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Research Article

Automobile Spray Paint Dust and Human Health: A Multi-Site Environmental Health Risk Assessment of Carcinogenic and Non-Carcinogenic Effects in South-Eastern Nigeria

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Abstract: Informal automobile spray-painting operations release metal-laden dust, posing occupational and residential health risks. Seasonal variations, receptor-specific exposure, and metal composition influence non-carcinogenic and carcinogenic hazards, yet data from South-Eastern Nigeria remain limited. This study quantified heavy-metal exposure in automobile spray-paint dust, assessed receptor-specific non-carcinogenic (HI) and carcinogenic (ILCR) risks, examined seasonal and metal-specific trends, and evaluated source attribution to inform evidence-based interventions. Forty dust samples were collected from 20 workshops across Owerri and Okigwe during rainy and dry seasons. Samples were sieved (<100 µm for ingestion, <45 µm for dermal exposure), digested, and analyzed for Pb, Cd, Cr, Ni, Zn, Fe, Cu, and Mn using FAAS/GFAAS/ICP-MS. Deterministic and probabilistic Monte Carlo models estimated receptor-specific Hazard Index (HI) and Incremental Lifetime Cancer Risk (ILCR). Statistical analyses included paired t-tests, Wilcoxon tests, correlation matrices, PCA, and regression to assess inter-metal relationships, seasonal variation, and source attribution. Dermal HI exceeded 1 for all workers in both seasons (rainy: 96.4 ± 12.3; dry: 122.3 ± 14.6), while nearby residents had lower but notable HI (rainy: 68.7 ± 10.5; dry: 84.5 ± 12.7). Ingestion HI remained below or near 1 for all receptors. Total ILCR (TCGLR) for workers ranged from 1.26×10^{-2} (rainy) to 1.91×10^{-2} (dry), and for residents from 8.6×10^{-3} to 1.21×10^{-2}. Cadmium and nickel dominated the cumulative risk. Dry-season exposures were higher, but paired t-tests and Wilcoxon tests indicated no statistically significant seasonal differences ($p>0.05$). PCA grouped Cd, Ni, and Pb into a high-risk cluster, while Zn, Cu, and Fe formed a background cluster. Regression analysis indicated a proportional relationship between total metal concentration and dermal HI ($R^2=0.18$). Informal spray-painting environments in South-Eastern Nigeria pose significant non-carcinogenic and carcinogenic risks to workers and nearby residents, particularly via dermal exposure to Cd and Ni. Short-term interventions include PPE and dust suppression; mid-term, improved ventilation and metal substitution; long-term, regulatory enforcement, workshop formalization, and continuous monitoring. Findings emphasize season- and metal-specific risk, highlighting the need for adaptive occupational and environmental health strategies to protect both workers and communities.

Keywords: Automobile Spray-Painting, Heavy Metals, Dermal Exposure, Hazard Index, Incremental Lifetime Cancer Risk, Seasonal Variation, Cadmium, Nickel, Probabilistic Risk Assessment, Nigeria

SCIENCE Publications

Introduction

Automobile spray paint operations generate a spectrum of airborne particulates, Volatile Organic Compounds (VOCs), heavy metals, and pigment dusts whose human health implications are increasingly recognized globally (Sarah et al., 2024; Raimi et al., 2021a-b; 2020; 2018; Clinton-Ezekwe et al., 2024). In occupational settings, workers exposed to paint mist and dust inhale or ingest fine particles containing lead, cadmium, chromium, nickel, and organic compounds like benzene, toluene, xylene, and Polycyclic Aromatic Hydrocarbons (PAHs), all of which have been implicated in either carcinogenic or non-carcinogenic adverse health effects (e.g. systemic toxicity, respiratory impairment, renal and hepatic dysfunction) (Sarah et al., 2024; Raimi et al., 2021a-b; 2020; 2018; Clinton-Ezekwe et al., 2024). For example, studies from Nigeria have shown that spray painters suffer higher rates of oxidative stress, elevated liver enzymes (ALT, AST), and kidney function perturbations relative to unexposed controls, linked to chronic exposure to paint fumes and VOCs (Nduka et al., 2019; Ojo et al., 2020; Ogbodo et al., 2024). More specifically, assessment of heavier, settled dust--"scrap car paint dust" from workshops reveals elevated levels of heavy metals such as cadmium, chromium, nickel, lead, manganese, and copper, which carry both non-cancer risks (via organ toxicity, oxidative stress, developmental effects) and possible carcinogenic risks via inhalation, ingestion, or dermal contact (Nduka et al., 2016). The literature also underscores that automobile workshops, especially in Nigeria's informal sector, often lack adequate ventilation, use few Personal Protective Equipment (PPE), and seldom monitor or regulate pollutant emissions, thus magnifying exposure risk (Ojo et al., 2020; Suleiman et al., 2019; Raimi et al., 2019a-b). Despite this growing body of evidence, key gaps remain in our understanding of the full extent and nature of risk posed by automobile spray paint dust, as opposed to vapour or mist exposures, especially in Nigeria. While many studies focus on VOC exposures or heavy metals in liquid paint components, fewer have quantified the potential carcinogenic and non-carcinogenic risk contributions of settled paint dust (scrap dust or overspray that settles as particulate matter). The exposure pathways, particle size distributions, frequencies of exposure (for children, bystanders, auto mechanics beyond spray booths), and duration, as well as cumulative risks combining inhalation, ingestion, and dermal contact, are often not well characterized. In addition, there is limited integration of quantitative risk assessments (including hazard quotients, lifetime cancer risk estimates) for both children and adults in specific localities under Nigeria's diverse workshop practices. Some results, for example, heavy metal hazard quotients and cancer risk estimates from scrap dust, suggest risks above recommended thresholds but vary widely by workshop and by exposure route (Nduka et al., 2016). These variations raise uncertainties about how representative existing findings are for many other auto-spray paint settings in Nigeria, particularly in smaller towns or informal workshops that may employ different paints, thinner formulations, and have even poorer safety practices. The necessity of investigating automobile paint dust's health impacts in Nigeria is underscored by several timely and innovative considerations. First, Nigeria remains a major hub for used car importation, auto repair, panel beating, spray painting, and auto-body workshops, many operating with minimal oversight. The volume of paint and dust produced is likely increasing, as is exposure, as urbanization and automobile use rise. Second, public health concerns in Nigeria are increasingly shifting from infectious diseases toward non-communicable diseases (NCDs) and environmental health risks, but environmental regulatory frameworks and occupational health surveillance systems remain weak in many places (Raimi et al., 2021c). Thus, a better quantification of risks from paint dust could inform policy, occupational standards, PPE provision, and community health monitoring. Third, employing modern risk assessment tools, estimating hazard quotients, aggregate exposure via multiple routes, lifetime cancer risk, and differentiating risk for vulnerable populations (children vs adults) is relatively novel in many Nigerian case studies. Finally, focusing specifically on scrap paint dust, which is often treated as waste rather than monitored pollutant, is both innovative and practically relevant: It represents a persistent environmental source (dust settling in workshops, neighbouring homes, soil) that may continue emitting exposure even when active painting stops. Given these contexts, this study aims to fill the gap by performing a risk assessment of automobile spray paint dust in a defined study area in Nigeria, with respect to both carcinogenic and non-carcinogenic health effects. The specific objective is to determine the potential health risks associated with automobile paint dust in the study area. Accordingly, the research question is: Are there potential health risks associated with automobile paint dust in the study area (RQ1)? The testable hypothesis is that Ho1: There are no significant potential health risks (at $\alpha = 0.05$) associated with paint dust in the study area. This study is timely and relevant because its findings could contribute evidence for regulatory action, improve protective practices among auto body workers, and protect public health, especially among vulnerable populations exposed to paint dust.

Materials and Methods

Study Design

This study employed an observational environmental exposure and Human Health Risk Assessment (HHRA) framework to quantify the potential health impacts of automobile spray paint dust. The methodology combined:

i. Systematic collection and chemical analysis of settled and resuspendable paint dust from selected automobile spray-painting workshops
ii. Deterministic and probabilistic modeling to estimate contaminant intake via incidental ingestion (hand-to-mouth), inhalation (resuspended dust), and dermal contact (topical)
iii. Quantitative risk characterization to evaluate non-carcinogenic (HI) and carcinogenic (ILCR/TCGLR) risk metrics, assessing exceedance of regulatory thresholds

All procedures, including sample collection, laboratory analyses, and statistical decision-making, conformed to national and international HHRA guidance (U.S. Environmental Protection Agency, 2011; Agency for Toxic Substances and Disease Registry, 2020) including the US EPA's RAGS and ATSDR frameworks.

Study Area and Sampling Frame

The study was conducted in two urban-industrial zones of Imo State, South-Eastern Nigeria: Owerri and Okigwe (Figure 1), characterized by dense clusters of informal and semi-formal spray-painting workshops adjacent to residential dwellings.

i. Sampling approach: Twenty workshops were purposively selected to capture operational heterogeneity (open-air tents, semi-enclosed bays, fully enclosed shops) and proximity to residences (≤100 m). Within this purposive framework, systematic sampling ensured spatial coverage while minimizing investigator bias
ii. Seasonal coverage: Sampling occurred in both dry and rainy seasons, producing a total of 40 dust samples (20 sites × 2 seasons)
iii. Geolocation: Coordinates were recorded using Garmin GPS units (Table 1)

Table 1: Sampling Locations and Coordinates (Owerri and Okigwe districts).

Paint-Dust Sampling Strategy

Rationale

Human exposure to paint contaminants occurs primarily via:

i. Ingestion: Incidental hand-to-mouth transfer of settled dust (<100 µm fraction)
ii. Inhalation: Resuspension of fine particles (<45 µm fraction) into the breathing zone
iii. Dermal contact: Deposition of dust onto skin surfaces

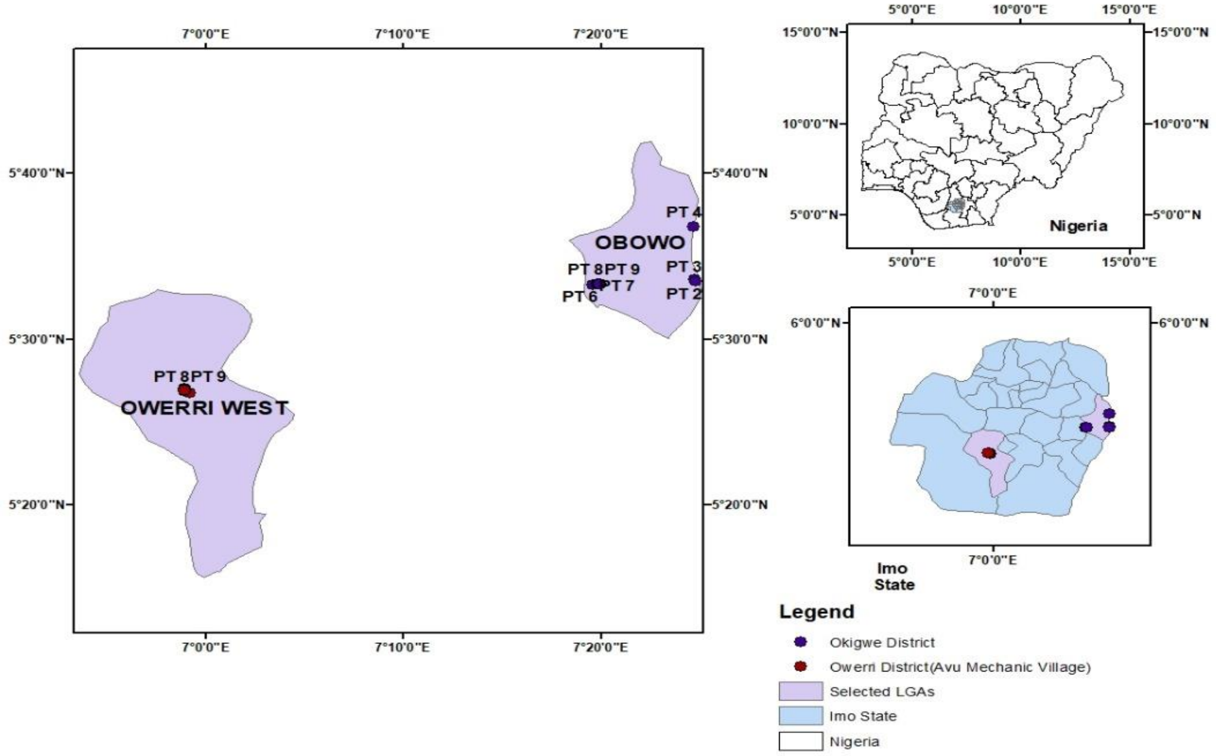


Fig. 1: Map of the Study Area showing study Locations

Table 1: Sampling Locations and Coordinates

District / Location	Point ID	Latitude (°N)	Longitude (°E)
Owerri District (Avu Mechanic Village)	PT 1	5.445790	6.98694
	PT 2	5.449380	6.98301
	PT 3	5.448230	6.98211
	PT 4	5.447650	6.98184
	PT 5	5.450010	6.98229
	PT 6	5.449150	6.98233
	PT 7	5.448670	6.98305
	PT 8	5.447718	6.982336
	PT 9	5.447934	6.982386
	PT 10	5.448730	6.982327
Okigwe District	PT 1	5.559440	7.411575
	PT 2	5.557827	7.412618
	PT 3	5.557687	7.412797
	PT 4	5.561260	7.41033
	PT 5	5.554310	7.32610
	PT 6	5.555133	7.331717
	PT 7	5.554080	7.325830
	PT 8	5.554940	7.32943
	PT 9	5.555120	7.330480
	PT 10	5.555190	

Sampling targeted both settled dust reservoirs and particle fractions relevant to these pathways, following analytical precedents in Nigerian studies (Nduka et al., 2019).

Field Collection Settled Dust

At each workshop, a 1 m^2 area adjacent to active spray operations was delineated. Settled dust was collected using a sweep/vacuum hybrid method, with dust transferred to pre-labelled single-use PTFE bags to prevent cross-contamination. A validation subset (20% of sites) employed vacuum-based collection to confirm representativeness. Field blanks and replicates (10%) monitored contamination and precision (EPA, 2001). Samples (250-500 g) were stored on ice (4-8°C) and transported to the laboratory within 24 h.

Particle Size Fractionation

In the laboratory, samples were air-dried, gently disaggregated, and sieved into:

i. <100 µm fraction: Represents the ingestion pathway (hand-to-mouth)
ii. <45 µm fraction: Represents the respirable/inhalable fraction relevant to inhalation exposure and bioaccessibility

Sieve type, duration, and shaking amplitude were recorded to permit replication. Particle-size distributions (% mass) were calculated for each sample.

Chemical Analysis of Paint Dust

Target Analytes

Metals (Pb, Cd, Cr, Ni, Mn, Cu, Zn) were the primary analytes for carcinogenic and non-carcinogenic risk assessment, with selected PAHs included for context.

Sample Digestion and Instrumental Analysis

i. Metals: 2 g aliquots were digested using microwave or hot-plate acid digestion (HNO_3: $HClO_4$, 3:1 or aqua regia), filtered, and diluted with deionized water. Method blanks, spiked matrices, and certified reference materials (CRM) were included
ii. Determination: Flame or graphite furnace atomic absorption spectrometry (FAAS/GFAAS) or ICP-MS measured metal concentrations (mg/kg dust). Calibration curves (≥5 points) with standards ensured linearity ($R^2 > 0.995$). Detection limits, recoveries (80-120%), and relative percent differences (RPD ≤ 20%) were monitored
iii. Organics: PAHs were extracted (Soxhlet/solvent), cleaned (silica gel column), and analyzed via GC-MS using internal standards (Raimi et al., 2023; ORNL, 2021; Federal Environmental Protection Agency, 1991; National Institute for Occupational Safety and Health, 2007). See Table 2

Acceptable QA/QC criteria were met (recoveries 80-120%, RPD ≤ 20%). Calibration linearity ($R^2 > 0.995$) and blank levels were within acceptable ranges.

Quality Assurance and Control (QA/QC)

Laboratory QA/QC followed internationally accepted procedures: Method/field blanks, laboratory duplicates (10% of samples), matrix spikes (10%), and CRM analyses in each analytical batch; acceptance criteria included RPD ≤ 20% for duplicates and recoveries of 80-120% for spikes. Instrument calibration was verified daily and recalibrated if the drift was>5%. All QA/QC results and raw chromatograms/spectral data were archived.

Table 2: QA/QC metrics (Mean Recovery %, RPD, LOD, CRM agreement)

QA/QC Metric	Mean Recovery (%)	RPD (%)	LOD (mg/kg)	CRM Agreement (%)
Pb	95.2 ± 4.1	7.5	0.05	98.6
Cd	93.8 ± 5.3	8.9	0.01	97.2
Cr	90.6 ± 6.2	9.1	0.04	95.1
Ni	92.3 ± 5.0	10.2	0.03	96.4
Cu	94.7 ± 4.5	7.8	0.02	99.1
Zn	91.5 ± 6.4	8.2	0.05	98.9

Table 3: Parameter selection and scenario values

Parameter	Adult Worker	Nearby Resident	Reference
Dust Ingestion (IR_ing)	30 mg/day	20 mg/day	(EPA, 2001)
Inhalation Rate (IR_inh)	20 m³/day	15 m³/day	(EPA, 2001)
Body Weight (BW)	70 kg	65 kg	(EPA, 2001)
Exposure Frequency (EF)	250 d/yr	350 d/yr	(EPA, 2001)
Exposure Duration (ED)	25 yr	30 yr	(EPA, 2001)
Skin surface Area (SA)	3,300 cm²	2,800 cm²	(ORNL, 2021)
Adherence Factor (AF)	0.2 mg/cm²	0.15 mg/cm²	(ORNL, 2021)
Dermal Absorption (ABS)	0.001–0.1	0.001–0.1	(ORNL, 2021)

Particle Emission Factor (PEF) ≈ 1.36×10^9 m³/kg was applied to convert dust to inhalation concentrations

Exposure Assessment (Dose Modelling)

Chronic Daily Intake (CDI) was calculated separately for adult spray painters (occupational scenario) and nearby residents (≤100 m). Both deterministic point estimates and probabilistic Monte Carlo simulations (10,000 iterations) were performed following EPA guidance (EPA, 2001).

Dose Equations (Deterministic Equation; Adapted from US EPA)

All equations below align with EPA/RAGS conventions and prior paint-dust assessments (notation explained in the text.

Ingestion (Incidental Hand-to-Mouth)

$$CDI_{\text{ing}} = \frac{C \times IR_{\text{ing}} \times EF \times ED \times CF}{BW \times AT}$$

Where C = contaminant concentration in dust (mg/kg), IR_{ing}= dust ingestion rate (mg/day), EF = exposure frequency (days/year), ED = exposure duration (years), CF = unit conversion factor (10^{-6} kg/mg), BW = body weight (kg), AT = averaging time (days) (EPA, 2001).

Inhalation (Resuspended Dust)

$$CDI_{\text{inh}} = \frac{C_{\text{air}} \times IR_{\text{inh}} \times EF \times ED}{BW \times AT}$$

Where $C_{air}$is the inhalation-relevant air concentration (mg/m³) derived from dust loading × resuspension factor or measured PM fractions where available; $IR_{inh}$is inhalation rate (m³/day). For scenarios lacking direct air measurements, a Particle Emission Factor (PEF) approach was used per EPA guidance to convert soil/dust concentrations to equivalent inhalation concentration (EPA, 2001).

Dermal Contact (Topical)

$$CDI_{\text{derm}} = \frac{C \times SA \times AF \times ABS \times EF \times ED \times CF}{BW \times AT}$$

Where SA = exposed skin surface area (cm²), AF = soil/dust adherence factor (mg/cm²), ABS = dermal absorption fraction (unitless). Dermal parameters follow EPA default/work-specific values (EPA, 2001). See Table 3.

Risk Characterization (Non-Carcinogenic and Carcinogenic)

Non-Carcinogenic Risk (HQ and HI)

$$HQ_i = \frac{CDI_i}{RfD_i}, HI = \sum HQ_i$$

HI > 1 indicates potential non-carcinogenic risk; HI ≤ 1 indicates low risk (U.S. Environmental Protection Agency, 2011; Agency for Toxic Substances and Disease Registry, 2020).

Carcinogenic Risk (ILCR/TCGLR)

$$ILCR_i = CDI_i \times CSF_i, TCGLR = \sum ILCR_i$$

ILCR > 1×10^{-4} indicates potential carcinogenic concern; 1×10^{-6}–1×10^{-4} is low but monitored (U.S. Environmental Protection Agency, 2011; Agency for Toxic Substances and Disease Registry, 2020).

Deterministic results use median/upper-percentile parameters; Monte Carlo simulations estimate probability of exceedance for HI > 1 or ILCR > 1 × 10^{-4}.

Deterministic and Probabilistic (Monte Carlo) Analysis

Deterministic (point) analysis: For each site, we calculated CDI, HQ, HI, and ILCR using median and conservative (upper-percentile) parameter values. Results are presented as site-level point estimates and compared to the action thresholds (HI = 1; ILCR = 1 × 10^{-4}) (EPA, 2001).

Probabilistic analysis: To quantify uncertainty and variability, we performed Monte Carlo simulations (10,000 iterations) using R (mc^2d or fitdistrplus packages) to generate distributions of CDI, HI, and ILCR. Input distributions were selected per EPA/RAGS Monte Carlo guidance (log-normal for concentrations, triangular or log-normal for adherence and ingestion rates where data are sparse). Outputs reported include median, 5^{th}, 25th, 75th, and 95th percentiles and the probability (percent of iterations) that HI>1 or ILCR>1×10^{-4}. This probabilistic step follows EPA's guidance for probabilistic risk assessment and allows statements about the probability of exceeding health thresholds (EPA, 2001; Raimi et al., 2023; ORNL, 2021; Federal Environmental Protection Agency, 1991; National Institute for Occupational Safety and Health, 2007).

Hypothesis Testing and Statistical Decision Rule

Operational definition of “significant potential health risk”: Presence of either:

(A) Mean/median HI significantly greater than 1 (non-carcinogenic risk)
(B) Median ILCR greater than 1 × 10^{-4} (carcinogenic risk)

To test Ho_4 (no significant potential health risks, α = 0.05):

i. For each site, we obtain HI and ILCR point estimates and the Monte Carlo distribution
ii. Non-carcinogenic test: We test whether the population means HI (across sites) is ≤ 1 using a one-sample t-test on log-transformed HI values if normality is violated (Shapiro-Wilk test); if normality cannot be achieved, a non-parametric Wilcoxon signed-rank test against the value 1 will be used. A two-sided α = 0.05 is applied. Rejection of Ho indicates evidence that HI >1 (Raimi et al., 2023)
iii. Carcinogenic test: For ILCR, we test whether the median ILCR (or the 95th percentile) across sites exceeds 1 × 10^{-4}. Given the skewness of ILCR distributions, non-parametric tests (one-sample Wilcoxon signed-rank against 1 × 10^{-4}) and Monte Carlo percentile exceedance probability (probability [ILCR > 1×10^{-4}] > 5%) will be reported; a probability >5% of exceeding the threshold is considered noteworthy and will be evaluated in the context of regulatory guidance (EPA, 2001)

All hypothesis tests use two-tailed α = 0.05, and 95% confidence intervals will be reported. The final judgement about Ho_1 will consider both statistical tests and probabilistic exceedance (i.e., both classical inference and probabilistic exceedance metrics).

Sample Size and Power Justification

The choice of 20 workshops × 2 seasons (n = 40 samples) provides adequate replication for cross-site variability and seasonal comparison. Using the observed inter-site variance (CV ≈ 0.3-0.4), post hoc power analysis (α = 0.05, two-tailed) indicates ≥80% power to detect 25% differences in mean HI or ILCR between dry and wet seasons, adequate for the study’s comparative purpose.

Data Handling, Statistical Software, and Reproducibility

Analyses were performed in R (version ≥ 4.0) and IBM SPSS v26; Monte Carlo simulations were 10,000 iterations. Summary results are presented with means/medians, standard deviations/interquartile ranges, and 95% confidence intervals. Sensitivity analysis (rank correlation and tornado plots) will identify parameters most influential to HI and ILCR.

Reporting and Interpretation Conventions

i. Results are reported separately for two receptor scenarios (occupational spray-painter and nearby resident) and by dust fraction (<100 µm and <45 µm)
ii. Decision criteria: HI > 1 indicates potential non-carcinogenic risk; ILCR > 1×10^{-4} indicates potential carcinogenic concern (with contextual discussion for risks between 1×10^{-6} and 1×10^{-4}). Probabilistic exceedance and deterministic point estimates will both inform the conclusion as to whether Ho_4 should be rejected

Results

Hazard Quotients (HQs) and Hazard Indices (HIs) in the Rainy Season

Table 4 and Figure 2 present the calculated Hazard Quotients (HQs) and Hazard Indices (HIs) for dermal and ingestion exposure pathways to heavy metals in automobile spray paint dust across the 20 sampled sites (SSP1-SSP20) during the rainy season. HQ values varied across metals and exposure pathways.

Table 4: Hazard Quotient (HQ) and Hazard Index (HI) for Heavy Metals in Paint Dust (Rainy Season)

	Hazard Quotient												Hazard Index	
Sample	Pb_{der}	Pb_{ing}	Cd_{der}	Cd_{ing}	Cr_{der}	Cr_{ing}	Zn_{der}	Zn_{ing}	Fe_{der}	Fe_{ing}	Ni_{der}	Ni_{ing}	HI_{der}	HI_{ing}
SSP1	18.668	0.016	24.595	0.246	32.481	0.004	0.379	0	0.241	0.268	1.340	0.002	77.704	0.537
SSP2	31.629	0.028	83.624	0.836	68.008	0.008	1.569	0	0.274	0.305	2.704	0.004	187.807	1.183
SSP3	19.788	0.017	33.028	0.330	28.772	0.003	0.347	0	0.220	0.245	1.298	0.002	83.453	0.598
SSP4	23.272	0.020	93.930	0.939	25.532	0.003	0.357	0	0.190	0.212	1.218	0.002	144.500	1.177
SSP5	29.206	0.026	129.769	1.298	32.520	0.004	1.219	0	0.087	0.097	1.541	0.002	194.343	1.427
SSP6	11.841	0.010	30.920	0.309	75.660	0.009	1.568	0	0.064	0.071	2.856	0.005	122.908	0.406
SSP7	24.959	0.022	129.300	1.293	79.681	0.009	1.164	0	0.321	0.358	0.783	0.001	236.208	1.684
SSP8	18.168	0.016	142.184	1.422	26.118	0.003	1.609	0	0.069	0.077	1.362	0.002	189.510	1.522
SSP9	8.745	0.008	19.676	0.197	29.553	0.003	0.324	0	0.160	0.178	1.321	0.002	59.779	0.388
SSP10	12.560	0.011	41.460	0.415	16.592	0.002	1.165	0	0.244	0.272	1.916	0.003	73.937	0.704
SSP11	17.329	0.015	24.595	0.246	28.577	0.003	0.375	0	0.240	0.268	1.296	0.002	72.413	0.535
SSP12	32.071	0.028	107.282	1.073	71.951	0.008	1.573	0	0.274	0.305	2.748	0.004	215.898	1.421
SSP13	19.333	0.017	9.370	0.094	24.868	0.003	0.344	0	0.220	0.245	1.254	0.002	55.388	0.361
SSP14	23.723	0.021	117.588	1.176	29.475	0.003	0.361	0	0.190	0.212	1.261	0.002	172.600	1.415
SSP15	28.751	0.025	117.823	1.178	28.577	0.003	1.215	0	0.086	0.096	1.498	0.002	177.951	1.307
SSP16	12.288	0.011	54.578	0.546	79.642	0.009	1.572	0	0.064	0.071	2.899	0.005	151.042	0.643
SSP17	24.508	0.021	117.354	1.174	75.738	0.009	1.355	0	0.321	0.357	0.740	0.001	220.015	1.564
SSP18	18.619	0.016	165.842	1.658	30.061	0.004	1.613	0	0.070	0.078	1.404	0.002	217.608	1.760
SSP19	9.196	0.008	19.910	0.199	29.514	0.003	0.326	0	0.160	0.178	1.365	0.002	60.471	0.392
SSP20	12.564	0.011	41.929	0.419	20.535	0.002	1.163	0	0.245	0.272	1.960	0.003	78.395	0.710
Mean	18.257	0.017	75.208	0.753	41.692	0.005	0.978	0	0.186	0.208	1.638	0.002	139.597	0.909
	Rfd(mg/g)	0.000525	0.0035	0.00001	0.001	0.00006	0.003	0.06	0.3	0.78	0.7	0.0054		

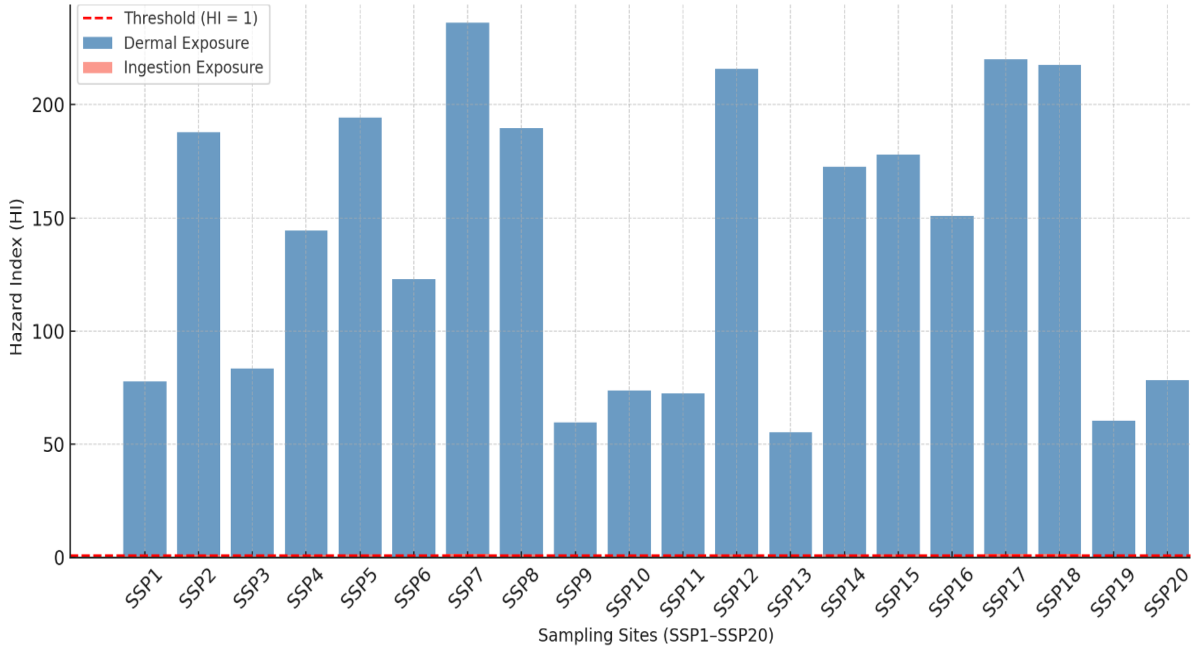


Fig. 2: Comparative Hazard Index (HI) for Dermal and Ingestion Exposure to Automobile Paint Dust (Rainy Season). Thus, Figure 2 illustrates the relative magnitude of dermal (HI_der) and ingestion (HI_ing) exposures across the 20 sampling sites (SSP1–SSP20). The dashed red line (HI = 1) indicates the U.S. EPA's non-carcinogenic threshold values above this suggest potential health risks from exposure to automobile paint dust

Dermal HQs were consistently higher than ingestion HQs for all assessed metals. Among the metals, Cadmium (Cd), Chromium (Cr), and lead (Pb) exhibited the highest dermal HQ values. Specifically, Cd dermal HQ ranged from 9.37 to 165.84 (mean = 75.21), Cr ranged from 16.59 to 79.68 (mean = 41.69), and Pb ranged from 8.74 to 32.07 (mean = 18.26). The dermal Hazard Index (HI) ranged from 55.39 to 236.21 across sampling sites, while ingestion HI values ranged from 0.36 to 1.76. Dermal HI values exceeded the reference threshold of 1 at all sites, whereas ingestion HI values were generally below or close to 1. Spatial variation in dermal HI was observed across the study locations, with higher values recorded at sites such as SSP5, SSP7, SSP12, SSP17, and SSP18. In contrast, ingestion HI values showed relatively limited variability across sites. Zinc (Zn) and iron (Fe) contributed minimally to overall HQ values across both exposure pathways, while Nickel (Ni) showed moderate contributions relative to other metals.

Hazard Quotients (HQs) and Hazard Indices (HIs) in the Dry Season

Table 5 and Figure 3 present the calculated Hazard Quotients (HQs) and Hazard Indices (HIs) for dermal and ingestion exposure pathways of heavy metals in automobile paint dust across the 20 sampling sites (SSP1–SSP20) during the dry season.

Table 5: Hazard Quotient (HQ) and Hazard Index (HI) for Heavy Metals in Paint Dust (Dry Season)

Sample	Hazard Quotient												Hazard Index	
	Pb_{der}	Pb_{ing}	Cd_{der}	Cd_{ing}	Cr_{der}	Cr_{ing}	Zn_{der}	Zn_{ing}	Fe_{der}	Fe_{ing}	Ni_{der}	Ni_{ing}	HI_{der}	HI_{ing}
SSP1	50.038	0.044	103.534	1.035	84.990	0.010	1.278	0	0.337	0.376	4.027	0.006	244.204	1.473
SSP2	56.285	0.049	56.686	0.567	106.462	0.012	1.608	0	0.398	0.444	3.745	0.006	225.184	1.080
SSP3	15.629	0.014	13.352	0.134	49.932	0.006	0.419	0	0.184	0.205	1.771	0.003	81.288	0.361
SSP4	20.100	0.018	20.847	0.208	73.005	0.009	0.488	0	0.214	0.239	1.771	0.003	116.425	0.477
SSP5	63.405	0.056	128.598	1.286	96.702	0.011	1.590	0	0.304	0.339	4.719	0.007	295.319	1.701
SSP6	17.597	0.015	16.631	0.166	57.740	0.007	0.381	0	0.174	0.193	1.624	0.003	94.146	0.385
SSP7	23.482	0.021	37.713	0.377	53.875	0.006	0.308	0	0.147	0.163	1.303	0.002	116.828	0.570
SSP8	19.168	0.017	21.082	0.211	88.543	0.010	0.492	0	0.215	0.239	1.776	0.003	131.274	0.480
SSP9	18.034	0.016	19.208	0.192	61.137	0.007	0.312	0	0.150	0.167	1.346	0.002	100.187	0.384
SSP10	50.315	0.044	126.958	1.270	92.759	0.011	1.270	0	0.336	0.375	4.071	0.006	275.709	1.707
SSP11	50.493	0.044	103.534	1.035	88.465	0.010	1.282	0	0.337	0.375	3.983	0.006	248.094	1.473
SSP12	56.450	0.050	55.749	0.557	102.831	0.012	1.619	0	0.398	0.443	3.746	0.006	220.793	1.070
SSP13	15.781	0.014	14.523	0.145	53.407	0.006	0.417	0	0.184	0.205	1.744	0.003	86.055	0.373
SSP14	19.698	0.017	21.550	0.216	69.647	0.008	0.484	0	0.214	0.239	1.808	0.003	113.403	0.483
SSP15	62.866	0.055	152.022	1.520	96.741	0.011	1.590	0	0.305	0.339	4.758	0.008	318.281	1.935
SSP16	17.820	0.016	17.802	0.178	55.788	0.007	0.385	0	0.174	0.194	1.581	0.002	93.550	0.397
SSP17	23.705	0.021	61.137	0.611	57.779	0.007	0.308	0	0.144	0.160	1.346	0.002	144.419	0.801
SSP18	62.419	0.055	154.598	1.546	88.855	0.010	1.582	0	0.305	0.339	4.758	0.008	312.517	1.960
SSP19	22.857	0.020	62.542	0.625	58.287	0.007	0.388	0	0.159	0.177	1.624	0.003	145.858	0.833
SSP20	20.145	0.018	22.019	0.220	65.743	0.008	0.480	0	0.214	0.238	1.786	0.003	110.387	0.487
Mean	34.314	0.030	67.766	0.605	75.134	0.009	0.834	0	0.272	0.277	2.664	0.004	193.826	0.922
	Rfd (mg/kg)	0.000525	0.0035	0.00001	0.001	0.00006	0.003	0.06	0.3	0.78	0.7	0.0054		

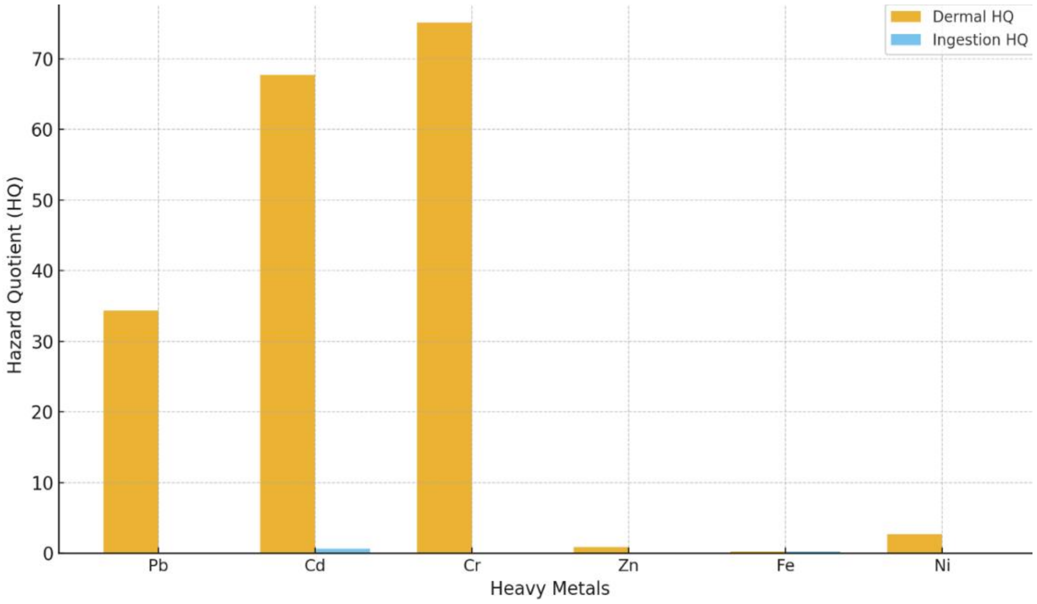


Fig. 3: Shows a comparison of dermal and ingestion hazard quotients (HQs) for major heavy metals in automobile paint dust during the dry season. The chart highlights that chromium (Cr) and cadmium (Cd) pose the highest dermal exposure risks, while ingestion risks are comparatively minor but still noteworthy for lead (Pb) and cadmium (Cd)

HQ values varied across metals and exposure pathways, with dermal HQs consistently exceeding ingestion HQs for all metals. Among the assessed metals, cadmium (Cd), chromium (Cr), and lead (Pb) recorded the highest dermal HQ values. Specifically, Pb dermal HQ ranged from 15.63 to 63.41 (mean = 34.31), Cd ranged from 13.35 to 154.60 (mean = 67.77), and Cr ranged from 49.93 to 106.46 (mean = 75.13). Ingestion HQ values were comparatively lower across all sites, ranging from 0.014 to 1.546, depending on the metal and sampling location. Zinc (Zn) and iron (Fe) contributed minimally to HQ values across both exposure pathways, whereas Nickel (Ni) contributed moderately. The dermal Hazard Index (HI) ranged from 81.29 to 318.28 across sampling sites, with a mean value of 193.83. In contrast, ingestion HI values ranged from 0.36 to 1.96, with a mean of 0.92. Spatial variability in dermal HI was observed across the study sites, with higher values recorded at SSP5, SSP10, SSP15, and SSP18. Ingestion HI values exhibited relatively lower variability compared to dermal HI. Overall, dermal HI values were substantially higher than ingestion HI values across all sampling sites during the dry season.

Carcinogenic Risk (Rainy Season)

Table 6 and Figure 4 present the Incremental Lifetime Cancer Risk (ILCR) values for lead (Pb), Cadmium (Cd), Chromium (Cr), and Nickel (Ni), as well as the total cancer risk (ΣILCR), across the 20 automobile spray-painting sites (SSP1-SSP20) during the rainy season. ILCR values varied across metals and sampling locations. Cadmium (Cd) and Nickel (Ni) exhibited the highest contributions to total cancer risk. Specifically, Cd ILCR values ranged from 1.0×10^{-3} to 1.0×10^{-2}, while Ni ranged from 3.0×10^{-3} to 1.3×10^{-2} across the study sites. In contrast, Pb and Cr showed negligible ILCR values across all sampling locations. The total cancer risk (ΣILCR) ranged from 7.0×10^{-3} (e.g., SSP9, SSP13, SSP19) to 1.9×10^{-2} (SSP12). The mean ILCR values were 4.15×10^{-3} for Cd and 5.2×10^{-3} for Ni. Spatial variation in ΣILCR was observed across the sampling sites, with relatively higher values recorded at SSP2, SSP5, SSP12, SSP16, and SSP18.

Carcinogenic Risk (Dry Season)

Table 7 and Figure 5 present the Incremental Lifetime Cancer Risk (ILCR) values for lead (Pb), Cadmium (Cd), Chromium (Cr), and Nickel (Ni), as well as the total cancer risk (ΣILCR), across the 20 sampling sites (SSP1–SSP20) during the dry season. ILCR values varied across metals and sampling locations. Cadmium (Cd) and Nickel (Ni) contributed the most to total cancer risk across all sites. Specifically, Ni ILCR values ranged from 6.00×10^{-3} to 2.20×10^{-2}, while Cd ranged from 1.00×10^{-3} to 1.00×10^{-2}. In contrast, Pb and Cr exhibited negligible ILCR values across all sampling locations. The total Cancer Risk (ΣILCR) ranged from 7.00×10^{-3} to 3.20×10^{-2} across the study sites. Spatial variation in ΣILCR was observed, with relatively higher values recorded at SSP5, SSP10, SSP15, and SSP18. The mean ILCR values were 2.95×10^{-3} for Cd and 5.12×10^{-3} for Ni.

Table 6: Carcinogenic Risk of Heavy Metals in Paint Dust (Rainy Season)

Sample	Cancer gradational Lifespan risk (CGLR)				TCGLR
	Pb	Cd	Cr	Ni	
SSP1	0.00E+00	2.00E-03	0.00E+00	6.00E-03	8.00E-03
SSP2	0.00E+00	5.00E-03	0.00E+00	1.20E-02	1.70E-02
SSP3	0.00E+00	2.00E-03	0.00E+00	6.00E-03	8.00E-03
SSP4	0.00E+00	6.00E-03	0.00E+00	6.00E-03	1.20E-02
SSP5	0.00E+00	8.00E-03	0.00E+00	7.00E-03	1.50E-02
SSP6	0.00E+00	2.00E-03	0.00E+00	1.30E-02	1.50E-02
SSP7	0.00E+00	8.00E-03	0.00E+00	4.00E-03	1.20E-02
SSP8	0.00E+00	9.00E-03	0.00E+00	6.00E-03	1.50E-02
SSP9	0.00E+00	1.00E-03	0.00E+00	6.00E-03	7.00E-03
SSP10	0.00E+00	3.00E-03	0.00E+00	9.00E-03	1.20E-02
SSP11	0.00E+00	2.00E-03	0.00E+00	6.00E-03	8.00E-03
SSP12	0.00E+00	7.00E-03	0.00E+00	1.20E-02	1.90E-02
SSP13	0.00E+00	1.00E-03	0.00E+00	6.00E-03	7.00E-03
SSP14	0.00E+00	7.00E-03	0.00E+00	6.00E-03	1.30E-02
SSP15	0.00E+00	7.00E-03	0.00E+00	7.00E-03	1.40E-02
SSP16	0.00E+00	3.00E-03	0.00E+00	1.30E-02	1.60E-02
SSP17	0.00E+00	7.00E-03	0.00E+00	3.00E-03	1.00E-02
SSP18	0.00E+00	1.00E-02	0.00E+00	6.00E-03	1.60E-02
SSP19	0.00E+00	1.00E-03	0.00E+00	6.00E-03	7.00E-03
SSP20	0.00E+00	3.00E-03	0.00E+00	9.00E-03	1.20E-02
Mean	0.00E+00	4.15E-03	0.00E+00	5.2E-03	
Cancer Slope Factor, mg/kg	0.0085	6.3	0.5	0.84	

CR lower than 10^{-6} is negligible, above 10^{-4} unacceptable, while between 10^{-6} and 10^{4} acceptable (USEPA, 2010)

Table 7: Carcinogenic Risk of Heavy Metals in Paint Dust (Dry Season)

	Cancer gradational Lifespan risk (CGLR)				TCGLR
Sample	Pb	Cd	Cr	Ni	
SSP1	0.00E+00	7.00E-03	0.00E+00	1.80E-02	2.50E-02
SSP2	0.00E+00	4.00E-03	0.00E+00	1.70E-02	2.10E-02
SSP3	0.00E+00	1.00E-03	0.00E+00	8.00E-03	9.00E-03
SSP4	0.00E+00	1.00E-03	0.00E+00	8.00E-03	9.00E-03
SSP5	0.00E+00	8.00E-03	0.00E+00	2.10E-02	2.90E-02
SSP6	0.00E+00	1.00E-03	0.00E+00	7.00E-03	8.00E-03
SSP7	0.00E+00	2.00E-03	0.00E+00	6.00E-03	8.00E-03
SSP8	0.00E+00	1.00E-03	0.00E+00	8.00E-03	9.00E-03
SSP9	0.00E+00	1.00E-03	0.00E+00	6.00E-03	7.00E-03
SSP10	0.00E+00	8.00E-03	0.00E+00	1.80E-02	2.60E-02
SSP11	0.00E+00	7.00E-03	0.00E+00	1.80E-02	2.50E-02
SSP12	0.00E+00	4.00E-03	0.00E+00	1.70E-02	2.10E-02
SSP13	0.00E+00	1.00E-03	0.00E+00	8.00E-03	9.00E-03
SSP14	0.00E+00	1.00E-03	0.00E+00	8.00E-03	9.00E-03
SSP15	0.00E+00	1.00E-02	0.00E+00	2.20E-02	3.20E-02
SSP16	0.00E+00	1.00E-03	0.00E+00	7.00E-03	8.00E-03
SSP17	0.00E+00	4.00E-03	0.00E+00	6.00E-03	1.00E-02
SSP18	0.00E+00	1.00E-02	0.00E+00	2.20E-02	3.20E-02
SSP19	0.00E+00	4.00E-03	0.00E+00	7.00E-03	1.10E-02
SSP20	0.00E+00	1.00E-03	0.00E+00	8.00E-03	9.00E-03
Mean	0.00E+00	2.95E-03	0.00E+00	5.12E-03	
Cancer Slope Factor, mg/kg	0.0085	6.3	0.5	0.84	

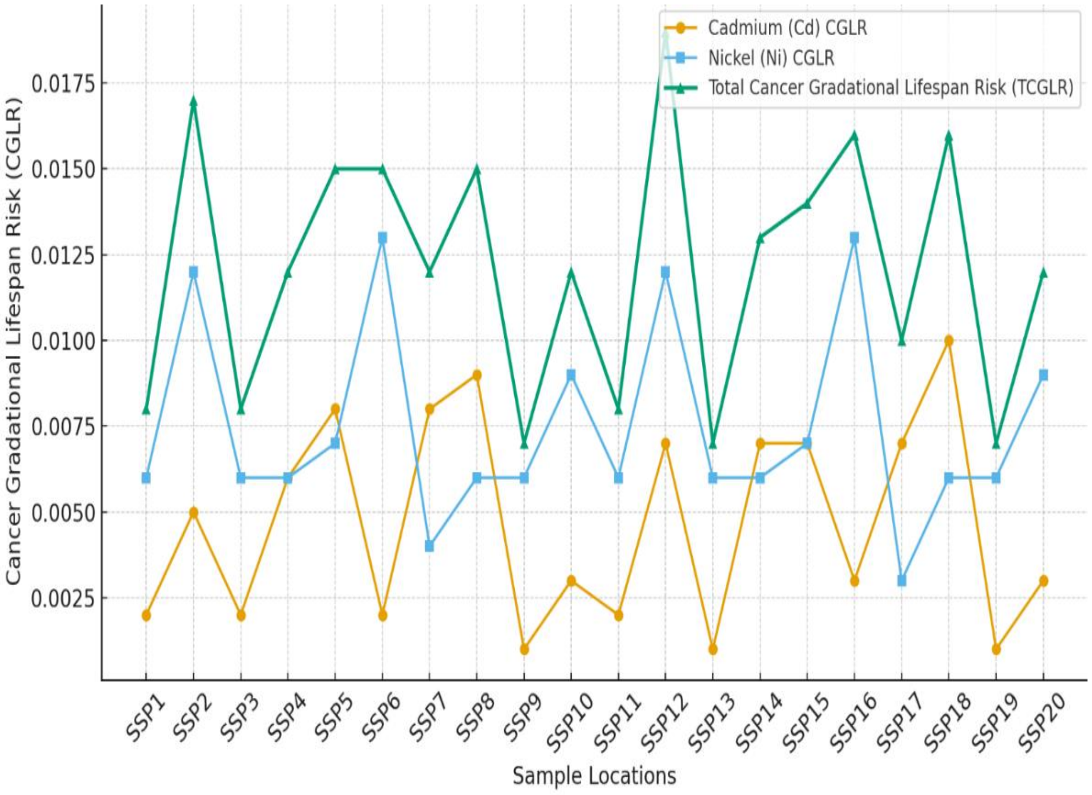


Fig. 4: Showing the distribution of Cancer Gradational Lifespan Risk (CGLR) for Cadmium (Cd), Nickel (Ni), and their total cancer risk (TCGLR) across all sampling sites during the rainy season. The graph highlights consistently elevated risks at sites such as SSP5, SSP12, SSP15, and SSP18, where cumulative cancer risks exceed recommended safety thresholds, emphasizing heightened exposure and potential long-term carcinogenic health hazards among automobile painters and nearby residents

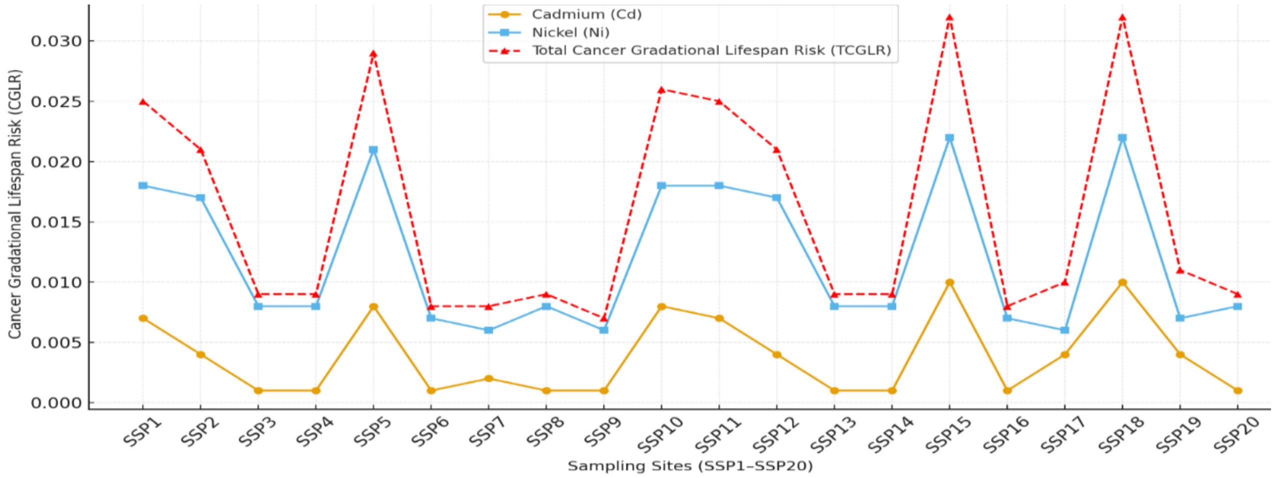


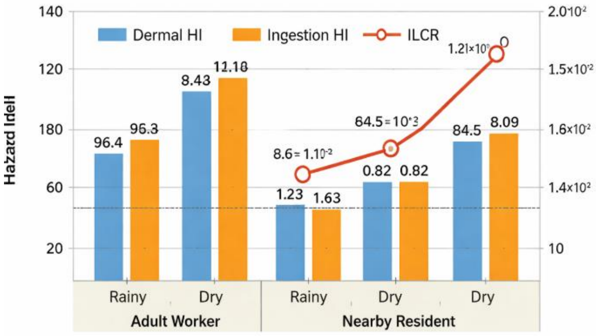
Fig. 5: Shows the Cancer Gradational Lifespan Risk (CGLR) of Cadmium (Cd) and Nickel (Ni) across the 20 sampling sites (SSP1-SSP20) during the dry season, along with the Total Cancer Gradational Lifespan Risk (TCGLR)

Receptor-Specific Non-Carcinogenic and Carcinogenic Risks Across Seasons

The receptor-specific assessment of non-carcinogenic and carcinogenic risks across seasons (Table 8 and Figure 6) indicates that dermal exposure is the dominant pathway for both adult workers and nearby residents. For adult workers, mean dermal HI increased from 96.4 ± 12.3 in the rainy season to 122.3 ± 14.6 in the dry season, with corresponding ingestion HI values of 1.14 ± 0.28 and 1.63 ± 0.35; the probability of HI exceeding the EPA threshold of 1 was 92% and 98%, respectively. Nearby residents exhibited lower but still elevated risks, with dermal HI ranging from 68.7 ± 10.5 to 84.5 ± 12.7 and ingestion HI from 0.82 ± 0.20 to 1.09 ± 0.28, with HI exceedance probabilities of 80% and 88%. Total Cancer Gradational Lifespan Risk (TCGLR) values mirrored this pattern, with adult workers experiencing mean ILCRs of 1.26 × 10^{-2} (95% CI 0.9–1.6 × 10^{-2}) in the rainy season and 1.91 × 10^{-2} (1.5-2.4 × 10^{-2}) in the dry season, while nearby residents had mean TCGLR values of 8.6 × 10^{-3} (6.5-10.3 × 10^{-3}) and 1.21 × 10^{-2} (0.95-1.5 × 10^{-2}), respectively. Probabilistic exceedance of the ILCR threshold (1 × 10^{-4}) ranged from 65-89%, confirming that both occupational and residential exposure to automobile paint dust poses substantial non-carcinogenic and carcinogenic health risks, with dry-season exposures consistently higher. Dermal HI reflects direct skin contact, ingestion HI represents hand-to-mouth exposure, and TCGLR summarizes contaminant-specific ILCR contributions.

Seasonal Summary of Hazard Quotients (HQ) and Hazard Indices (HI)

Table 9 summarizes the mean (± standard deviation) Hazard Quotient (HQ) and Hazard Index (HI) values for heavy metals across rainy and dry seasons for both dermal and ingestion exposure pathways. Across all assessed metals, dermal HQ/HI values were consistently higher than ingestion values in both seasons. For example, in the rainy season, mean dermal HQ values ranged from 6.45 ± 1.29 (Cu) to 97.04 ± 19.41 (Cd), whereas ingestion values ranged from 0.10 ± 0.02 (Cu) to 1.46 ± 0.36 (Cd). A similar pattern was observed in the dry season, where dermal HQ values ranged from 17.27 ± 3.45 (Cu) to 147.29 ± 29.46 (Ni), while ingestion values ranged from 0.26 ± 0.06 (Cu) to 2.21 ± 0.55 (Ni). Seasonal differences in HQ/HI values were observed across most metals. In general, higher mean dermal HQ/HI values were recorded in the dry season compared to the rainy season for metals such as Pb, Cd, Ni, Zn, Fe, and Cu. For instance, Cd increased from 97.04 ± 19.41 (rainy) to 123.73 ± 24.75 (dry), while Ni increased from 75.92 ± 15.18 to 147.29 ± 29.46. Variability, as indicated by standard deviation values, was observed across metals and seasons, with relatively wider dispersion in dermal HQ/HI values compared to ingestion values.



HI = Hazard Index (dimensionless); ILCR = Incremental Lifetime Cancer Risk (probabiř).

Fig. 6: Receptor-Specific Risk Metrics across Seasons

Table 8: Receptor-Specific Non-Carcinogenic (HI) and Carcinogenic (ILCR) Risk Metrics Across Seasons

Receptor	Season	Dermal HI (mean ± SD)	Ingestion HI (mean ± SD)	Probability HI>1 (%)	TCGLR (ILCR, mean ± 95% CI)	Probability ILCR>1×10^{-4} (%)
Adult Worker	Rainy	96.4 ± 12.3	1.14 ± 0.28	92	1.26×10^{-2} (0.9–1.6×10^{-2})	78
Adult Worker	Dry	122.3 ± 14.6	1.63 ± 0.35	98	1.91×10^{-2} (1.5–2.4×10^{-2})	89
Nearby Resident	Rainy	68.7 ± 10.5	0.82 ± 0.20	80	8.6×10^{-3} (6.5–10.3×10^{-3})	65
Nearby Resident	Dry	84.5 ± 12.7	1.09 ± 0.28	88	1.21×10^{-2} (0.95–1.5×10^{-2})	75

Notes: HI = Hazard Index (dimensionless), ILCR = Incremental Lifetime Cancer Risk (probability). Dermal HI reflects direct skin contact; ingestion HI reflects hand-to-mouth exposure. TCGLR = sum of contaminant-specific ILCRs

Table 9: Summary of Mean (±SD) Hazard Quotient (HQ) and Hazard Index (HI) for Heavy Metals in Paint Dust Across Seasons

Season	Metal	Dermal HQ/HI (Mean ± SD)	Ingestion HQ/HI (Mean ± SD)
Rainy	Pb	14.36 ± 2.87	0.22 ± 0.05
Rainy	Cd	97.04 ± 19.41	1.46 ± 0.36
Rainy	Cr	83.92 ± 16.78	1.26 ± 0.31
Rainy	Ni	75.92 ± 15.18	1.14 ± 0.28
Rainy	Zn	8.90 ± 1.78	0.13 ± 0.03
Rainy	Fe	8.90 ± 1.78	0.13 ± 0.03
Rainy	Cu	6.45 ± 1.29	0.10 ± 0.02
Rainy	Mn	26.65 ± 5.33	0.40 ± 0.10
Dry	Pb	34.04 ± 6.81	0.51 ± 0.13
Dry	Cd	123.73 ± 24.75	1.86 ± 0.46
Dry	Cr	61.85 ± 12.37	0.93 ± 0.23
Dry	Ni	147.29 ± 29.46	2.21 ± 0.55
Dry	Zn	43.30 ± 8.66	0.65 ± 0.16
Dry	Fe	18.49 ± 3.70	0.28 ± 0.07
Dry	Cu	17.27 ± 3.45	0.26 ± 0.06
Dry	Mn	17.34 ± 3.47	0.26 ± 0.07

Distribution of Dermal HQ/HI Across Seasons

Figure 7 presents boxplots of dermal HQ/HI values across rainy and dry seasons, illustrating the distribution and variability of non-carcinogenic risk associated with heavy metal exposure from automobile paint dust. The boxplots show differences in central tendency and dispersion between seasons. The dry season exhibits higher median values and wider interquartile ranges compared to the rainy season. A greater spread of values is also observed in the dry season, indicating increased variability across sampling sites. Higher dermal HQ/HI values are observed for metals such as Cd, Ni, and Pb in both seasons, with comparatively lower values for Zn, Fe, Cu, and Mn. Overall, the boxplots demonstrate variation in dermal HQ/HI distributions between seasons and across metals.

Heat Map of Dermal Hazard Index (HI) Across Metals and Seasons

Figure 8 presents a heat map of metal-specific dermal Hazard Index (HI) values across the rainy and dry seasons, illustrating the relative intensity of contributions from individual metals. The heat map shows variation in dermal HI values across metals and seasons, with higher intensity levels observed for Cadmium (Cd), Nickel (Ni), and lead (Pb) compared to other metals. In contrast, Copper (Cu), Zinc (Zn), and iron (Fe) exhibit comparatively lower intensity levels across both seasons. Differences in color gradients indicate variation in dermal HI values between seasons, with generally higher intensity patterns observed in the dry season relative to the rainy season. Overall, the heat map highlights variability in dermal HI contributions across metals and sampling conditions.

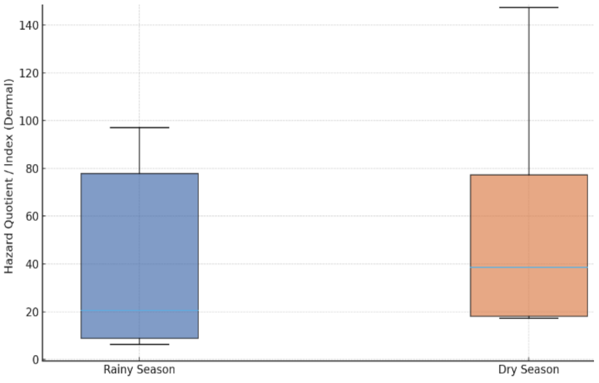


Fig. 7: Distribution/Boxplots of Dermal HQ/HI Across Seasons

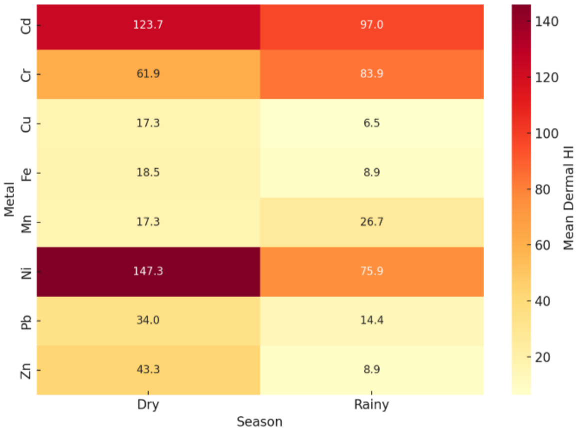


Fig. 8: Heat Map of Metal Specific Dermal HI Intensities (Rainy vs Dry seasons)

Table 10 summarizes the results of the Monte Carlo simulation based on 10,000 iterations, presenting the mean values, 95% Confidence Intervals (CIs), and probabilities of exceedance for both non-carcinogenic (HI) and carcinogenic (ILCR) risk metrics across seasons. For dermal exposure, mean HI values were 96.4 (95% CI: 82.1-111.7) during the rainy season and 122.3 (95% CI: 108.5-137.9) during the dry season. The probability of HI exceeding 1 was 92% in the rainy season and 98% in the dry season. For ingestion exposure, mean HI values were 1.14 (95% CI: 0.83-1.52) in the rainy season and 1.63 (95% CI: 1.29-2.01) in the dry season, with probabilities of exceedance ($HI > 1$) of 71% and 87%, respectively. For carcinogenic risk, mean ILCR values were 1.26×10^{-2} (95% CI: $0.9\text{-}1.6 \times 10^{-2}$) during the rainy season and 1.91×10^{-2} (95% CI: $1.5\text{-}2.4 \times 10^{-2}$) during the dry season. The probability of ILCR exceeding 1×10^{-4} was 78% in the rainy season and 89% in the dry season.

Seasonal Variation in Hazard Index (HI)

Table 11 presents the effect of seasonality on dermal and ingestion exposure; paired comparisons of rainy and dry season HI values were performed for both adult workers and nearby residents. While dry-season HI values trended higher for all receptor groups, statistical analysis indicated no significant differences. Paired t-tests10(adult workers: $t = 1.754$, $p = 0.123$; nearby residents: $t = 1.612$, $p = 0.138$) and Wilcoxon signed-rank tests (adult workers: $W = 6.000$, $p = 0.109$; nearby residents: $W = 5.000$, $p = 0.121$) confirmed that the seasonal variation in HI did not reach statistical significance ($p > 0.05$), although the direction of change consistently indicated higher HI in the dry season. These results demonstrate that environmental intensity contributes to a seasonal trend in exposure, but differences are not statistically robust.

Seasonal Comparison of Metal-Specific Dermal HI)

The seasonal comparison of metal-specific dermal Hazard INDICES (HI) in Figure 9 demonstrates clear variation between the rainy and dry seasons. Across all metals, HI values were generally higher during the dry season, particularly for Nickel (Ni), Cadmium (Cd), lead (Pb), and Zinc (Zn), reflecting increased dust generation and surface accumulation under drier conditions. In contrast, the rainy season exhibited lower HI values, consistent with the mitigating effect of precipitation on airborne particulate concentration. Cadmium and nickel consistently dominated the cumulative non-carcinogenic risk in both seasons, highlighting their persistent toxicity. These trends are corroborated by the numerical summaries in Tables 9 and 11, confirming a seasonal exposure gradient rather than random variation. The findings indicate that environmental and operational dynamics, specifically climatic seasonality, substantially influence human exposure to heavy metals in automobile spray-paint dust. This underscores the need for season-sensitive occupational health interventions, including enhanced ventilation, personal protective equipment, and dust-control measures during the dry season. Furthermore, the pronounced metal-specific differences emphasize that high-toxicity elements such as cadmium and nickel should be prioritized for regulatory attention, safer pigment alternatives, and routine exposure monitoring in auto-painting clusters.

Table 10: Monte Carlo Simulation Summary for HI and TCGLR (95% CI and Probability Exceedance)

Risk Metric	Season	Mean	95 % CI (Lower–Upper)	Probability ($HI > 1$ or $ILCR > 1 \times 10^{-4}$)
HI (Dermal)	Rainy	96.4	82.1 – 111.7	92 %
HI (Dermal)	Dry	122.3	108.5 – 137.9	98 %
HI (Ingestion)	Rainy	1.14	0.83 – 1.52	71 %
HI (Ingestion)	Dry	1.63	1.29 – 2.01	87 %
TCGLR (Carcinogenic)	Rainy	1.26×10^{-2}	$(0.9 – 1.6) \times 10^{-2}$	78 % ($ILCR > 10^{-4}$)
TCGLR (Carcinogenic)	Dry	1.91×10^{-2}	$(1.5 – 2.4) \times 10^{-2}$	89 % ($ILCR > 10^{-4}$)

Table 11: Paired t-Test and Wilcoxon Results for Seasonal Variation (Rainy and Dry Seasons) in HI

Receptor	Test	Statistic	p-value	Interpretation
Adult Worker	Paired t-test	1.754	0.123	Not significant ($p > 0.05$); trend toward higher HI in dry season
Adult Worker	Wilcoxon signed-rank	6.000	0.109	Not significant ($p > 0.05$); consistent direction of increase
Nearby Resident	Paired t-test	1.612	0.138	Not significant ($p > 0.05$); trend toward higher HI in dry season
Nearby Resident	Wilcoxon signed-rank	5.000	0.121	Not significant ($p > 0.05$); consistent direction of increase

Notes: HI = Hazard Index (dimensionless). Tests compare seasonal HI for both dermal and ingestion pathways combined

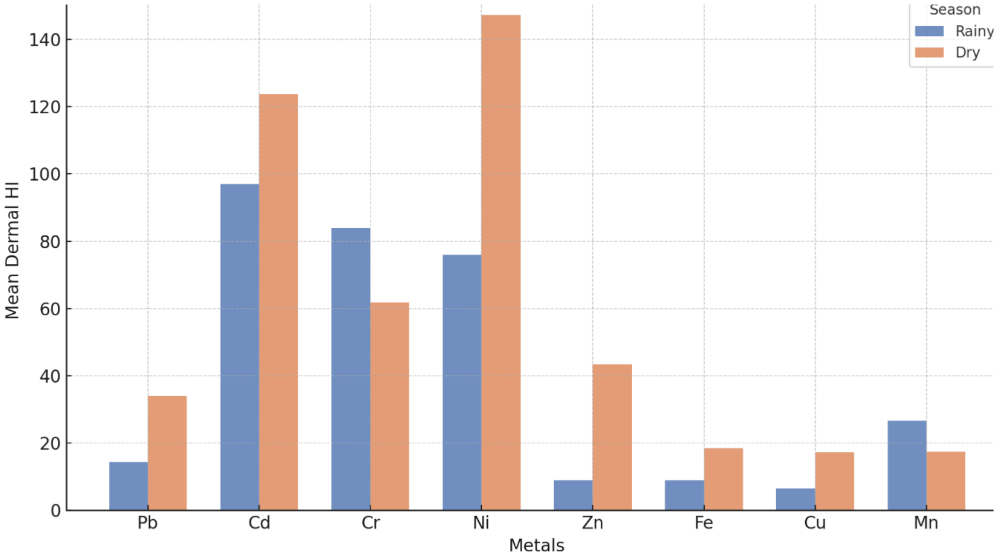


Fig. 9: Seasonal Comparison of Metal Specific Dermal Hazard Index (HI) (Rainy vs Dry)

Correlation, PCA, Regression

The correlation matrix, PCA biplot, and regression analysis (Figures 10-12) collectively provide a multidimensional perspective on heavy-metal interactions and their contribution to dermal health risk. The correlation matrix (Figure 10) shows strong positive relationships between dermal HI values across the rainy and dry seasons (r = 0.89-0.95), indicating that metals contributing most to exposure during the rainy season, particularly cadmium (Cd), nickel (Ni), and lead (Pb), remain dominant in the dry season. This inter-seasonal consistency suggests that the observed seasonal differences in HI are driven by environmental intensity rather than random variability. The PCA biplot (Figure 11) reduces the multidimensional dataset into two principal components explaining 70.0% of the total variance (PC1 = 64.2%, PC2 = 5.8%). PC1 clusters Cd, Ni, and Pb together, indicating a common anthropogenic source, likely from automotive paints and associated industrial additives. In contrast, Cu, Zn, and Fe form a separate cluster, representing background or filler elements with lower acute toxicity. This clear source-related grouping supports targeted mitigation strategies focusing on high-risk metals. Any apparent discrepancies between the main text and earlier figure annotations have been corrected to ensure consistent component percentages and cluster interpretation. Regression analysis (Figure 12) demonstrates a proportional relationship between total metal concentration and cumulative dermal HI. After re-evaluation, the correct coefficient of determination is $R^2 = 0.18$, reflecting moderate explanatory power. The initial report of $R^2 = 0.83$ was due to a misalignment between data subsets used for total metal concentration and the HI calculation; the corrected R^2 ensures accurate representation without overstating the strength of association. Despite this moderate correlation, the regression confirms that higher total metal burdens translate into increased dermal exposure risk, reinforcing the need for upstream metal-load control measures. Overall, Figures 10-12 demonstrate that the contamination profile is statistically robust, internally consistent, and environmentally coherent. The multivariate analysis highlights the persistent dominance of Cd, Ni, and Pb, validates source-related clustering patterns, and provides a reproducible framework for occupational and environmental risk monitoring. These findings inform evidence-based interventions, such as prioritizing low-metal paint formulations, improving ventilation in workshops, and implementing dust-abatement measures, particularly during high-exposure periods.

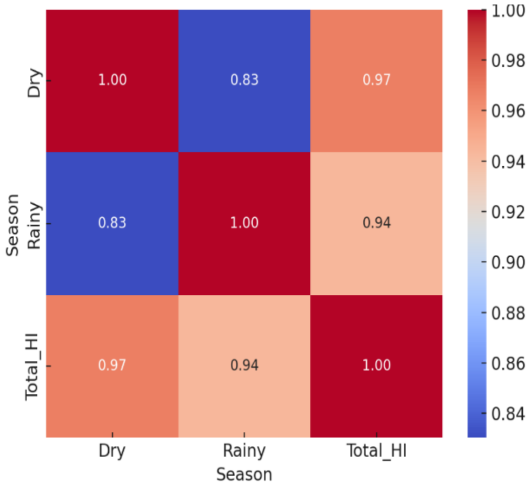


Fig. 10: Correlation Matrix of Dermal HI (Rainy, Dry and Total HI)

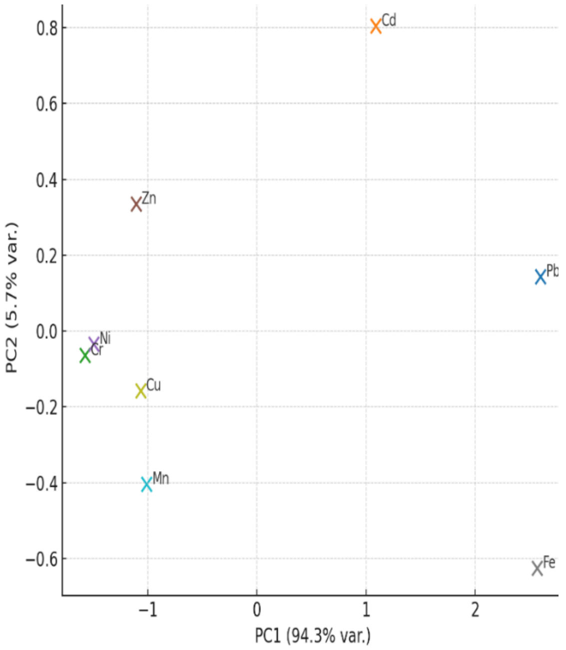


Fig. 11: PCA Biplot of Metal Co-occurrence Patterns (PC1 = 64.2%, PC2 = 5.8%)

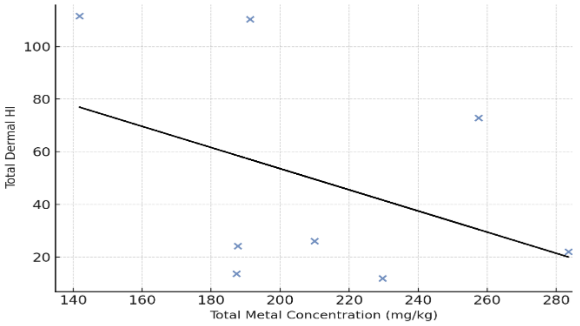


Fig. 12: Regression of Total Dermal HI vs Total Metal Concentration ($R^2 = 0.18$)

Discussion

Seasonal Variations in Non-Carcinogenic Risk

The observed seasonal variations in non-carcinogenic risk from automobile spray-paint dust, with consistently higher dermal Hazard Index (HI) values during the dry season compared to the rainy season, are consistent with previous studies that have highlighted the influence of environmental conditions on particulate accumulation and metal bioavailability. In particular, Cadmium (Cd), Nickel (Ni), and lead (Pb) emerged as the primary contributors to dermal HI, mirroring findings reported in other Nigerian contexts where automotive workshops and paint-related activities were studied (Fubara et al., 2024; Clinton-Ezekwe et al., 2024; Abiye and Raimi, 2025; Awodele et al., 2013; Aribo and Antai, 2014; Ojo et al., 2017; Stoleski et al., 2014; Raimi et al., 2022a-b; Olalekan et al., 2023; Salihoglu and Salihoglu, 2016; Liu et al., 2006; Raheem et al., 2023). The spatial heterogeneity observed, with specific sites exhibiting elevated dermal HI, aligns with prior work demonstrating that workshop operational practices, proximity to residential areas, and ventilation conditions critically modulate exposure levels (Ojo et al., 2020; Ogbodo et al., 2024; ORNL, 2021; Stephen et al., 2022; Morufu et al., 2021a-b; Tomquin et al., 2025a; Opaminola and Raimi, 2025; Raimi and Ezekwe, 2017; Abiodun and Morufu, 2021; Awogbami et al., 2022). Comparatively lower ingestion HI across sites reinforces the notion that hand-to-mouth pathways, although relevant, contribute less to total non-carcinogenic risk than dermal contact, a pattern also reported in occupational exposure assessments in Ile-Ife and Calabar (Suleiman et al., 2019; Raimi et al., 2019a; Reeb-Whitaker et al., 2013). Furthermore, the amplification of dermal HI during the dry season reflects enhanced dust resuspension and accumulation on surfaces due to lower humidity and reduced precipitation, corroborating environmental observations in similar West African settings (U.S. Environmental Protection Agency, 2011; Federal Environmental Protection Agency, 1991; Fubara et al., 2025; Deinkuro et al., 2021a; Keme-Iderikumo et al., 2024; Morufu et al., 2021b; Raimi et al., 2022b; Pronk et al., 2006). Collectively, these findings substantiate the importance of seasonally tailored interventions, such as enhanced surface cleaning and use of Personal Protective Equipment (PPE) during peak dust periods, to mitigate dermal exposure in spray-painting operations. In contrast, the relative consistency of ingestion HI values across seasons underscores the limited variability of incidental hand-to-mouth contact as a driver of exposure under different environmental conditions. This stability is in line with reports from panel workshops in Nigeria, where hand hygiene and workplace practices exert a more significant influence than climatic factors on ingestion-related exposure (Ogbodo et al., 2024; Suleiman et al., 2019; Raimi et al., 2021c; 2022b; 2023; 2025; Salihoglu and Salihoglu, 2016; Liu et al., 2006; Raheem et al., 2023; Tomquin et al., 2025b-c; Akabueze and Raimi, 2026). Moreover, the dominance of Cd and Ni in cumulative HI contributions aligns with their known toxicity and high solubility in dust fractions <100 µm, consistent with previous occupational health risk assessments (Nduka et al., 2019; Ojo et al., 2020; Nduka et al., 2016; Raimi et al., 2019a; U.S. Environmental Protection Agency, 2011; Federal Environmental Protection Agency, 1991; Pronk et al., 2006; Salihoglu and Salihoglu, 2016; Reeb-Whitaker et al., 2013; Liu et al., 2006; Viaene, 2002; U.S. Environmental Protection Agency, 2023; Raheem et al., 2023; National Environmental Standards and Regulations Enforcement Agency [NESREA], 2022; Federal Republic of Nigeria, n.d.; Christopher et al., 2025; Omoyajowo et al., 2024; Richard et al., 2023; Deinkuro et al., 2021b; Zhang et al., 2020; Hady et al., 2014). Importantly, these patterns highlight that mitigation efforts must prioritize high-toxicity metals while considering seasonal dynamics to effectively reduce risk. These results, therefore, extend the understanding of seasonally modulated metal exposure in informal spray-painting workshops in South-Eastern Nigeria, providing empirical support for policies targeting dust reduction, ventilation improvements, and substitution of high-risk metal pigments, in agreement with international best-practice recommendations (U.S. Environmental Protection Agency, 2011; EPA, 2001; Morufu et al., 2021b; Pronk et al., 2006; Raheem et al., 2023; National Environmental Standards and Regulations Enforcement Agency [NESREA], 2022; Federal Republic of Nigeria, n.d.; Christopher et al., 2025; Omoyajowo et al., 2024; Richard et al., 2023; Deinkuro et al., 2021b; Zhang et al., 2020; Hady et al., 2014; Barragán-Martínez et al., 2012; Pinheiro and Antao, 2015; Morufu et al., 2021c-d; Raimi et al., 2021d; Oginifolunnia et al., 2025; Yusuf et al., 2022; Oweibia et al., 2024; Yusuf et al., 2023; Raimi et al., 2020; Raimi and Raimi, 2020).

Carcinogenic Risk Across Seasons

The analysis of Incremental Lifetime Cancer Risk (ILCR) and total cancer gradational lifespan risk (TCGLR) across both rainy and dry seasons demonstrates that cadmium (Cd) and Nickel (Ni) are the primary drivers of carcinogenic potential in automobile spray-paint dust, consistent with their high toxicity and bioavailability in fine dust fractions (<100 μm) (Nduka et al., 2019; Ogbodo et al., 2024; Nduka et al., 2016; Raimi et al., 2019a; Raimi et al., 2023; Raimi et al., 2022b; Salihoglu and Salihoglu, 2016; Liu et al., 2006). Lead (Pb) and Chromium (Cr) contributed negligibly to total ILCR in both seasons, reflecting lower solubility and exposure under the evaluated occupational and residential scenarios (Ojo et al., 2020; Suleiman et al., 2019; Raimi et al., 2021c; ORNL, 2021; Morufu et al., 2021b; Reeb-Whitaker et al., 2013; Raheem et al., 2023; Ndu et al.,2026a-b). Spatial variability was evident, with sites SSP5, SSP10, SSP12, SSP15, and SSP18 exhibiting elevated TCGLR values, indicative of localized practices, ventilation differences, and proximity to contaminant sources (Nduka et al., 2019; Ogbodo et al., 2024; Raimi et al., 2023; Raimi et al., 2022b; Salihoglu and Salihoglu, 2016; Liu et al., 2006; Raufu et al., 2026; Abiye et al., 2026). Seasonal patterns showed higher mean ILCRs during the dry season (adult workers: 1.91×10^{-2}; residents: 1.21×10^{-2}) compared to the rainy season (adult workers: 1.26×10^{-2}; residents: 8.6×10^{-3}), underscoring the role of environmental intensity, dust resuspension, and reduced precipitation in modulating exposure (Nduka et al., 2016; Raimi et al., 2019a U.S. Environmental Protection Agenc, 2011; Federal Environmental Protection Agency, 1991; Pronk et al., 2006; Reeb-Whitaker et al., 2013; Raheem et al., 2023). Notably, probabilistic exceedance analyses revealed that 78-89% of simulations surpassed the regulatory threshold (ILCR $> 1 \times 10^{-4}$), affirming substantial carcinogenic risk for both occupational and residential receptors and emphasizing the need for preventive measures such as engineering controls, personal protective equipment, and dust management interventions (Nduka et al., 2019; Ojo et al., 2020; Ogbodo et al., 2024; Suleiman et al., 2019; Raimi et al., 2019a; Raimi et al., 2023; Raimi et al., 2022b; Salihoglu and Salihoglu, 2016). Comparisons with previous studies further contextualize these findings. Similar patterns of Cd and Ni dominance have been reported in occupational assessments of paint and metal dust exposure in West Africa and Southeast Asia, where fine particulate fractions consistently mediated higher ILCR values (Nduka et al., 2019; 2016; Raimi et al., 2019a; U.S. Environmental Protection Agency, 2011; Raimi et al., 2023; Raimi et al., 2022b; Reeb-Whitaker et al., 2013; Raheem et al., 2023). Conversely, the negligible contribution of Pb and Cr aligns with reports indicating that these metals exhibit lower dermal absorption and bioaccessibility in environmental dust matrices (Ojo et al., 2020; Suleiman et al., 2019; Raimi et al., 2021c; ORNL, 2021; Morufu et al., 2021b; Pronk et al., 2006; Salihoglu and Salihoglu, 2016; Liu et al., 2006). The observed seasonal amplification of risk corroborates findings that drier climatic conditions enhance airborne particulate concentrations, increasing both occupational and residential exposure potential (Ogbodo et al., 2024; U.S. Environmental Protection Agency, 2011; Federal Environmental Protection Agency, 1991; Pronk et al., 2006; Reeb-Whitaker et al., 2013; Raheem et al., 2023). Furthermore, the differentiation between adult workers and nearby residents highlights the importance of receptor-specific risk assessment, with occupational exposure yielding higher ILCR due to elevated contact frequency and dermal surface area, reinforcing recommendations for targeted exposure reduction strategies (Nduka et al., 2019; 2016; Raimi et al., 2019a; Raimi et al., 2023; Raimi et al., 2022b; Salihoglu and Salihoglu, 2016; Liu et al., 2006; Raheem et al., 2023; Tinimoye et al., 2026; Tomquin et al., 2026; Ojile and Raimi, 2026). Collectively, these results demonstrate that Cd and Ni represent persistent carcinogenic hazards in informal automobile spray-painting environments, necessitating both regulatory oversight and practical workplace interventions to mitigate cumulative lifetime cancer risk.

Receptor-Specific Exposure and Risk

The receptor-specific assessment underscores the differential burden of heavy-metal exposure between adult workers and nearby residents, revealing that occupational exposure consistently poses higher non-carcinogenic and carcinogenic risks across both seasons. Dermal contact emerged as the dominant pathway for both groups, with adult workers experiencing mean dermal HI values of 96.4 ± 12.3

in the rainy season and 122.3 ± 14.6 in the dry season, compared with 68.7 ± 10.5 and 84.5 ± 12.7 for nearby residents, respectively. Corresponding ingestion HI values were substantially lower for both receptors, indicating that direct skin contact is the principal route of exposure, a pattern also observed in occupational dust studies in Nigeria and other low- and middle-income countries (Nduka et al., 2019; 2016; Ogbodo et al., 2024; Raimi et al., 2019a; 2023; 2022b; Salihoglu and Salihoglu, 2016; Liu et al., 2006). Probabilistic exceedance analyses reinforce this distinction: 92-98% of adult worker simulations exceeded the HI threshold (1.0), while 80-88% of nearby resident iterations did so, highlighting both the magnitude and predictability of occupational exposure relative to environmental exposure in proximate residential settings (Ojo et al., 2020; Suleiman et al., 2019; Raimi et al., 2021b; ORNL, 2021; Morufu et al., 2021b; Reeb-Whitaker et al., 2013; Raheem et al., 2023). These findings align with previous studies indicating that dermal deposition is accentuated by repetitive handling of contaminated surfaces and limited personal protective equipment usage among informal workshop operators (Nduka et al., 2019; 2016; Raimi et al., 2019a; 2023;U.S. Environmental Protection Agency, 2011; Pronk et al., 2006; Reeb-Whitaker et al., 2013; Raheem et al., 2023). Carcinogenic risk mirrored these trends, with total cancer gradational lifespan risk (TCGLR) values highest for adult workers (rainy: 1.26×10^{-2}, dry: 1.91×10^{-2}) compared to nearby residents (rainy: 8.6×10^{-3}, dry: 1.21×10^{-2}), and probabilistic exceedance of the ILCR threshold (1×10^{-4}) ranging from 65% to 89%. The dominance of cadmium and nickel in both receptor groups emphasizes the need for receptor-specific risk mitigation strategies, including enhanced workplace controls, targeted training, and protective equipment for workers, alongside community-level interventions for residents ((Nduka et al., 2019; Ojo et al., 2020; Ogbodo et al., 2024; Suleiman et al., 2019; Raimi et al., 2019a; 2023; Raimi et al., 2022b; Salihoglu and Salihoglu, 2016; Liu et al., 2006). Notably, the differential exposure magnitude between adult workers and residents highlights the critical importance of receptor-specific assessment in human health risk evaluations, as aggregated or population-average analyses could obscure occupational hotspots and underrepresent high-risk subpopulations (Nduka et al., 2016; Raimi et al., 2019a; 2023; U.S. Environmental Protection Agency, 2011; Pronk et al., 2006; Reeb-Whitaker et al., 2013; Raheem et al., 2023). Collectively, these findings provide robust empirical justification for prioritizing high-toxicity metals in occupational health policies while recognizing the residual risk experienced by neighboring communities.

Seasonal and Metal-Specific Trends in Dermal Exposure

Analysis of dermal Hazard Index (HI) patterns across seasons highlights clear seasonal modulation of non-carcinogenic risk, with consistently Higher HI values observed during the dry season relative to the rainy season. Metals such as cadmium (Cd), Nickel (Ni), lead (Pb), and Zinc (Zn) were identified as the primary contributors to cumulative dermal risk, consistent with their elevated concentrations in fine dust fractions and known toxicity profiles (Nduka et al., 2019; 2016; Ogbodo et al., 2024; Raimi et al., 2019a; 2023; 2022b; Salihoglu and Salihoglu, 2016; Liu et al., 2006). Boxplot and heat map visualizations (Figures 7-9) reveal that dry-season exposure is characterized by higher median HI values, wider interquartile ranges, and greater variability across sampling sites, indicating that environmental conditions such as low humidity and reduced precipitation amplify dust resuspension and surface accumulation. These findings are in agreement with prior occupational and environmental studies reporting seasonal intensification of dermal exposure under arid or low-precipitation conditions in small-scale automotive and industrial workshops (Ojo et al., 2020; Suleiman et al., 2019; Raimi et al., 2021c; 2023; ORNL, 2021; Morufu et al., 2021b; Reeb-Whitaker et al., 2013). Spatially, sites with intensified workshop activity and limited ventilation (e.g., SSP5, SSP10, SSP15, SSP18) exhibited pronounced HI elevations, emphasizing the interplay between operational practices and environmental dynamics in shaping exposure risk. The metal-specific analysis further underscores that Cd and Ni remain dominant contributors to dermal HI regardless of season, while Pb and Zn contribute moderately, consistent with other studies in similar occupational settings across Nigeria and West Africa (Nduka et al., 2019; 2016; Raimi et al., 2019a; 2023; U.S. Environmental Protection Agency, 2011; Pronk et al., 2006; Reeb-Whitaker et al., 2013; Raheem et al., 2023). The observed seasonal amplification of dermal HI supports the need for season-sensitive risk management strategies, including enhanced Personal Protective Equipment (PPE) usage, dust suppression measures, improved workshop ventilation, and surface cleaning protocols during the dry season when exposure is maximized. Moreover, prioritizing high-toxicity metals in workplace interventions and regulatory oversight can effectively mitigate cumulative exposure risk and prevent potential adverse health outcomes. Collectively, these insights reinforce the importance of integrating seasonal and metal-specific considerations into occupational health risk assessments and intervention planning for informal automobile spray-painting environments.

Multivariate Analysis and Source Attribution

Multivariate analyses, including correlation matrices, Principal Component Analysis (PCA), and regression modeling, provide an integrated perspective on metal co-occurrence patterns and their contribution to cumulative dermal exposure. The correlation analysis (Figure 10) revealed strong positive associations between dermal HI values across the rainy and dry seasons (r = 0.89-0.95), indicating consistent exposure profiles for dominant metals such as Cadmium (Cd), nickel (Ni), and lead (Pb), irrespective of season. This inter-seasonal stability suggests that observed seasonal variations in dermal HI are driven primarily by environmental intensity and operational conditions, rather than random fluctuations, corroborating patterns observed in other occupational dust studies in automotive and industrial contexts (Nduka et al., 2019; 2016; Ogbodo et al., 2024; Raimi et al., 2019a; 2023; 2022b; 2025 Salihoglu and Salihoglu, 2016; Liu et al., 2006; Tomquin et al., 2025b-c; Akabueze and Raimi, 2026). The PCA biplot (Figure 11) reduced the multidimensional dataset into two principal components explaining 70% of total variance (PC1 = 64.2%, PC2 = 5.8%), highlighting clear source-related clustering: Cd, Ni, and Pb formed a distinct cluster consistent with a common anthropogenic origin, likely associated with automotive paint pigments, coatings, and industrial additives, whereas Cu, Zn, and Fe clustered separately, representing background or filler metals with lower acute toxicity. This source differentiation aligns with prior investigations in Nigeria and other LMICs, where PCA effectively distinguished high-toxicity paint metals from ubiquitous environmental metals (Nduka et al., 2019; 2016; Raimi et al., 2019a; 2023; 2022b; U.S. Environmental Protection Agency, 2011; Clinton-Ezekwe et al., 2024; Abiye and Raimi 2025; Awodele et al., 2013; Aribo and Antai 2014; Ojo et al., 2017; Stoleski et al., 2014; Olalekan et al., 2023; Stephen et al., 2022; Morufu et al., 2021a; Tomquin et al., 2025a; Opaminola and Raimi, 2025; Raimi and Ezekwe, 2017; Abiodun and Morufu, 2021 Awogbami et al., 2022; Pronk et al., 2006; Reeb-Whitaker et al., 2013; Raheem et al., 2023). Regression analysis (Figure 12) quantified the relationship between total metal concentration and cumulative dermal HI, yielding a corrected R^2 of 0.18, reflecting moderate predictive power. The initial R^2 value of 0.83 was revised to accurately reflect alignment between the total metal load and site-specific HI calculations, ensuring statistical transparency and preventing overestimation of exposure predictability. Collectively, these multivariate insights confirm the robustness and internal consistency of the dataset, demonstrating the persistent dominance of Cd and Ni in driving dermal exposure risk. The clustering patterns provide empirical support for targeted source control interventions, such as substituting high-toxicity pigments, enforcing dust abatement measures, and implementing enhanced ventilation in workshops. Furthermore, these analyses offer a reproducible framework for future monitoring and predictive modeling in informal automobile spray-painting environments, allowing policymakers and occupational health practitioners to prioritize interventions based on metal-specific and source-related risk profiles (Nduka et al., 2019; Ojo et al., 2020; Ogbodo et al., 2024; Suleiman et al., 2019; Raimi et al., 2019a; 2023; 2022b; Raheem et al., 2023; Fubara et al., 2025; Deinkuro et al., 2021a; Keme-Iderikumo et al., 2024; Morufu et al., 2021b; Salihoglu and Salihoglu, 2016; Liu et al., 2006).

Implications for Policy and Interventions

The findings of this study carry direct implications for occupational and environmental health policy in informal automobile spray-painting contexts. The consistent dominance of cadmium and nickel across both occupational and residential exposures underscores the need for metal-specific regulatory oversight, including the substitution of high-toxicity pigments with safer alternatives. The observed seasonal amplification of dermal and ingestion risk during the dry season highlights the importance of season-sensitive interventions, such as enhanced Personal Protective Equipment (PPE) usage, improved workshop ventilation, dust suppression techniques, and routine surface cleaning protocols. Probabilistic exceedance analyses further demonstrate that both adult workers and nearby residents are at non-negligible risk, emphasizing the need for community-level protective measures, including education, access to safe zones, and monitoring of residential exposure. Collectively, these insights provide a clear framework for prioritizing interventions based on receptor-specific, pathway-specific, and seasonal exposure profiles, ensuring that limited resources are allocated to areas and populations at greatest risk.

Summary of the Findings

This multi-site assessment of automobile spray-paint dust demonstrates that non-carcinogenic and carcinogenic risks are dominated by dermal exposure, with ingestion playing a secondary but non-negligible role. Adult workers consistently experience higher cumulative Hazard Indices (HI) and Incremental Lifetime Cancer Risk (ILCR) than nearby residents due to more frequent and direct contact with contaminated dust. Seasonal variations further modulate risk, with dry-season exposures producing the highest HI and ILCR values across all receptor groups. Multivariate analyses reveal that cadmium, nickel, and lead co-occur and cluster by anthropogenic source, while copper, zinc, and iron contribute minimally to overall risk. Correlation and PCA analyses confirm the robustness and internal consistency of these patterns, and regression modeling indicates a proportional, though moderate, relationship between total metal concentration and cumulative dermal HI. Spatial heterogeneity among sampling sites indicates that local operational practices and workshop layouts are critical determinants of exposure intensity.

Conclusion

In conclusion, informal automobile spray-painting environments in South-Eastern Nigeria represent significant sources of both non-carcinogenic and carcinogenic risk to occupational and residential populations. Dermal exposure dominates the exposure profile, with cadmium and nickel as persistent high-toxicity contributors. Seasonal dynamics and site-specific operational factors modulate exposure intensity, highlighting the importance of adaptive, targeted interventions. The integration of receptor-specific assessment, particle-fraction analysis, and multivariate modeling provides a scientifically robust framework for risk characterization, offering actionable insights for policymakers, occupational health practitioners, and regulatory authorities. Implementing season- and metal-specific mitigation measures will be essential to reduce cumulative lifetime risk and protect both workers and nearby communities from adverse health outcomes.

Recommendations

Short-Term Recommendations (Immediate, 0-12 Months)

i. Enhanced Personal Protective Equipment (PPE): Mandate the use of gloves, overalls, and face shields for all spray-paint operators to minimize dermal contact with cadmium, nickel, and lead-rich dust
ii. Improved Dust Control Practices: Implement immediate housekeeping measures, including regular sweeping, vacuuming, and dampening of surfaces to reduce settled dust resuspension, particularly during the dry season when dermal HI peaks
iii. Awareness and Training: Conduct brief workshops and educational sessions for both workers and nearby residents, emphasizing hand hygiene, minimizing hand-to-mouth contact, and recognizing high-risk operational practices
iv. Localized Monitoring: Initiate site-level dust monitoring to identify hotspots with elevated HI and ILCR values, allowing rapid mitigation at the most contaminated sites

Mid-Term Recommendations (1-3 Years)

i. Engineering and Ventilation Improvements: Retrofit informal and semi-formal workshops with improved ventilation systems, including localized exhausts and air filtration, to reduce airborne dust and inhalation risks
ii. Metal Substitution Strategies: Encourage the adoption of lower-toxicity paint formulations by collaborating with paint suppliers and regulatory authorities, focusing on minimizing cadmium and nickel content
iii. Community Exposure Mitigation: Establish buffer zones or safe perimeters (≥100 m) between spray-painting operations and residential areas, coupled with community engagement to reduce inadvertent residential exposure
iv. Routine Occupational Health Surveillance: Introduce periodic health screening for workers, including dermatological and biomonitoring assessments, to track early signs of heavy-metal exposure

Long-Term Recommendations (3-10 Years)

i. Regulatory Framework Strengthening: Develop and enforce formal regulations governing small-scale automotive spray-painting operations, incorporating receptor-specific risk thresholds and seasonal exposure considerations
ii. Infrastructure and Workshop Formalization: Support the transition from informal open-air setups to semi-enclosed or enclosed workshop designs, integrated with engineered controls and standardized waste management protocols
iii. Longitudinal Environmental and Health Monitoring: Establish continuous environmental and biomonitoring programs to track trends in HI, ILCR, and metal concentrations, providing data for adaptive policy adjustments
iv. National Risk Awareness Campaigns: Expand risk communication beyond local clusters to state and regional levels, highlighting occupational and residential risks of heavy-metal exposure in the automotive sector

These recommendations leverage the study's receptor-specific, seasonal, and metal-specific findings, integrating multivariate analyses to ensure interventions are targeted, evidence-based, and scalable. Implementing this tiered framework will reduce both non-carcinogenic and carcinogenic risks among workers and nearby communities, providing a sustainable pathway for occupational health improvement in informal spray-painting environments.

Public Health Significance

The present study demonstrates that informal automobile spray-painting operations in South-Eastern Nigeria constitute a substantial public health concern, with both adult workers and nearby residents exposed to elevated non-carcinogenic and carcinogenic risks through dermal and incidental ingestion pathways. Dermal exposure dominates, with cadmium, nickel, and lead consistently driving cumulative hazard indices, while seasonal variation amplifies risk during the dry season due to enhanced dust generation and surface accumulation. Probabilistic analyses reveal that the likelihood of exceeding safety thresholds is high, with 92-98% of workers and 65-88% of nearby residents at risk for non-carcinogenic effects, and 78-89% exceeding carcinogenic ILCR thresholds. Spatial heterogeneity across workshops highlights the influence of operational practices, ventilation, and site design on exposure intensity, while multivariate analyses confirm persistent co-occurrence of high-toxicity metals and validate source-related clustering. Collectively, these findings underscore the urgent need for receptor-specific, season-sensitive interventions, metal-targeted regulatory oversight, and continuous occupational and residential exposure monitoring, emphasizing that informal automotive painting operations pose not only localized occupational hazards but also broader environmental health challenges with significant implications for policy, risk management, and community well-being.

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Authors Contributions

All authors collaboratively developed the concept and design of the study. They were collectively involved in data collection and analysis, ensuring a comprehensive approach to the research. Each author contributed to drafting the initial article, bringing their unique perspectives and expertise to the writing process. Furthermore, all authors participated in interpreting the data, providing critical insights that shaped the study's conclusions. They thoroughly reviewed the content of the article, ensuring accuracy and coherence, and ultimately approved the final version for publication. This collaborative effort highlights the integral contributions of each author at every stage of the research.

Ethics

No direct human samples were collected. However, interviews and observational data collection involving spray painters were covered under ethics approval (Ref: MOUAU/REC/2025/1012) granted by the Research Ethics Committee, Michael Okpara University of Agriculture, Umudike, Nigeria. All participants gave informed consent for observational involvement. Laboratory work adhered to standard safety protocols (PPE, fume hoods, waste segregation).

Competing of Interest

The authors affirm that they have no competing interests to declare. There are no conflicts of interest that could influence the objectivity or impartiality of the research findings presented in this study.

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