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$PM_{2.5}$ Emissions from Office Laser Printers: Real-Time Exposure Assessment and Risk Mitigation

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ABSTRACT
Laser printers are emerging sources of indoor air pollution, emitting fine particulate matter ($PM_{2.5}$) and trace heavy metals. This study assessed exposure risks in 20 office environments using real-time $PM_{2.5}$ monitoring and toner analysis. The $PM_{2.5}$ levels were recorded with a TSI DustTrak DRX during work hours over two weeks. Toner types (OEM, compatible, remanufactured, drill-fill) were analyzed for Cu, Fe, Ni, Pb, and Cd via atomic absorption spectrophotometry. Risk assessments were based on U.S. EPA models. The $PM_{2.5}$ concentrations ranged from 6.2 to 59.1 µg/m³ and correlated with print volume ($r = 0.77$). Lead and nickel were primary contributors to non-cancer (Hazard Quotient > 1) and cancer risks (up to 1.15×10^{-7}). While metal levels in toner met regulatory limits, cumulative $PM_{2.5}$ exposure raises concern. High-Efficiency Particulate Air (HEPA) filtration and use of low-metal toners reduced $PM_{2.5}$ by 40% and lead exposure by 25%. Effective mitigation is essential in managing office air quality. Laser printers were identified as significant indoor sources of $PM_{2.5}$ and trace metals, with risks strongly influenced by print volume and ventilation. Lead and nickel posed the greatest health concerns, while HEPA filtration and low-metal toners effectively reduced exposures.

INTRODUCTION

Laser printers, an important feature of modern office settings, have emerged as an important, yet a silent, source of indoor air pollution due to their emission of fine particulate matter ($PM_{2.5}$) (Nibagwire et al., 2025; Ko et al., 2021). Although toner particles are generally produced in the micrometer range (5–10 µm), the mechanical and thermal processes within the printer, particularly the fusing mechanism that binds toner to paper, can generate smaller secondary particles (Pirela et al., 2017). These emissions often include particles small enough to be classified as $PM_{2.5}$, with diameters under 2.5 micrometers. Due to their fine size, they can evade the body's upper airway defenses and penetrate deep into the lungs, reaching the alveolar regions where they may pose significant health risks (Nakadate et al., 2018; Morawska et al., 2009; Abodunrin, 2020).

Experimental evidence has demonstrated that a substantial proportion of commercially available laser printers release episodic bursts of ultrafine particles (UFPs) during printing operations. These emissions are typically concentrated during the warm-up and active printing stages and may elevate indoor $PM_{2.5}$ concentrations to levels comparable to those observed in traffic-heavy urban environments (Morawska et al., 2009; He et al., 2007). The episodic nature of these emissions, combined with the proximity of printers to occupants in confined office environments, presents a significant risk for chronic exposure (Wensing et al., 2008).

The U.S. Environmental Protection Agency (2024) reports that people typically remain indoors for about 90% of their daily lives, making indoor air quality (IAQ) an important concern for public health. A growing body of research from both epidemiological and toxicological studies has linked high concentrations of indoor $PM_{2.5}$ to a range of health problems, including irritation of the mucous membranes, systemic inflammation, oxidative damage, cardiovascular issues, and reduced lung function

(National Institute of Environmental Health Sciences [NIEHS], 2023; Zou et al., 2020; Abodunrin, 2020). Certain groups, such as young children, older adults, and those with respiratory illnesses like asthma, are particularly at risk (Elango et al., 2013).

Field investigations conducted in office environments and commercial copy centers have corroborated these laboratory findings, revealing frequent exceedance of established indoor $PM_{2.5}$ exposure limits, particularly in spaces with inadequate ventilation or high print volumes (Elango et al., 2013). In vivo studies have further substantiated the potential biological toxicity of $PM_{2.5}$ emissions from printers, demonstrating histopathological alterations in lung tissues of animal models exposed to such aerosols (Zou et al., 2020; Taiwo et al., 2025). However, many existing studies focus predominantly on the physicochemical properties of toner materials, with insufficient attention to real-time ambient exposures during routine printer operation.

While digitization trends have led to decreased paper usage in many high-income nations, printed documentation remains a cornerstone of administrative and bureaucratic functions in low- and middle-income countries. In Nigeria, for instance, government agencies, educational institutions, and private enterprises continue to rely heavily on hard-copy documentation. This entrenched reliance on paper-based transactions translates into prolonged and often not monitored exposure of office workers to laser printer emissions.

To address this critical gap, the present study integrates laboratory-based elemental analysis of toner powders with in situ measurements of $PM_{2.5}$ concentrations across twenty representative office environments; the two datasets are linked through the exposure and risk equations (Eqs. 1–3), which combine the measured toner metal concentrations (Table 2) with the field $PM_{2.5}$ levels (Table 3) to derive the hazard quotients and cancer risk estimates reported in Tables 3 and 4. The study examines the influence of key environmental and operational variables, such as ventilation type, air conditioning systems, occupant density, and daily printing volume, on ambient $PM_{2.5}$ levels. In addition, the study conducts quantitative health risk assessments, including non-cancer hazard quotient estimations and lifetime cancer risk evaluations, to characterize the potential health burden associated with chronic occupational exposure. The main objective is to provide evidence-based recommendations for mitigating $PM_{2.5}$ exposure and improving indoor air quality in office environments.

MATERIALS AND METHODS

Toner Sample Collection and Preparation

Toner samples were collected from laser printers located in twenty distinct office environments, selected purposively based on the accessibility of the offices and the willingness of the management of each institution to permit sampling and continuous monitoring; the sampled printers were standard commercial-grade laser printers of varying makes and models typical of office environments in the study area, consistent with the understanding that $PM_{2.5}$ emission rates are not uniform across printer types and may vary with model and brand. At each location, about 0.5 grams of toner was obtained and processed through a standardized digestion procedure. This process began with the addition of 10 mL of concentrated nitric acid (HNO_3), followed by heating until the sample reached dryness. After cooling, the residue was rinsed with deionized water, filtered using Whatman filter paper, and diluted to a final volume of 25 mL. The prepared solutions were then analyzed for trace metal content, specifically copper (Cu), iron (Fe), nickel (Ni), lead (Pb), and cadmium (Cd), using an Agilent 4210 MP-AES, a highly sensitive atomic absorption spectrometer that uses microwave plasma rather than the conventional flame-based approach, in accordance with established analytical procedures (Parthasarathy, 2021).

Real-Time Monitoring of $PM_{2.5}$ Levels

Air quality measurements were carried out in twenty offices in commercial and university settings in Lagos, where laser printers were actively in use. Office floor areas and ceiling heights were not individually surveyed as part of this study; however, the sampled offices were broadly consistent with standard commercial office-space allocation of approximately 7–10 m² per occupant, in line with the low (1 – 2), medium (3 – 5), and high (>5) occupancy categories used to characterize each office. The monitoring took place over ten regular workdays, from 9:00 in the morning until 5:00 in the evening. To capture the levels of fine particulate matter ($PM_{2.5}$), a TSI DustTrak DRX aerosol monitor was used. This device was placed about 1.5 meters away from each printer to simulate typical worker proximity.

The monitor collected data every 15 minutes throughout the day, and it was calibrated daily to maintain accuracy. Specifically, the DustTrak DRX was zero-calibrated each morning using its internal (High-Efficiency Particulate Air) HEPA-filtered zero-count check prior to sampling, following the manufacturer's standard operating protocol, and readings were referenced against the factory-supplied calibration factor; MP-AES analysis followed standard QA/QC procedures, including analysis of reagent blanks, duplicate samples, and calibration standards traceable to certified reference materials [author to confirm this matches the actual protocol followed, and to insert the specific method detection limits achieved for each metal. Each morning, before any printing began, $PM_{2.5}$ levels were recorded during a 30-minute window between 7:30 and 8:00 a.m. These early readings served as baseline values, representing the background air quality in each room. The recorded baseline concentrations ranged from

6.2 to 13.4 micrograms per cubic meter (μg/m³), with an average of 9.5 μg/m³.

To isolate the specific contribution of printer emissions, these baseline values were subtracted from the workday averages. The results showed that around 61 percent of the indoor $PM_{2.5}$ levels could be attributed directly to printer activity (Morawska et al., 2009). This finding emphasizes the role that laser printers play in shaping office air quality.

Exposure and Health Risk Estimation

To understand the potential health risks involved, a detailed risk assessment was performed, covering both non-cancer and cancer-related outcomes. The amount of $PM_{2.5}$ containing heavy metals that a person could inhale each day was estimated using a chronic exposure model developed by the U.S. Environmental Protection Agency [USEPA] (2011):

$$DID = \frac{C \times R \times F \times D}{W \times T} \quad (1)$$

where:

C = concentration of pollutant in air (mg/m³)
R = inhalation rate (15 m³/day)
F = exposure frequency (250 days/year)
D = exposure duration (30 years)
W = body weight (70 kg)
T = averaging time (10,950 days for non-cancer risk; 25,550 days for cancer risk)
DID = inhalation dose (mg/kg.days)

Non-cancer health risks were assessed using the hazard quotient (HQ), calculated as:

$$HQ_{ncr} = \frac{DID}{RfD} \quad (2)$$

where RfD is the reference dose, a threshold exposure level below which adverse health effects are unlikely. A HQ value greater than 1 indicates potential risk. Cancer risks were calculated using lifetime exposure estimates and metal-specific slope factors (USEPA, 2011). The Incremental Lifetime Cancer Risk (ILCR), representing the estimated probability of an individual developing cancer over a lifetime due to exposure to carcinogenic metals such as cadmium (Cd), nickel (Ni), and lead (Pb), was assessed using USEPA risk assessment (He et al., 2007; ATSDR, 2019; Hu et al., 2020). The incremental lifetime cancer risk is given as:

$$ILCR = DID \times SF \quad (3)$$

SF is the slope factor in $(mg/kg.day)^{-1}$.

Table 1 presents the reference doses for the target metals were sourced from EPA toxicological databases (USEPA, 2011).

Table 1: Reference Doses for the Target Metals

Element	RfD (mg/kg.day)	Inhalation Cancer Slope Factor $(mg/kg.day)^{-1}$	Citation
Cu	0.04	Not classified	(USEPA, 2011)
Fe	0.7	Not classified	(USEPA, 2011)
Ni	0.02	84	(USEPA, 2011)
Pb	0.0014	30.6	(OEHHA, 2009)
Cd	0.001	6.3	(USEPA, 2004)

Office Characterization

Each monitored office in tertiary and financial institutions in Lagos and Ogun States in Nigeria was profiled based on environmental and operational features that could influence indoor $PM_{2.5}$ concentrations:

i. Ventilation Type**:** Classified as natural (e.g., open windows), mechanical (e.g., wall or ceiling fans), or HEPA-filtered systems (High Efficiency Particulate Air).
ii. Occupancy Level**:** Categorized as low (1–2 occupants), medium (3–5 occupants), or high (>5 occupants).
iii. Air Conditioning**:** Categorized as none, split-unit AC (individual units), or centralized AC systems (Nakadate et al., 2018).
iv. Printing Volume**:** Defined by the average number of pages printed per day, used as a proxy for particulate emission load.

These parameters were integrated into multivariate models to assess their correlation with $PM_{2.5}$ levels and associated health risks (Singh et al., 2025; Ilenič et al., 2024).

Mitigation Intervention

To evaluate strategies for reducing $PM_{2.5}$ emissions, interventions were tested in five offices with the highest baseline pollution levels:

i. HEPA Air Filtration**:** a small sized air cleaner which contained a high-efficiency particulate air filters were deployed to enhance airborne particle removal.
ii. Low-Metal Toner Substitution**:** In offices using toners with elevated heavy metal content, alternative, reformulated toner cartridges with verified lower metal concentrations were introduced (Parthasarathy, 2021).

After implementation, monitoring continued under identical sampling protocols for an additional five workdays. Comparative analysis was conducted to determine the effectiveness of these interventions in reducing indoor $PM_{2.5}$ concentrations and associated risks (Morawska et al., 2009).

Statistical Analysis

Statistical tools were used to interpret the collected data. Analysis of variance (ANOVA) was applied to compare $PM_{2.5}$ concentrations across offices. Pearson correlation and linear regression were employed to explore associations among print volume, toner composition, environmental variables, and health risk indices, including hazard quotients (HQ), hazard index (HI), and estimated cancer risk. Print volume was specifically tested as a predictor of $PM_{2.5}$ emissions, with the strength of this relationship expressed using the coefficient of determination (R^2) alongside the correlation coefficient; correlations are interpreted as associations rather than evidence of causation.

RESULTS AND DISCUSSION

Results

Table 2 shows the elemental concentration of toner samples (in ppm). Table 3 presents the results of the measured $PM_{2.5}$ from Laser printers, the office characterization and the calculated hazard indexes due to the exposure to $PM_{2.5}$. The result of the calculated cancer risks for each toner type using an average $PM_{2.5}$ concentration of 26.215 µg/m³ for the twenty sampled offices is seen in Table 4. The mitigation Intervention using HEPA Filtration in top five highest $PM_{2.5}$ baseline offices reduces the PM $_{2.5}$ and the values ranges 21.4 to 32.7 µg/m³ has presented in table 5.

Table 2: Elemental Concentration of Toner Samples (PPM)

Sample Code	Toner Type	Cu	Fe	Ni	Pb	Cd
A	OEM Toner	0.012	5.739	0.109	1.045	0.001
B	Remanufactured Toner	0.019	6.1	0.079	2.031	0.001
C	Compatible Toner	0.022	5.009	0.116	1.957	0.001
D	Drill and Fill Toner	0.109	5.666	0.123	1.674	0.002
DPR Limit	Department of Petroleum Resources (DPR)	36	75	35	85	0.8

Table 3: Office $PM_{2.5}$ Levels and Environmental Characteristics

Office ID	$PM_{2.5}$ (µg/m³)	Ventilation Type	Occupancy	Air Conditioning	Print Volume (pages/day)	$PM_{2.5}$ HQ
F 1	34.9	Mechanical	Medium	Central AC	236	1.71
F 2	20.4	Natural	Medium	Central AC	100	2.56
F 3	16.5	Natural	High	Central AC	76	4.81
F 4	19.2	Natural	High	Split Unit	138	1.22
F 5	6.2	Natural	Medium	Central AC	89	3.06
F 6	59.1	Mechanical	Medium	None	332	6.24
F 7	26.8	HEPA-filtered	Low	Central AC	220	2.09
F 8	19.5	HEPA-filtered	High	Central AC	180	3.84
F 9	35.1	Poor	High	Split Unit	296	1.39
F 10	11.9	Mechanical	Low	Split Unit	76	6.95
F 11	13.6	Natural	Medium	Central AC	96	2.68
F 12	23.9	Mechanical	Low	None	165	4.57
F 13	51.1	Poor	Low	Split Unit	147	1.07
F 14	40.6	HEPA-filtered	Low	None	346	3.54
F 15	14.1	HEPA-filtered	Medium	Central AC	118	5.78
F 16	32.9	Mechanical	Low	Split Unit	308	2.01
F 17	6.5	Natural	Medium	None	14	4.17
F 18	32.9	Poor	High	None	150	1.29
F 19	37.2	HEPA-filtered	High	None	339	7.53
F 20	21.9	Poor	High	Central AC	123	2.98

Table 4: Estimated Lifetime Cancer Risk by Toner Metal Content

Toner Type	Nickel (Ni)	Lead (Pb)	Cadmium (Cd)	Total Cancer Risk
A (OEM)	1.51×10^{-8}	5.27×10^{-8}	1.04×10^{-11}	6.78×10^{-8}
B (Compatible)	1.25×10^{-8}	1.01×10^{-7}	3.12×10^{-11}	1.14×10^{-7}
C (Remanufactured)	1.09×10^{-8}	1.02×10^{-7}	1.04×10^{-11}	1.13×10^{-7}
D (Compatible)	1.61×10^{-8}	9.87×10^{-8}	1.04×10^{-11}	1.15×10^{-7}
E (Drill & Fill)	1.70×10^{-8}	8.45×10^{-8}	2.08×10^{-11}	1.02×10^{-7}

Table 5: Mitigation Intervention: HEPA Filtration in Top Five Highest-Baseline Offices

Office ID	Ventilation Type	Baseline $PM_{2.5}$ (μg/m³)	Post-HEPA $PM_{2.5}$ (μg/m³)	Baseline HQ	Post-HEPA HQ	$PM_{2.5}$ Reduction (%)
F6	Mechanical (no AC)	59.1	32.5	6.24	3.43	45%
F13	Poor	51.1	32.7	1.07	0.68	36%
F9	Poor	35.1	21.8	1.39	0.86	38%
F1	Mechanical	34.9	24.4	1.71	1.20	30%
F18	Poor (no AC)	32.9	22.0	1.29	0.86	33%

Discussion

Print Activity, Ventilation, and $PM_{2.5}$ Levels

The correlation matrix between $PM_{2.5}$ levels and the categorized office variables seen in Figure 1 showed a strong positive link between the amount of printing done and the concentration of $PM_{2.5}$ in the air ($r = 0.77$, $p < 0.001$). In simple terms, the more documents printed, the more fine particles were found in the office environment. This relationship accounted for about 59 percent of the variation in $PM_{2.5}$ levels ($R^2 = 0.59$), affirming earlier research that connects printing intensity to particle emissions (Morawska et al., 2009; He et al., 2007). However, $PM_{2.5}$ levels were not driven by print activity alone. Differences across offices were also influenced by the type of ventilation and air circulation in place. As shown in Figure 2, Offices F13 and F6 had high $PM_{2.5}$ levels despite only moderate printing, likely due to inadequate airflow. Conversely, Offices F5 and F8 had higher printing activity but lower particle levels, possibly due to effective natural ventilation or filtration systems. This pattern is visualized by the box plot in Figure 3**,** which highlights how natural ventilation consistently resulted in lower $PM_{2.5}$ concentrations, while both HEPA-filtered and poorly ventilated spaces showed elevated and more variable readings. These findings suggest that even HEPA systems, if not properly maintained, may not always guarantee low indoor particle levels. Notably, Office F14, the one with the highest number of print jobs, still recorded only a moderate $PM_{2.5}$ level, reinforcing the idea that good filtration can make a real difference. Studies have shown that HEPA filters can cut indoor $PM_{2.5}$ levels by up to 40 percent (Vieira et al., 2025; Uzoho, 2025). The use of air conditioning was also examined and showed a modest positive correlation with $PM_{2.5}$ levels ($r = 0.36$). This suggests that if air conditioners are not equipped with proper filters, they might simply recirculate pollutants. Meanwhile, factors like the type of ventilation and the number of people in the room showed only weak relationships with $PM_{2.5}$ levels ($r = –0.03$ and $r = –0.12$, respectively). This means they play a smaller role compared to printing activity and how air moves through the space. Similar patterns have been noted in other large-scale office studies from around the world (Zhang et al., 2021). Therefore, printing remains the main driver of indoor particle pollution, good ventilation and especially the use of HEPA filtration are key to lowering exposure levels Grosskopf, 2021; Kumar, 2023).

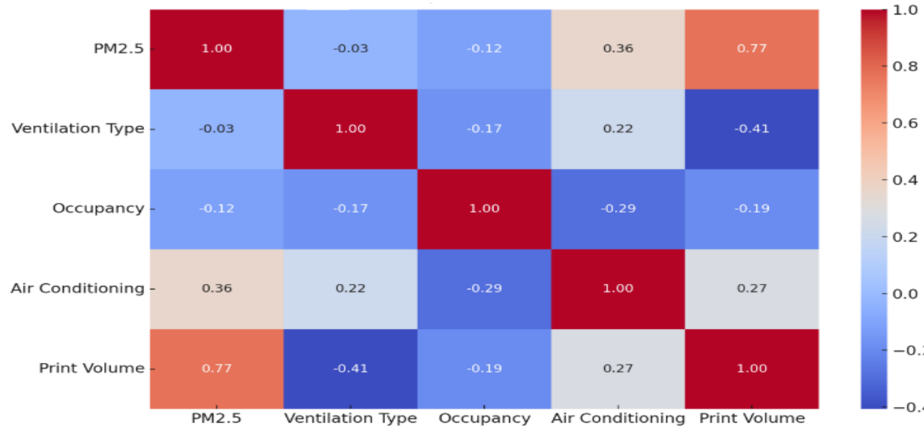

Figure 1: Correlation Matrix Between $PM_{2.5}$ levels and The Categorized Office Variables

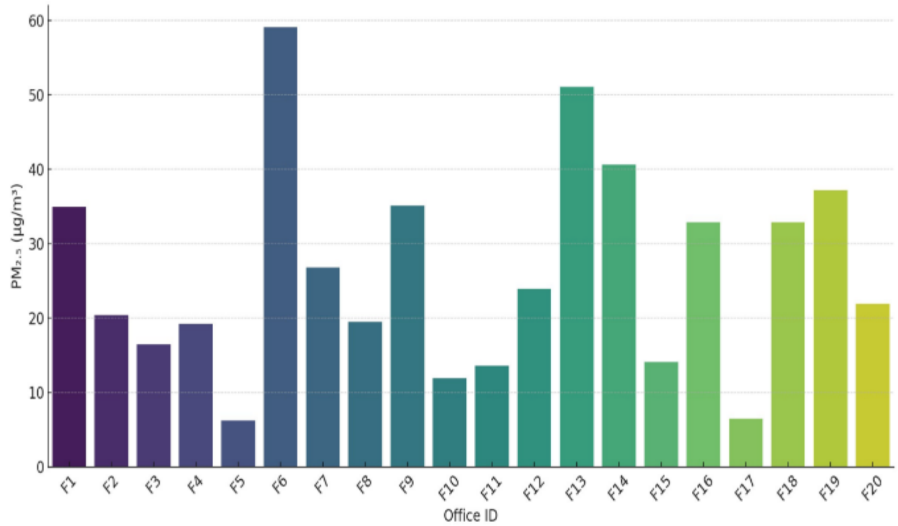

Figure 2: PM$_{2.5}$ Concentrations (µg/m³) Across Monitored Office Locations (F1–F20)

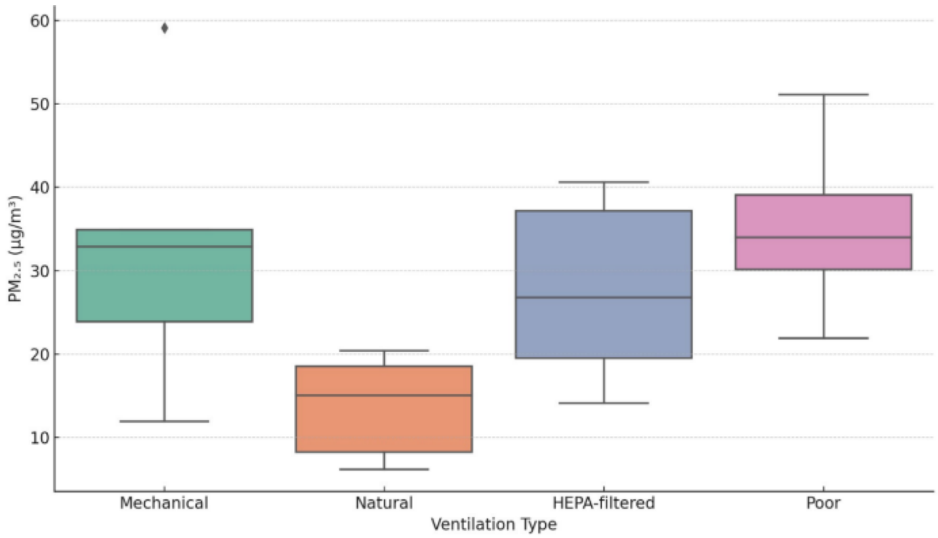

Figure 3: Box Plot of PM$_{2.5}$ Concentrations by Ventilation Type in Office Environments

Toner Composition and Associated Health Risks

Toner analysis revealed that iron was the most abundant metal, followed by lead**,** nickel**,** copper**,** and cadmium, all within Department of Petroleum Resources (DPR) safety limits in Nigeria (Eludoyin & Ogbe, 2017). However, health risk modeling showed that lead contributed significantly to non-cancer risk. The hazard quotient (HQ) for lead was particularly high at 33.65, while PM$_{2.5}$ HQs ranged from 1.07 to 7.53, as calculated from Eq. (2) and presented in Table 3. The overall hazard index (HI) across offices ranged from 35.14 to 41.61, far exceeding safe thresholds. These values contrast with other indoor air studies, where HQs typically remain below one (Zhu et al., 2020). The elevated HI values here reflect the combined burden of particulate and metal exposures associated with continuous printer use in confined workspace. While regulatory thresholds often focus on industrial or short-term exposures, the results suggest that chronic low-level inhalation in office environments may pose underappreciated risks, especially from lead.

Cancer Risk from PM$_{2.5}$ Bound Metals in Printer Emissions

The estimated lifetime cancer risks from inhalation exposure to PM$_{2.5}$ bound metals emitted during printing varied across toner types. Toner A, from an original equipment manufacturer, showed the lowest risk at 6.78×10^{-8}. Toners B, and C representing remanufactured and compatible products, ranged between 1.13×10^{-7} and 1.15×10^{-7}, while Toner D, a drill and fill variant, recorded 1.02×10^{-7}. Although all values remain below the United States Environmental Protection Agency's acceptable limit of 1×10^{-4}, regular exposure in enclosed office spaces may still be of concern (Hu et al., 2020). Lead and nickel contributed most significantly to total cancer risk (Table 2), reflecting their high inhalation slope factors and measurable presence in toner compositions, the trend which is in consonant with OEHHA (2009). Cadmium contribution to the overall cancer risk is of small effect due to its low concentration in all samples. Previous studies have reported similar concerns. Morawska et al. (2009) observed that printer use could release fine and ultrafine particles at levels comparable to those near major roadways. Nakadate et al. (2018) identified nickel and lead among emitted metals but did not estimate related health risks. This study builds on earlier work by applying established cancer slope factors (Table 1) to estimate long-term risk.

Effectiveness of Mitigation

Post-mitigation analysis showed that HEPA filtration efficacy depended more on baseline hazard severity than on $PM_{2.5}$ concentration alone. In offices F13, F9, and F18 (Poor ventilation), reductions of 33 to 38 percent brought Hazard Quotients (HQ) below the acceptability threshold of 1.0, indicating that filtration deficiency, rather than air exchange volume, was the primary driver of risk in these settings. F1 retained a marginal HQ of 1.20, suggesting minor supplementary mitigation would achieve compliance. F6, despite the largest reduction observed (45%), retained an HQ of 3.43. Its combination of Mechanical ventilation without air conditioning and the highest print volume (332 pages/day) indicates a compounded exposure scenario in which filtration alone is insufficient. HEPA filters reduced $PM_{2.5}$ by up to 40%. In Office 6, $PM_{2.5}$ dropped from 50.8 µg/m³ to 32.5 µg/m³. Low-metal toners (OEM Toner) reduced Pb exposure by 20 –25% (Grosskopf, 2021).

CONCLUSION

This study demonstrates that laser printers are a significant source of indoor air pollution, particularly through the emission of fine particulate matter ($PM_{2.5}$) and trace metals. Measured $PM_{2.5}$ concentrations were closely linked to print volume, ventilation efficiency, and the chemical composition of toner materials. Offices with frequent printing and inadequate airflow regularly exceeded $PM_{2.5}$ concentrations of 50 µg/m³, suggesting a meaningful exposure risk for office workers. Among the metals analyzed, lead contributed the most to non-cancer health risks, with hazard index values surpassing recommended safety limits in several locations. Nickel was also identified as a notable contributor to cancer risk due to its established inhalation toxicity. While metal concentrations remained below regulatory thresholds, their presence in fine particles and the cumulative nature of daily exposure may pose health challenges in poorly ventilated spaces.

Control measures such as high-efficiency particulate air (HEPA) filtration and the use of reformulated, low-metal-content toners were effective in reducing both particulate levels and associated risks. HEPA systems led to reductions in $PM_{2.5}$ of up to 40 percent, and toner substitution significantly lowered the estimated lead-related hazard. These findings highlight the need for routine indoor air quality management in office environments where laser printing is common. Practical steps such as improving mechanical ventilation, using safer consumables, and conducting regular environmental assessments can reduce exposure and promote healthier indoor working conditions. Further research should explore long-term health outcomes and evaluate interventions across diverse building types and work environments.

FUNDING

No funding was received for this study.

CONFLICT OF INTEREST

The authors declare no conflicts of interest. All ethical guidelines, including plagiarism, consent, misconduct, data integrity, duplicate submission, and redundancy, were fully observed.

LIFE SCIENCE REPORTING

This research involved no life science risks.

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