<sub>6</sub></b>	360.88
PCB -149		2,2',3,4',5',6—Hexachlorobiphenyl	<b>C<sub>12</sub>H<sub>4</sub>Cl<sub>6</sub></b>	360.88
PCB-153		2,2',4,4',5,5'-hexachlorobiphenyl (source: ( <a href="https://www.chemspider.com">https://www.chemspider.com</a> ))	<b>C<sub>12</sub>H<sub>4</sub>Cl<sub>6</sub></b>	360.88
PCB -170		2,2', 3,3', 4,4',5—Heptachlorobiphenyl	<b>C<sub>12</sub>H<sub>3</sub>Cl<sub>7</sub></b>	395.32

TABLE 2: Continued.

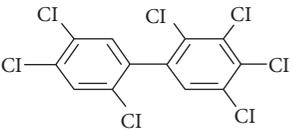
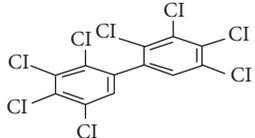
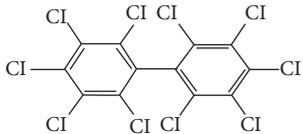
PCB analyte	Structure	IUPAC nomenclature	Chemical formula	Molecular weight (g/mol)
PCB -180		2,2', 3,4,4',5,5'—Heptachlorobiphenyl	$C_{12}H_3Cl_7$	395.32
PCB-194		2,2',3,3', 4,4',5,5'—Octachlorobiphenyl	$C_{12}H_2Cl_8$	429.77
PCB-209		2,2',3,3',4,4',5,5',6,6'—Decachlorobiphenyl	$C_{12}Cl_{10}$	498.66

TABLE 3: GC-MS instrument accuracy for PCB congeners.

PCB congener	Highest accuracy (%)	Concentration ( $\mu\text{g/L}$ )
PCB 18	101.6069	100
PCB 28	102.0053	100
PCB 31	102.0053	100
PCB 44	101.2898	500
PCB 52	104.3422	5
PCB 101	102.036	100
PCB 118	108.0074	5
PCB 138	103.9564	100
PCB 149	103.9564	100
PCB 153	103.9235	100
PCB 170	101.9921	100
PCB 180	101.9921	100
PCB 194	169.97094	100
PCB 209	608.7813	20

mean level after filtration (Figure 7). This could be peculiar to that isomer.

One of the 14 congeners in the PCB mixture analyzed, PCB 118 has a co-planar structure, with one chlorine substituent atom in the ortho-position of the biphenyl ring and is dioxin-like in behavior (Table 2). This congener saw a mean reduction of 22.40% by the charcoal filter beds (Table 5). This suggests that dioxins, furanes, and other dioxin-like PCBs are possibly removed by the charcoal beds. Thus, the three charcoal filter beds achieved PCB reductions in smoke ranging from 3.67% (for PCB 31) to 54.9% (for PCB 190) as shown in Figure 7.

**3.3. Design and Uncertainty Analyses of Incinerator Emissions.** As the design was based on an existing incinerator (Figure 1), the volume of exhaust gas produced was estimated using the bed complement of 75 beds at the UCC hospital in Ghana [9] and the average generation rate of infectious

waste of 1.5 kg/bed/day [14]. Also, incineration of waste at this facility was intermittent at approximately 1 cycle per month and not continuous. The estimations were computed as follows:

Bed complement = 75 beds.

Daily medical waste generation at UCC hospital  $\cong (1.5 \text{ kg/bed/day}) \times 75 \text{ beds} \cong 112.5 \text{ kg/day}$ .

Monthly waste generation rate  $\cong (112.5 \text{ kg/day}) \times (30 \text{ days/month}) \cong 3,375 \text{ kg/month}$ .

Approximately, 15% of medical waste generated in hospitals is infectious [15,16], and even though the feedstock may vary slightly from time to time, about 35% of infectious medical waste is PVC plastics [21] which contains about 60% w/w chlorine [22].

Monthly infectious waste generation rate  $\cong 0.15 \times 3,375 \text{ kg/month} = 506.25 \text{ kg/month}$ .

Frequency of incineration  $\cong 1 \text{ cycle/month}$ .

Therefore, the approximate feed rate of infectious waste = 506.25 kg feed/cycle.

Assuming an exhaust gas ratio of 20 kg of gases/kg of feed [23].

Exhaust gases/cycle = (20 kg gases/kg feed) (506.25 kg feed/cycle) = 10,125 kg gases/cycle.

Again, assuming average gas molar mass of 30 kg/kg-mole [23].

Total moles of exhaust gas/cycle,  $E_t = 10,125 \text{ kg/cycle} / 30 \text{ kg/kgmole} = 337.5 \text{ kg-mole gas/cycle}$ .

Assuming that the exhaust gases contain about 12%  $\text{CO}_2$  and 8%  $\text{H}_2\text{O}$  as emitted [23], we calculate, on a dry basis, the molar flow rate of dry exhaust gases ( $E_d$ ) leaving the incinerator chimney as follows:

$E_d = E_t - \text{moles of water leaving with exhaust gas/cycle} = 337.5 (1 - 0.08) = 310.5 \text{ kg-mole/cycle}$ .

Now, we apply the Ideal Gas Law to calculate the "number of dry standard cubic meters (dscm) of gas flowing per cycle (at standard conditions of  $T = 298 \text{ K}$  ( $25^\circ\text{C}$ ) and  $P = 1 \text{ atmosphere}$ )

## Pesticide Residues Analysis Report

Agilent Technologies

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	Compound Name	RT	Transition (T)	Transition (D)	T-Resp	GC/MS Conc. (ppb)	QRatio	Sample (mg/kg)
1)	PCB 18	10.16	255.8 -> 186.0	256.0 -> 186.0	0	0.00		0.000
2)	PCB 28	14.19	255.8 -> 186.0	256.0 -> 186.0	2810	0.00	103.3	0.000
3)	PCB 31	14.19	255.8 -> 186.0	256.0 -> 186.0	2810	0.00	103.3	0.000
4)	PCB 44	15.91	292.0 -> 220.0	291.8 -> 222.0	2005	0.00	27.0	0.000
5)	PCB 52	15.91	292.0 -> 220.0	291.8 -> 222.0	2005	0.00	27.0	0.000
6)	PCB 101	23.57	325.9 -> 256.0	326.0 -> 256.0	477	0.00	24.1	0.000
7)	PCB 138	24.53	359.8 -> 290.0	361.7 -> 290.0	666	0.00	65.4	0.000
8)	PCB 149	24.53	359.8 -> 290.0	361.7 -> 290.0	666	0.00	65.4	0.000
9)	PCB 153	24.52	360.0 -> 290.1	360.0 -> 325.0	302	0.00	26.0	0.000
10)	PCB 180	27.77	393.7 -> 324.0	393.7 -> 359.0	423	0.00	41.7	0.000
11)	PCB 118	28.59	325.9 -> 256.0	328.0 -> 258.0	52	0.00		0.000
12)	PCB 170	28.61	393.7 -> 324.0	393.7 -> 359.0	404	0.00	43.1	0.000
13)	PCB 194	30.32	427.8 -> 357.8	428.0 -> 358.0	149	0.00	70.6	0.000
14)	PCB 209	31.95	214.0 -> 178.0	428.0 -> 356.0	47	0.00	32.8	0.000

FIGURE 5: Laboratory blanks analysis results.

## Pesticide Residues Analysis Report

Agilent Technologies

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	Compound Name	RT	Transition (T)	Transition (Q)	T-Resp	GC/MS Conc. (ppb)	QRatio	Sample (mg/kg)
1)	PCB 18	13.11	255.8 -> 186.0	256.0 -> 186.0	96	0.00	25.1	0.000
2)	PCB 44	14.85	291.8 -> 222.0	292.0 -> 220.0	15	0.00	664.7	0.000
3)	PCB 52	15.37	291.8 -> 222.0	291.8 -> 257.0	10	0.00	111.5	0.000
4)	PCB 28	19.44	255.8 -> 186.0	256.0 -> 186.0	66	0.00	54.7	0.000
5)	PCB 31	19.44	255.8 -> 186.0	256.8 -> 186.0	66	0.00	54.7	0.000
6)	PCB 101	22.36	325.9 -> 256.0	326.0 -> 256.0	188	0.00		0.000
7)	PCB 138	24.28	359.8 -> 290.0	361.7 -> 290.0	198	0.00	29.6	0.000
8)	PCB 149	24.28	359.8 -> 290.0	361.7 -> 290.0	198	0.00	29.6	0.000
9)	PCB 153	24.47	360.0 -> 290.1	360.0 -> 325.0	67	0.00	38.7	0.000
10)	PCB 118	26.83	325.9 -> 256.0	328.7 -> 258.0	0	0.00		0.000
11)	PCB 170	29.30	393.7 -> 359.0	393.7 -> 324.0	28	0.00	209.9	0.000
12)	PCB 180	29.30	393.7 -> 359.0	393.7 -> 324.0	28	0.00	209.9	0.000
13)	PCB 194	32.07	427.8 -> 357.8	428.0 -> 358.0	0	0.00		0.000
14)	PCB 209	32.30	214.0 -> 178.0	428.0 -> 356.0	0	0.00		0.000

FIGURE 6: Solvent run using ethyl acetate (EA.D).

$$V = \frac{E_d}{P} RT = \frac{310.5 \text{ kg} \cdot \text{mole/cycle}}{1 \text{ atm}} \left( 0.08206 \frac{\text{m}^3 \cdot \text{atm}}{\text{kg} \cdot \text{mole} \cdot \text{K}} \right) (298\text{K})$$

$$= 7,592.93 \frac{\text{dscm}}{\text{cycle}} \text{ at } 25^\circ \text{C.} \quad (2)$$

Assuming that gases discharge into the atmosphere at 200°C (473K),

Then, by using Charles Law,  $V_1/T_1 = V_2/T_2$

Dry volumetric discharge,  $V_2 = (T_2/T_1)(V_1) = (473\text{K}/298\text{K})(7,592.93) = 12,051.86 \text{ dscm/cycle}$ .

The levels of the indicator PCBs (in  $\mu\text{g/L}$ ), determined in the 5 ml vials by the GC-MS equipment, were converted to their gaseous concentrations in the chimney of the incinerator by dividing each  $\mu\text{g/L}$  by the dry volumetric discharge of 12,051.86 dscm/cycle (Table 6).

It can be seen from Table 5 that the gaseous concentrations of PCBs before filtration ranged from 0.0000788 ng/

TABLE 4: GC-MS calibration parameters of the PCB standard at 6-point concentrations over the 5–500 µg/L range.

PCB congener	Molecular weight (g/mol)	Determination coefficient ( $R^2$ )	Mean recoveries (%)
PCB 18	257.5	1.0000	96.16
PCB 28	257.54	0.9998	100.28
PCB 31	257.54	0.9998	100.3
PCB 44	291.99	0.9999	98.54
PCB 52	291.99	1.0000	95.64
PCB 101	326.43	1.0000	83.12
PCB 118	326.43	1.0000	100.75
PCB 138	360.88	0.9998	100.81
PCB 149	360.88	0.9998	100.81
PCB 153	360.88	1.0000	103.19
PCB 170	395.32	1.0000	93.94
PCB 180	395.32	1.0000	93.66
PCB 194	429.77	1.0000	101.11
PCB 209	498.66	0.9982	101.58

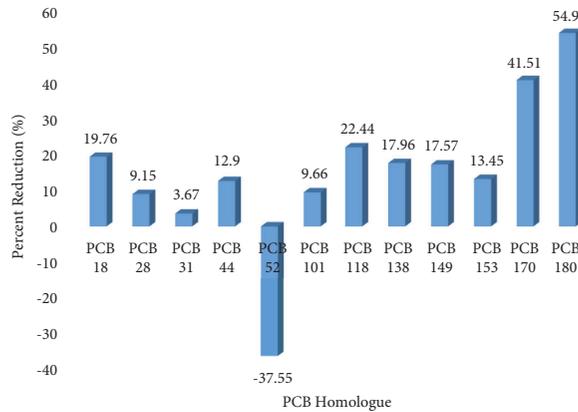


FIGURE 7: Percent Reductions in PCBs by the charcoal filter beds.

TABLE 5: GC-MS analysis results of polychlorinated biphenyl (PCB) samples (µg/L).

	PCB18	PCB28	PCB31	PCB44	PCB52	PCB101	CB138	CB149	CB153	CB118	CB170	CB180
	0.59	0.4	0.4	0.32	0.39	0.19	0.4	0.4	0.56	1.23	0	0
	0.59	3.14	3.13	0.33	0.4	0.19	1.72	1.72	3.98	1.23	0.28	0.28
	0.56	2.95	2.77	0.33	0.21	0.19	1.66	1.66	3.68	1.37	0.3	0.26
Before	0.58	3.23	2.21	0.33	0.43	0.19	1.57	1.51	3.96	1.29	0.26	0.23
filtration	1.52	0.66	0.66	0.76	0.51	0.4	0.81	0.81	0.74	1.48	0	0
	1.53	3.86	3.86	0.76	0.29	0.41	1.9	1.91	3.91	1.48	0.27	0.28
	1.54	3.85	3.84	0.77	0.26	0.41	1.84	1.84	4.07	1.49	0.3	0.28
	1.54	3.87	3.86	0.74	0.28	0.4	1.85	1.82	4	1.48	0.18	0.2
Mean	1.05625	2.745	2.59125	0.5425	0.34625	0.2975	1.46875	1.45875	3.1125	1.38125	0.19875	0.19125
S.D	0.50925541	1.41469	1.40294	0.23002	0.10155	0.11498	0.55489	0.55197	1.52491	0.11667	0.12833	0.12135
	0.48	0.43	0.43	0.17	0.35	0.12	0.32	0.32	0.29	0.18	0	0
	0.5	2.73	2.72	0.37	0.29	0.2	1.15	1.15	3.36	1.85	0.14	0.14
	0.48	2.83	2.82	0.37	0.29	0.21	1.16	1.16	3.41	1.13	0.09	0
After	0.48	2.79	2.74	0.36	0.29	0.21	1.18	1.17	3.34	1.12	0	0
filtration	1.21	0.61	0.61	0.62	0.66	0.3	0.54	0.54	0.51	0.59	0	0
	1.2	3.53	3.58	0.62	0.66	0.37	1.77	1.77	3.21	1.29	0.22	0.22
	1.19	3.52	3.57	0.63	0.65	0.36	1.78	1.78	3.45	1.2	0.22	0.15
	1.24	3.51	3.5	0.64	0.62	0.38	1.74	1.73	3.98	1.21	0.26	0.18
Mean	0.8475	2.49375	2.49625	0.4725	0.47625	0.26875	1.205	1.2025	2.69375	1.07125	0.11625	0.08625
S.D	0.387842015	1.266265	1.274844	0.177904	0.184541	0.096871	0.556417	0.555125	1.434981	0.495968	0.109536	0.09516
Percent reduction	19.76	9.15	3.67	12.90	-37.55	9.66	17.96	17.57	13.45	22.44	41.51	54.90

TABLE 6: Indicator PCB concentrations in the chimney (in ng/m<sup>3</sup>).

	Mean concentration ( $\mu\text{g/L}$ )		Volume of extract (ml)	Amount( $\mu\text{g}$ ) in 5 ml		X/12051.86 ( $\mu\text{g/m}^3$ )		ng/m <sup>3</sup>	
	Before filtration	After filtration		Before	After	Before	After	Before	After
PCB 18	1.06 $\pm$ 0.50	0.85 $\pm$ 0.39	5	0.0053	0.00425	4.39766E-07	3.52643E-07	0.00044	0.00035264
PCB 28	2.75 $\pm$ 1.41	2.49 $\pm$ 1.41	5	0.013725	0.01245	1.13883E-06	1.03304E-06	0.001139	0.00103304
PCB 31	2.59 $\pm$ 1.40	2.50 $\pm$ 1.27	5	0.01295	0.0125	1.07452E-06	1.03718E-06	0.001075	0.00103718
PCB 44	0.54 $\pm$ 0.23	0.47 $\pm$ 0.18	5	0.0027	0.00235	2.24032E-07	1.94991E-07	0.000224	0.00019499
PCB 52	0.35 $\pm$ 0.10	0.48 $\pm$ 0.18	5	0.00175	0.00235	1.45206E-07	1.94991E-07	0.000145	0.0001991
PCB 101	0.3 $\pm$ 0.11	0.27 $\pm$ 0.10	5	0.0015	0.00135	1.24462E-07	1.12016E-07	0.000124	0.00011202
PCB 118	1.38 $\pm$ 0.12	1.07 $\pm$ 0.50	5	0.0069	0.00535	5.72526E-07	4.43915E-07	0.000573	0.00044391
PCB 138	1.47 $\pm$ 0.55	1.21 $\pm$ 0.56	5	0.00735	0.00605	6.09864E-07	5.01997E-07	0.00061	0.000502
PCB 149	1.46 $\pm$ 0.55	1.20 $\pm$ 0.56	5	0.0073	0.006	6.05716E-07	4.97848E-07	0.000606	0.00049785
PCB 153	3.11 $\pm$ 1.52	2.69 $\pm$ 1.43	5	0.01555	0.0135	1.29026E-06	1.12016E-06	0.00129	0.00112016
PCB 170	0.2 $\pm$ 0.13	0.12 $\pm$ 0.11	5	0.001	0.0006	8.29747E-08	4.97848E-08	8.3E-05	4.9785E-05
PCB 180	0.19 $\pm$ 0.12	0.09 $\pm$ 0.12	5	0.00095	0.00045	7.8826E-08	3.7339E-08	7.88E-05	3.734E-05

m<sup>3</sup> for PCB 180 to 0.00129 ng/m<sup>3</sup> for PCB 153. After the filtration by the charcoal adsorbent, they ranged from 0.00003734 ng/m<sup>3</sup> for PCB 170 to 0.00112016 ng/m<sup>3</sup> for PCB 153. The congener with dioxin-like character (PCB 118) registered 0.000573 ng/m<sup>3</sup> and 0.00044391 ng/m<sup>3</sup> before and after the filter, respectively.

PCB concentrations in ambient air are estimated to vary widely over 3 orders of magnitude, from about 0.003 ng/m<sup>3</sup> in nonurban areas to an averaged 3 ng/m<sup>3</sup> in urban/industrial areas [15]. Their higher concentrations in urban environments could be attributed to emissions from point sources such as incinerators without air pollution control devices [20]. The lack of testing capacity and congener-specific analytical data in many jurisdictions have made the estimation of levels of dioxin-like PCBs difficult [15]. Thus, PCB concentrations in rural outdoor air are background concentrations in pg/m<sup>3</sup> levels.

The tentative guideline value for PCBs in indoor air in Switzerland is 6000 ng/m<sup>3</sup> and is based on a daily exposure of 8 hours [21].

**3.4. Novelty of the Study.** The novelty of this study comes from the deployment of powdered activated charcoal commercially prepared from 3 tree species, namely *Mangifera indica*, *Zea mays*, and *Eucalyptus globulus*. It was deployed on 3 filter bed supports in a gas chamber unit mounted on a chimney in real time during combustion and to reduce concentrations of polychlorinated biphenyls in the exhaust.

## 4. Conclusions

This study sought to evaluate the effectiveness of a charcoal adsorbent for reducing gaseous PCBs in a gas filter unit designed, constructed, and mounted in real time on the chimney of an incinerator.

Twelve of the 14 indicator PCBs analyzed in the smoke samples were present, and 11 of them saw mean reductions ranging from 3.47% to 52.63% by the charcoal filter beds. The highest mean reduction of 52.63% came from the

homologue PCB 180, whilst the isomer with a dioxin-like character (PCB 118) saw a 22.46% reduction. The gaseous concentrations of PCBs before filtration ranged from 0.0000788 ng/m<sup>3</sup> for PCB 180 to 0.00129 ng/m<sup>3</sup> for PCB 153. After the filtration by the charcoal adsorbent, they ranged from 0.00003734 ng/m<sup>3</sup> for PCB 170 to 0.00112016 ng/m<sup>3</sup> for PCB 153. The congener with dioxin-like character (PCB 118) registered 0.000573 ng/m<sup>3</sup> and 0.00044391 ng/m<sup>3</sup> before and after the filter, respectively. This suggests that dioxins and other dioxin-like compounds are most likely adsorbed by the charcoal adsorbent.

**4.1. Limitations of Research.** The testing process of the filter unit on the chimney of the incinerator could only be performed over a short period and not the 4 hours as anticipated. This was because the filter unit could not withstand the hot fly ashes, and their impact on the device detached it from the chimney stack. As a result, the proposed testing of bacterial strains on the filter beds for comparison could not be carried out.

Assumptions were needed to convert the PCB amounts in  $\mu\text{g/l}$  from the GC-MS analyses into gas-phase concentrations in ng/m<sup>3</sup> at an estimated chimney temperature of 200°C, using 20 kg-gases/kg of waste feed, with estimates of about 12% CO<sub>2</sub> and 8% H<sub>2</sub>O as emitted.

**4.2. Future Research Perspectives.** The success of a filter unit such as used in this study for removing certain PCB congeners suggests that other persistent organic pollutants, namely dioxins and furans (PCDDs/Fs), are likely to be removed as well. Further research study can be carried out to test this filter system for its efficiency at gas-phase PCDDs/Fs removal from incinerators in hospitals.

Suitable bacteria or microbes can also be grown on filters to biodegrade the PCBs into their metabolites. At gas stream temperatures in the range 150–250°C, dechlorinating microcosms of bacteria can function as hyperthermophiles. These dechlorinating bacteria usually colonize soils and sediments where PCB-rich products from combustion are

deposited over time. They can be isolated and grown on these filter bed supports to reduce highly-chlorinated PCBs into less-chlorinated congeners [22], after which aerobic PCB-degrading bacteria can take over the process and metabolize them into carbon dioxide, chlorine, and water [23].

When the gas-phase PCBs in the flue gas are degraded by the growth film on the charcoal filter beds, the resulting metabolites will be chlorides such as hydrogen chloride. After flue gas treatment, the metabolites which are residual chlorine or chlorides left on the filter system can be disposed of safely by washing them off with water or other suitable solvent into the hospital drains. Chlorine is usually added in water treatment systems during the final disinfection stage and should not pose any problems.

### Data Availability

The authors declare that data for this work are available upon request.

### Conflicts of Interest

The authors declare no conflicts of interest in this study.

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