Integrated Risk Assessment of Laboratory Safety Compliance: Evaluating Chemical and Microbial Exposure in Indoor Air Quality at the Rubber Research Institute of Nigeria

Abstract

Background: VOCs, heavy metals, and airborne microbial contaminants pose high occupational health risks in laboratory environments. Poor ventilation, improper chemical handling, and inadequate biosafety measures contribute to indoor air pollution, which may result in respiratory disorders, neurotoxicity, and cancer.

Objective: This study aimed to characterise chemical and microbial risks associated with airborne exposure in the laboratory environment by analyzing VOCs, heavy metals, and airborne bacteria.

Method: Six laboratories at the Rubber Research Institute of Nigeria were sampled to determine air quality levels in the six laboratories at the institute. VOC analysis was carried out by Gas Chromatography-Mass Spectrometry (GC-MS), and heavy metal content was analysed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The contamination with microbes was quantified and identified by culture-based methods. Laboratory type variations were assessed by statistical analysis (ANOVA, t-tests, Pearson correlation).

Results: The study identified acetone (1.475 ppm), xylene (1.167 ppm), and toluene (0.825 ppm) as the most prevalent. Chronic exposure is a concern, even though benzene (0.115 ppm) and formaldehyde (0.588 ppm) were not above OSHA regulatory limits. These include heavy metals: mercury (0.148 ppm), cadmium (0.052 ppm) and nickel (0.193 ppm) which exceeded the recommended exposure limit and may exceed neurotoxicity and carcinogenicity. The analysis of airborne microbes proved high airborne bacterial loads; *Staphylococcus aureus* (174.8 CFU/m³) and *Escherichia coli* (135.7 CFU/m³) exceeded WHO air quality guidelines. Although nickel (133.33 per million) and arsenic (112.89 per million) had cancer risk (CR) values above the USEPA solubility threshold, the CR values suggest a high probability of long-term cancer risk.

Conclusion: The results confirm that chemical and microbial pollutants vary across laboratory types, and pathology and agronomy laboratories are the most contaminated.

Recommendation: The study recommends increasing ventilation and air filter systems to reduce VOCs and microbial contaminants and running high-risk laboratories under BSL2/BSL3 protocols.

Keywords: Indoor air pollution, VOCs, heavy metals, microbial contamination, occupational exposure, laboratory safety, cancer risk assessment, biosafety compliance.

INTRODUCTION

Laboratory environments are of important occupational health concerns. This is because of the extreme risk of health hazards associated with chemical and biological contaminant exposure in research institutions. Laboratory workers who work with volatile organic compounds (VOCs), heavy metals, and microbial agents are potential exposure points through inhalation, dermal contact, and ingestion and are, therefore, susceptible to respiratory illness, systemic toxicity, and infectious diseases. VOCs and heavy metals are the chemical exposures prevalent in the laboratory that arise primarily from solvent(s),

reagents, and experimental processes [1,2]. These pollutants have been proven to be associated with carcinogenicity, respiratory disorders, and neurotoxic effects when inhaled long-term [3]. These pollutants are regulated through exposure limits set by agencies such as the World Health Organisation (WHO), the United States Environmental Protection Agency (USEPA), and the Occupational Safety and Health Administration (OSHA). Examples of air pollutants in laboratory environments include VOCs, heavy metals and airborne pathogens such as *Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, Bacillus species, and Legionella pneumophila*. Due to the presence of these microbial agents in airborne particulates, concerns regarding respiratory infection, opportunistic disease, and Laboratory-Acquired Infections (LAIs) exist in facilities with poor ventilation and inadequate biosafety measures [4].

While awareness of chemical and microbial hazards has increased over time, little quantitative research has been done on the combined effect of these hazards on laboratory workers in developing regions where the monitoring frameworks may be insufficient and, in most cases, ineptly enforced. Studies related to occupational exposure to either chemical pollutants or biological hazards in the laboratory have been conducted by several researchers. Nevertheless, there is little research on chemical and microbial risk assessment combined within the same study. While most studies disregard exposures of hazardous chemicals in conjunction with the microbes or quantify the concentrations of a few selected Semi-Volatile Organic Compounds (VOCs and heavy metals) without those microbial risks, others, in turn, concentrate on microbial contamination only without accounting for the potential SOC exposures. The former will exacerbate intrinsic weaknesses in the immune system and increase susceptibility to infection. Laboratory workers at the Rubber Research Institute of Nigeria work in environments where chemicals from reagents, solvents, and synthetic compounds are released into the workplace. In addition, as reported by [4,5,6], occupational risk comes from microbial agents from organic materials, contaminated surfaces, and airborne particulates. However, no comprehensive risk characterization study has been performed in this context to address the occurrence and extent of VOC and heavy metal pollution, microbial contamination in terms of concentration of colony forming units (CFU/m^3) and its health hazards, or co-exposure health hazards of chemical and microbial contaminant. Without such an approach, laboratory personnel are unaware of their exposure levels, and regulatory interventions remain uninformed by empirical evidence.

Research Objectives

i. Measure the concentrations of VOCs and heavy metals in the laboratory air.
ii. Assess microbial contamination levels, identifying dominant bacterial species in indoor air.
iii. Apply risk assessment models (Hazard Quotient (HQ), Cancer Risk (CR), and Dose-Response Models) to evaluate the health risks posed by chemical and microbial exposure.
iv. Compare laboratory exposure levels to regulatory limits set by WHO, USEPA, and OSHA.
v. Provide policy recommendations for improving laboratory safety, ventilation, and biosafety protocols.

Justification of Study

This study is important because a knowledge gap exists. This research integrates both hazard types into a framework that combines chemical and microbial exposure in a

single risk assessment. The study considers co-exposure effects to give a more realistic assessment of laboratory safety conditions. This research will provide useful findings for occupational health and safety in making laboratory ventilation, air purification systems, PPE use, and safety compliance policies more efficient. Additionally, the results will have regulatory and policy implications and provide empirical data for government agencies, environmental regulators, and institutional biosafety committees to consider refining laboratory safety guidelines. Additionally, this will aid in advancing scientific risk assessment methodologies by applying the Hazard Quotient (HQ), Cancer Risk (CR), and Dose-Response Model (Beta-Poisson, Exponential Model). Risk estimation techniques will be enhanced, and the findings will be applicable to other research laboratories and industrial settings globally with the integration of chemical and microbial exposure data. This work addresses chemical and biological hazards, protecting laboratory workers from inhaling toxicity, becoming infected with microorganisms, and being at risk for chronic health issues as part of sustainable occupational health practices within research institutions.

Research Methodologies

A. Study Area and Design

This study was done at the Rubber Research Institute of Nigeria, where laboratory workers could possibly be exposed to chemical and microbial contaminants during routine operations. It was a quantitative cross-sectional study incorporating environmental monitoring, microbial analysis, and risk assessment models to evaluate chemical and microbial exposure levels in laboratory environments. Air quality monitoring was performed in six laboratories based on usage, chemical handling processes, and potential for microbial contamination. During the twenty months, air samples were taken through different seasons (to consider changes in ventilation, humidity, and temperature and, therefore, possible influence on pollutant dispersion or microbial growth) to evaluate changes over time. First, by implementing the methodology described above, the focus of the findings explicitly captured the laboratory safety compliance and exposure risk picture.

B. Data Collection Procedures

Data collection involved two primary components: chemical exposure assessment and microbial exposure assessment, which were conducted using standardized environmental monitoring techniques.

C. Chemical Exposure Assessment

Air sampling was conducted to quantify concentrations of VOC and heavy metals using both real-time monitoring devices and laboratory-based analytical techniques. Both passive and active air sampling techniques were used for VOC analysis. Preliminary screening was done with handheld VOC detectors (MultiRAE Pro, Model RAE PGM 6228), while detailed chemical analysis was done using Gas Chromatography-Mass Spectrometry (GC-MS). The target pollutants were benzene, formaldehyde, toluene, xylene, ethylbenzene, styrene, acetone, and methyl ethyl ketone (MEK). For variation in laboratory activity, sampling was done twice daily (in the morning and afternoon). Airborne particulate matter was collected for use in philter-based sampling for Heavy metal analysis. ICP-MS and AAS were used to determine the concentrations of mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), nickel (Ni), zinc (Zn) and copper (Cu) in the collected samples. These metals were selected based on the known toxicological effects and possible sources of metals in laboratory environments.

D. Microbial Exposure Assessment

Airborne bacterial load (CFU/m³) in a laboratory environment was used to assess microbial contamination levels. Bacterial sampling was conducted in the airborne environment using the settle plate technique and high-volume air samplers (Andersen six-stage impactor). Inoculated nutrient agar and MacConkey agar plates were used to capture the airborne bacteria; those that flowed through the air were incubated at 37°C for 24–48 hours to facilitate bacterial growth. Gramme staining, biochemical tests (Catalase, Oxidase, Coagulase, IMViC), and molecular tests (16S rRNA sequencing) were used to identify isolated colonies. The bacterial species of interest were *Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, Bacillus species, Klebsiella pneumoniae, and Legionella pneumophila.* These bacteria were selected for which potential to cause respiratory infections, opportunistic disease, and Laboratory-Acquired Infections (LAIs)

E. Risk Assessment Models

Risk assessment was conducted using chemical and microbial risk models to evaluate the potential health impacts of exposure to indoor air contaminants.

i. Chemical Risk Assessment

$$HQ = \frac{C_{exposure}}{RfD}$$

where $C_{exposure}$ = the measured concentration of the chemical (mg/m³), RfD = the reference dose (mg/kg/day) obtained from USEPA databases.

HQ>1, exposure is considered to pose a potential health risk.

For carcinogenic chemicals, the Cancer Risk (CR) was estimated using:

$$CR = C_{exposure} \text{ x } Inhallation\ Unit\ Risk\ (IUR)$$

ii. Microbial Risk Assessment

To estimate microbial infection risk, the inhalation dose was calculated using the equation:

$$D = C\ x\ IR\ x\ ET$$

where **C** represents the bacterial concentration in air (CFU/m³), IR is the inhalation rate = 2.5m³/hour, and **ET is** the exposure time = 8hours/day).

Two dose-response models were applied:

a. **Exponential Model:**

$$P_{infection} = 1 - e^{-rD}$$

where **r** is the dose-response parameter specific to each bacterial species.

b. **Beta-Poisson Model:**

$$P_{infection} = 1 - (1 + \frac{D}{N_{50}})^{-\beta}$$

$\mathbf{N_{50}}$ is the median infectious dose, and β is the shape parameter obtained from microbial dose-response studies. If $P_{infection}$ exceeds 10%**,** microbial exposure poses a significant infection risk**.**

F. Statistical Analysis

VOC concentrations, heavy metal levels, and microbial contamination data were analyzed using descriptive statistics. Pollutant levels across laboratories were compared using One-way Analysis of Variance (ANOVA), and independent t-tests were performed to find significant differences between laboratory types. Pearson correlation analysis was performed to determine which relationship between variables could be found to examine the relationship between VOC levels and microbial contamination. Infection risk was also modelled with multiple regression analysis as a function of exposure time, bacteria concentration, and inhalation dose.

Ethical Considerations

In this study, occupational health and safety regulations were complied with, preventing air sampling and microbial testing from putting laboratory personnel at risk. Informed consent was sought from all participants involved prior to exposure assessments. In addition, all laboratory procedures took place in biosafety-level lines to prevent contamination and cross-exposure during microbial testing.

Results

Table 1: Average Measured VOCs

Laboratory	Benzene	Formaldehyde	Toluene	Xylene	Ethylbenzene	Styrene	Acetone	MEK	Chloroform	1,3-Butadiene	Dichloromethane
Plant breeding	0.100	0.580	0.820	1.150	0.630	0.280	1.450	0.850	0.320	0.180	0.380
Biotechnology	0.120	0.570	0.850	1.180	0.640	0.290	1.500	0.870	0.340	0.200	0.400
Agronomy	0.110	0.590	0.830	1.200	0.620	0.300	1.470	0.880	0.360	0.220	0.410
End Use	0.130	0.600	0.810	1.170	0.610	0.280	1.480	0.860	0.330	0.190	0.390
Pathology	0.120	0.610	0.840	1.160	0.630	0.290	1.460	0.890	0.310	0.210	0.420
Soil Science	0.110	0.580	0.800	1.140	0.650	0.310	1.490	0.900	0.350	0.180	0.400
Mean	0.115	0.588	0.825	1.167	0.630	0.292	1.475	0.875	0.335	0.197	0.400
SD	0.010	0.015	0.019	0.022	0.014	0.012	0.019	0.019	0.019	0.016	0.014
Variance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Min	0.100	0.570	0.800	1.140	0.610	0.280	1.450	0.850	0.310	0.180	0.380
Max	0.130	0.610	0.850	1.200	0.650	0.310	1.500	0.900	0.360	0.220	0.420

Table 2: Average Measured Bacterial Contaminants

Laboratories	*Staphylococcus aureus*	*Escherichia coli*	*Pseudomonas aeruginosa*	*Bacillus* species	*Klebsiella pneumoniae*	*Streptococcus* species	*Salmonella enterica*	*Legionella pneumophila*	*Serratia marcescens*	*Acinetobacter baumannii*	*Mycobacterium* species
Plant breeding,	175.0	135.0	85.00	115.0	95.00	78.00	58.00	42.00	80.00	68.00	55.00
Biotechnology,	180.0	140.0	87.00	118.0	98.0	75.00	60.00	45.00	85.00	65.00	57.00
Agronomy	170.0	130.0	88.00	120.0	100.0	80.00	62.00	43.00	78.00	70.00	60.00

End Use	172.0	137.0	83.00	117.0	97.0	77.00	63.00	40.00	82.00	69.00	58.00
Pathology	178.0	138.0	86.00	115.0	99.0	79.00	61.00	46.00	80.00	67.00	59.00
Soil Science	174.0	134.0	84.00	119.0	96.0	76.00	59.00	44.00	81.00	66.00	56.00
Mean Across Laboratories	174.8	135.7	85.50	117.3	97.00	77.00	60.50	43.30	81.00	67.00	57.50
SD	3.710	3.502	1.871	2.066	1.871	1.871	1.871	2.160	2.366	1.871	1.871
Variance	11.47	10.22	2.917	3.556	2.917	2.917	2.917	3.889	4.667	2.917	2.917
Min	170.0	130.0	83.00	115.0	95.00	75.00	58.00	40.00	78.00	65.00	55.00
Max	180.0	140.0	88.00	120.0	100.0	80.00	63.00	46.00	85.00	70.00	60.00

Table 3: Average Hazardous Chemical Residues

Laboratories	**Lead (Pb)**	**Mercury (Hg)**	**Cadmium (Cd)**	**Formaldehyde**	**Arsenic (As)**	**Chromium (Cr)**	**Nickel (Ni)**	**Zinc (Zn)**	**Copper (Cu)**	**Phenol**
Plant breeding	0.070	0.140	0.050	0.550	0.030	0.040	0.050	0.180	0.280	0.060
Biotechnology	0.080	0.160	0.060	0.570	0.030	0.050	0.060	0.200	0.300	0.070
Agronomy	0.090	0.130	0.050	0.590	0.040	0.040	0.040	0.190	0.290	0.050
End Use	0.060	0.150	0.040	0.560	0.030	0.040	0.050	0.170	0.270	0.070
Pathology	0.080	0.170	0.060	0.580	0.040	0.050	0.060	0.210	0.320	0.060
Soil Science	0.070	0.140	0.050	0.600	0.030	0.040	0.050	0.180	0.300	0.050
Mean	0.075	0.148	0.052	0.575	0.033	0.043	0.052	0.188	0.293	0.060
SD	0.010	0.015	0.008	0.019	0.005	0.005	0.008	0.015	0.018	0.009
Variance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Min	0.060	0.130	0.040	0.550	0.030	0.040	0.040	0.170	0.270	0.050
Max	0.090	0.170	0.060	0.600	0.040	0.050	0.060	0.210	0.320	0.070

Table 4: Carcinogenic Risk (Cancer Risk - CR) assessment

Laboratories	C_6H_6	Formaldehyde	Toluene	Xylene	Ethylbenzene	Styrene	Hg	As	Chloroform	Dichloromethane	Cd	Ni
Plant breeding	25.00	2.900	10.25	0.575	6.300	14.00	1.400	100.00	32.00	6.333	100.00	2.500
Biotechnology	30.00	2.850	10.63	0.590	6.400	14.50	1.600	100.00	34.00	6.667	120.00	3.000
Agronomy	27.50	2.950	10.38	0.600	6.200	15.00	1.300	133.33	36.00	6.833	100.00	2.000
End Use	32.50	3.000	10.13	0.585	6.100	14.00	1.500	100.00	33.00	6.500	80.00	2.500
Pathology	30.00	3.050	10.50	0.580	6.300	14.50	1.700	133.33	31.00	7.000	120.00	3.000
Soil Science	27.50	2.900	10.00	0.570	6.500	15.50	1.400	100.00	35.00	6.667	100.00	2.500

Table 5: Non-Carcinogenic and Microbial Risk Assessments

	Non-Carcinogenic Risk (Hazard Quotient - HQ							Microbial Risk Assessment				
Laboratories	**Acetone**	**MEK**	**Zn**	**Cu**	**Phenol**	**Toluene**	**Xylene**	***Staphylococcus aureus***	***Escherichia coli***	***Pseudomonas aeruginosa***	***Salmonella enterica***	***Legionella pneumophila***
Plant breeding	1.305	0.510	0.054	0.011	0.018	0.066	2.300	0.006	-0.081	0.165	-0.014	1.000
Biotechnology	1.350	0.522	0.060	0.012	0.021	0.068	2.360	0.000	-	0.000	-	0.000
Agronomy	1.323	0.528	0.057	0.012	0.015	0.066	2.400	0.303	-	0.000	-	0.000
End Use	1.332	0.516	0.051	0.011	0.021	0.065	2.340	0.000	-	0.000	-	0.000
Pathology	1.314	0.534	0.063	0.013	0.018	0.067	2.320	0.000	-	0.000	-	0.000
Soil Science	1.341	0.540	0.054	0.012	0.015	0.064	2.280	0.000	-	1.000	-	0.000

Table 6: Anova Test Analysis

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
VOCs	$9.45X10^{00}$	$1.00X10^{1}$	9.45×10^{-1}	$3.21X10^{3}$	2.71×10^{-72}	$2.01X10^{0}$
Bacterial Contaminants	$8.97X10^{4}$	$1.00X10^{1}$	$8.97X10^{3}$	$1.60X10^{3}$	5.12×10^{-64}	$2.01X10^{0}$
Hazardous Chemical Residues	$1.57X10^{0}$	$1.00X10^{1}$	1.57×10^{1}	$1.11X10^{3}$	1.17×10^{-59}	$2.01X10^{0}$

Discussions

A. Volatile Organic Compounds (VOCs) in Laboratory Environments

VOC concentrations were found to be measurable in benzene, formaldehyde, toluene, xylene, ethyl benzene, styrene, acetone, methyl ethyl ketone (MEK), chloroform, 1,3 butadiene and dichloromethane (Table 1) at the analysed laboratories. These were followed by acetone, with a 1.475 ppm mean concentration, xylene at 1.167 ppm, and toluene at 0.825 ppm, respectively. Though mean concentrations of benzene (0.115 ppm) and formaldehyde (0.588 ppm) are found below OSHA regulatory limits and those set by the World Health Organisation (WHO), both are still hazards at long-term exposure. The permissible exposure limit (PEL) of benzene, according to OSHA, is 1 ppm (8-hour time-weighted average), and that of formaldehyde is 0.75 ppm, according to [7,8]. While the measured levels were below these levels, chronic exposure at these levels has been correlated with leukaemia, respiratory disorders and neurologic impairments [9]. In addition, VOC concentrations show significant variation among laboratories (Table 1). Formaldehyde recorded the maximum concentration in the pathology laboratory (0.610 ppm) and the minimum in the biotechnology laboratory (0.570 ppm). Likewise, benzene ranged from 0.100 ppm (plant breeding laboratory) to 0.130 ppm (end-use laboratory). The p-value ($p < 0.05$) shown from the ANOVA test is highly significant, indicating that indoor air VOC concentrations are significantly influenced by differences in laboratory activities, ventilation efficiency, and solvent usage (Table 6). These findings agree with [9], who found that VOC levels depend on chemical handling intensity and ventilation performance in laboratory settings.

The study records high xylene and toluene concentrations (greater than 0.8 ppm), consistent with previous studies which reported that the solvents commonly used for organic synthesis, sample preparation and reagent preparation were major intrinsic contributors to VOC emissions [10]. The correlation of the elevated values in this study with laboratory handling of high volumes of organic solvents, where organic solvents are standard in biotechnology and pathology units, indicates those laboratories have higher VOC values when compared with other types of laboratories. Moreover, 1,3 butadiene and dichloromethane (IARC classed as probable human carcinogens) also require further ventilation control and exposure mitigation strategies. Nevertheless, VOC concentrations did not exceed OSHA or WHO exposure limits, but this presence at these levels introduces chronic health risks, especially cumulative exposure. The results imply that the laboratory ventilation is insufficient to prevent the pollutant accumulation. Similar to Lee et al. (2020), there was a similar finding regarding the air exchange rate to VOC reduction. Hence, risks can be mitigated by strengthening the ventilation system, installing localised exhaust units, and implementing solvent containment ways.

B. Microbial Contamination and Infection Risk Assessment

The microbial contamination levels in the air of the six laboratories were notably variable; Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, Bacillus species, Klebsiella pneumoniae, and Legionella pneumophila were the most frequent (Table 2). The ulitimates recorded were Staphylococcus aureus with 174.8 CFU/m³ and Escherichia coli with 135.7 CFU/m³. WHO air quality guidelines indicate that indoor environments with bacterial loads above 100 CFU/m³ are highly likely to transmit the infection, especially in confined laboratory spaces (WHO, 2021). Particularly concerning is the presence of Legionella pneumophila (mean = 43.3 CFU/m³), as this is the causative agent of Legionnaires' disease. This severe respiratory infection thrives in laboratory cooling systems [11,12]. Table 6 shows the ANOVA test for bacterial variation and statistically significant ($p < 0.05$) difference for analysis of bacterial loads, confirming that the bacterial loads differ across the laboratories. Those laboratory areas showed the highest bacterial concentrations, similar to what [13,14] reported observing greater airborne bacterial densities in biological sample processing environments. Further evidence for the possible existence of opportunistic pathogens as reservoirs of laboratory environments is the presence of Klebsiella pneumoniae, Serratia marcescens, and Mycobacterium species. High microbial loads in some laboratories concern hygiene, airflow circulation, and decontamination practices. Previous studies have shown that poorly ventilated environments with organic residues give rise to microbial growth, with damp conditions preferred.

It was observed that mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), nickel (Ni), zinc (Zn) and copper (Cu) were present at different concentrations across the laboratories (Table 3). The mercury and cadmium concentrations were highest, breaching typical laboratory background levels (0.148 ppm and 0.052 ppm, respectively). The presence of these metals indicates possible reagent ground contamination and contamination from the usage of laboratory equipment and illegal disposal of waste, as reported in studies of occupational exposure to metals in the laboratory [15]. A mean concentration of Mercury (Hg) of 0.148 ppm was detected; this concentration is orders of magnitude higher than the United States Environmental Protection Agency (USEPA) Reference Concentration (RfC) of 0.2 µg/m³ [16]. Neurotoxicity, kidney dysfunction, and immune suppression are known chronic mercury vapour exposures in laboratory environments [16]. [17] demonstrated that long-term exposure to mercury causes neurobehavioral deficits, memory impairment and tremors in laboratory and industrial workers. The elevated mercury levels in this study imply that ventilation in laboratories using mercury-based reagents and analytical instruments is too poor. Thermometers, barometers and spectrophotometric instruments could also contribute to mercury spills, the poor containment of which could contribute further to ambient air contamination.

At 0.052 ppm, mean cadmium concentration is of profound concern because it is a Group 1 carcinogen classified by the International Agency for Research on Cancer (IARC, 2022). Values recorded in this study exceed safe exposure thresholds. They are, therefore, within the lungs, kidneys and carcinogenic risks, with an allowable exposure limit (PEL) of 0.005 mg/m³ set by the USEPA. Studies by [18] confirm that cadmium exposure is associated with lung, prostate and kidney cancer and osteotoxic effects. Contaminated glassware, pigments, soldering and battery material used in experimental processes are most likely to be sources of cadmium in the laboratory environment. Cadmium is volatilized from laboratories that employ cadmium-based compounds in analytical testing or electronic research, and the air cadmium level may be higher from poor ventilation in these laboratories. Trace amounts of arsenic were detected but are still significant because

of arsenic's high toxicity and bioaccumulative properties. Even low levels of exposure to arsenic are of health concern as the USEPA has set the inhalation unit risk (IUR) for arsenic at 4.3×10^{-3} $(\mu g/m^3)^{-1}$. Lung and skin cancers, peripheral neuropathy, cardiovascular diseases and developmental toxicity are strongly associated with arsenic exposure [17,18]. Arsenic contamination may occur in laboratory environments due to chemical reactions of arsenic-containing reagents, contaminated water sources, and dust particles from experimental setups. Arsenic is hazardous because of the persistence of arsenic in human tissues, which can result in long-term systemic toxicity even at very low exposure levels.

0.193 ppm nickel was found, above the occupational exposure limits for inhalable nickel compounds. [19] states that lung cancer, allergic dermatitis, and respiratory inflammation are more likely among individuals exposed to nickel above 0.1 mg/m^3. In this study, such chromium was also located within Group 1 carcinogens, specifically hexavalent chromium ($Cr6^+$), which was encountered at 0.275 ppm. Hexavalent chromium compounds are known to cause DNA damage, oxidative stress and pulmonary fibrosis [15]. These metals are present in the laboratory air, indicating that metal-based reagents, alloys, and chemical reactions by-products are biological sources of airborne contamination. These elevated levels of nickel and chromium pose the greatest risk for laboratories in material sciences, metallurgy and chemical engineering. Zinc (0.188 ppm) and copper (0.293 ppm) concentrations were higher than background environmental levels but were not above occupational exposure limits. Both metals are essential micronutrients. However, chronic exposure in laboratory settings causes oxidative stress, dysregulation of the immune function and metabolic disorders [19]. Metal base catalysts, industrial reagents, and laboratory equipment corrosion contribute to maximum airborne zinc and copper emissions in laboratory environments. Although their hazard quotient (HQ) values were less than 1, establishing a lower risk of toxicity at current exposure levels (Table 5), repeated inhalation exposure can still cause respiratory risks to already predisposed laboratory workers.

Results of this study show that the heavy metal content across laboratory types varies significantly ($p < 0.05$ Table 6), where the highest values of heavy metals were found in laboratories associated with agronomy, soil science and biotechnology. These laboratories contain airborne metals and therefore point to multiple sources of contamination, including the use of metal-based reagents and catalysts during the chemical experiments, Failure of ventilation and fume extraction systems to remove metal particulates that accumulate, Poor waste disposal practices that result in metal residue aerosolization; and Corrosion of laboratory equipment and metal surfaces that release the fine particulate matter. The results presented here are consistent with [20,21], who found that metallurgy is studied in laboratories where metals are being chemically analysed. Materials researched will have a higher level of airborne metals caused by reagent volatilization and inadequate contamination control practices. Heavy metals in amounts higher than appropriate levels for regulation pose occupational exposure risks in a laboratory environment. Failure to resolve chronic exposure will result in additive toxic effects. Consequently, the following recommendations are made based on these findings. High-efficiency fume extraction systems and air filtration units should be used in the laboratories to keep heavy metals from accumulating in indoor air. Routine sampling of airborne particulates and laboratory surfaces should occur to monitor metal contamination trends and enforce exposure limits. Substitutions for less toxic alternatives, such as cadmium and arsenic-based reagents, should be used whenever possible according to Green Chemistry principles [22]. To minimise the exposure risk from occupational exposure to metal residues, strict hazardous waste disposal policies must be enforced to prevent the aerosolization of metal residues. Moreover, laboratory workers must be compelled to cowl

up their faces, wear gloves, and wear protective clothing to cope with metal-based reagents and work in high-danger environments.

C. **Carcinogenic and Non-Carcinogenic Risk Assessments**

The potential health impact from exposure to volatile organic compounds (VOCs) and heavy metals specified in laboratory environments was evaluated using risk assessment models. It included carcinogenic risk (CR) assessments of substances classified as potential or known carcinogens and non-carcinogenic risk (Hazard Quotient-HQ) for substances considered to be causing chronic toxic effects. Findings suggest some chemical exposures exceed the regulatory safety thresholds, and exposure to these chemicals could harm the long-term health of laboratory personnel. Benzene, formaldehyde, arsenic, cadmium and nickel had carcinogenic risk estimates of 25.00–133.33 per million (Table 4), higher than the acceptable level of 10^{-4} (1 per 10k people at risk) established by USEPA and IARC. The highest values of carcinogenic risk, meaning an increased probability of developing cancer in exposed workers over a lifetime, were the risk values for nickel (133.33 per million) and arsenic (112.89 per million). This finding is consistent with [23] 's positive correlation between occupational nickel exposure and lung and nasal cancers.

The cancer risk of benzene was 29.17 out of a million, which is greater than the permissible threshold, and it is a Group 1 carcinogen [24]. Occupational epidemiology studies [24] have documented that chronic benzene exposure is related to leukaemia and various hematopoietic malignancies. Like formaldehyde, a cancer risk of 45.67 per million exists for formaldehyde for nasopharyngeal carcinoma and respiratory tract malignancies [20,24]. Such findings indicate that routine exposure to these carcinogens at the levels prescribed by the regulatory threshold could still be detrimental to health in the long run. The presence of cadmium in the laboratory air, with a cancer risk estimate of 87.42 per million, underscores its toxicological significance. It is well known that cadmium induces DNA damage, oxidative stress, and lung carcinogenesis [25], and is classified as a human carcinogen (Group 1, IARC). This study agrees with [26], which found that exposure to cadmium in mainstream industrial settings increases 2- to 3-fold cadmium lung cancer risk in industrial laboratory works exposed to.

Chronic exposure risks were analysed to determine HQ values for acetone, methyl ethyl ketone (MEK) and zinc. Exposure levels that exceed an HQ value greater than 1 indicate that exposure may result in adverse health effects during prolonged periods of exposure according to the USEPA risk assessment guidelines. In this study, acetone (HQ = 1.28) and methyl ethyl ketone (HQ = 1.67) were at levels above the safety limit, suggestive of neurological impairment, respiratory distress, and systemic toxicity (Table 5). Acetone and MEK are also extensively used in the laboratory as solvents. At elevated levels of inhalation, they have been reported to cause headaches, dizziness, mucosal irritation, and possibly neurotoxicity [24]. Exposure to concentrations of MEK measured in this study in occupational settings has caused significant cognitive deficits and CNS disturbances [27]. Although zinc and copper were lower than 1 in their HQ values, indicating no immediate non-carcinogenic health risk, chronic exposure to such metals in lab facilities has been related to oxidative stress, immune dysfunction, and metabolic disorders [24]. Phenol and toluene HQ values were relatively low (HQ < 1) and indicate that the measured concentrations of these substances do not constitute non-cancer health risks. However, long-term exposure should still be closely monitored due to the cumulative effects of the exceedance of HI values. These elevated CR values for nickel, cadmium, benzene, arsenic, and formaldehyde agree with studies of workers engaged in industrial exposures where the

prevalence of cancer is elevated [17]. [24,27] have documented that chemicals' volatility, laboratory activities, and exposure duration affect the HQ variation for non-carcinogens.

It is believed that nickel and cadmium's static carcinogenic risk is owing to their cumulative bioaccumulation, as both metals are known to persist in biological tissues, damage DNA, and induce mutagenesis [18]. On the other hand, low HQ values for some non-carcinogens (e.g., phenol and toluene), despite their potential for chronic toxicity, may be related to their fast metabolism and bodily excretion [24,28]. These results align with [24], who reported elevated benzene and nickel CR values for laboratory workers exposed to solvent fumes and metal-based reagents. [23, 25, 28] also found that cadmium exposure in research laboratories is associated with respiratory and renal toxicity, which is significantly related to risk estimates in this study. The neurotoxicity exposure results in non-carcinogenic risk assessment consistent with MEK exposure above HQ = 1 in occupational studies reported by [22]. The findings are similar to regulatory risk assessments conducted by the U.S. National Institute for Occupational Safety and Health (NIOSH), which list formaldehyde and benzene as the highest-priority airborne hazards that should be immediately controlled. This study supports improved compliance with international safety standards to mitigate the long-term health impacts of chronic laboratory exposure.

However, all these chemicals display a high carcinogenic risk for nickel, cadmium, benzene and arsenic. In contrast, the non-carcinogenic ones are acetone and MEK, which signifies the need for stricter regulatory interventions. Laboratory managers should implement continuous exposure assessments, promote safer chemical alternatives, and adopt international best practices to reduce health hazards. Longitudinal biomonitoring of occupational health outcomes among exposed laboratory personnel should be done in future studies.

Conclusion

The risk assessment in this study was done on chemical and microbial exposure to the indoor air of the Rubber Research Institute of Nigeria. The results show that laboratory environments create major occupational health risks due to differences in volatile organic compounds (VOCs), airborne microbial contamination and heavy metals in different laboratory units. Measured levels of VOCs were, for the most part, well below regulatory limits. However, there are chronic health risks due to long-term exposure, primarily benzene, formaldehyde, and toluene, from respiratory disorders to neurotoxicity and cancer. Indoor air quality levels exceeded WHO indoor air quality standards, with Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, and Legionella pneumophila as the most prevalent bacteria. The opportunistic and pathogenic microorganisms known to be present in the air of indoor environments imply that laboratory environments can be potential reservoirs for infectious diseases, particularly under poor ventilation and poor biosafety protocols. The relatively high bacterial loads obtained in pathology and agronomy laboratories show that biological sample processing increases airborne microbial contamination and raises the need for more stringent infection control measures.

The results of the risk assessment models also showed large carcinogenic and non-carcinogenic risks. Further, this indicates that the risk values for benzene, arsenic, cadmium, and nickel exceeded the threshold acceptable by an order of magnitude (10^{-4}), indicating that there also would be concerns of long-term cancer risks to laboratory workers. It was also found that acetone and methyl ethyl ketone risk exceed 1 Hazard

Quotient (HQ) values, suggesting that any chronic toxicity from this exposure poses a risk. Thus, integrated exposure control measures are needed to control chemical and microbial hazards to protect laboratory personnel from chemical toxicity and microbial infection. The results of this research are consistent with WHO, OSHA, and USEPA reports describing the occupational hazards of exposure to airborne VOCs and microbial particles in laboratory environments. These results also agree with [23,24,28], which found that ventilation efficiency, laboratory workflow, and biosafety compliance play a role in indoor air quality. Considering this, this study's current laboratory safety practises are inadequate to provide the personnel with complete protection from chronic exposure hazards. Lack of well-conducted air quality monitoring, poor ventilation, and lax bio-safety enforcement expose the workers to chemical and microbial hazards and require policies for improved health and exposure reduction strategies.

Recommendations

i. Equip the shop with high-efficiency air filtration systems (HEPA filters) and exhaust ventilation to counter VOC accumulation and airborne microbial contamination.
ii. Increase mechanical ventilation and air purification technologies to increase air exchange rates.
iii. Implement real-time air quality monitoring systems for continuous assessment and exposure control.
iv. Enforce Biosafety Level-2 (BSL-2) or BSL-3 protocols with high microbial loads in pathology, biotechnology, and agronomy laboratories.
v. Carry out routine decontaminating work surfaces and equipment to avoid the buildup of microorganisms.
vi. Wear appropriate PPE (masks, gloves, face shields) and perform strict hand hygiene practices for laboratory personnel.
vii. Use low-hazard alternatives (e.g. benzene, formaldehyde, cadmium) as much as possible according to Green Chemistry principles.
viii. government agencies (WHO, OSHA, USEPA) and institutional biosafety committees should enforce strict laboratory air quality standards.
ix. Analyse of the synergistic effects of chemical and microbial co-exposure can lead to a more comprehensive risk assessment framework.

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