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Research Article

Mitigating Airborne Occupational Hazards In Passaka's Industries In Bhutan: A Policy Brief On Enhancing Worker Health, Productivity, And Sustainable Economic Development

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ABSTRACT

Background: Bhutan's industrial growth, especially in Pasakha, creates significant occupational health and safety (OHS) challenges, particularly from airborne hazards. A lack of localized data hinders effective OHS policy development. This study addresses this gap by assessing airborne hazard exposure in selected Chukha Dzongkhag industries to inform national OHS strategies.

Methodology: Twenty-seven air samples were collected over 30-minute periods from 14 workplaces across seven industrial sectors. Samples were analyzed by an internationally accredited laboratory for 17 parameters including particulate matter (PM10, PM2.5), formaldehyde, heavy metals (lead, arsenic, chromium), and silica. Results were compared against Bhutan's 2022 OHS Regulation and international standards (OSHA, NIOSH, ACGIH).

Results: Findings show widespread exceedances of permissible exposure limits (PELs). Formaldehyde reached 1.11 ppm in plastics (PEL: 1.0 ppm). PM10 hit 1,165 μg/m³ in metals (PEL: 150 μg/m³). Heavy metal exceedances were significant: lead at 91 μg/m³ (PEL: 50 μg/m³), arsenic at 86 μg/m³ (PEL: 10 μg/m³), and chromium at 81 μg/m³ (PEL: 50 μg/m³). Silica reached 84.7 μg/m³ (PEL: 50 μg/m³).

Conclusion: The study highlights critical occupational health risks from airborne chemical exposure in Bhutanese industries. These widespread PEL exceedances threaten worker health and impede national development. Urgent policy interventions are needed, including immediate action plans, strengthened regulations, robust OHS monitoring, capacity building, promoting engineering controls, and multi-stakeholder collaboration to safeguard Bhutan's workforce and ensure sustainable economic growth.

Keywords: Airborne hazards, PM2.5, Heavy metals, Chemicals, health hazards, Occupational Health & Safety

Introduction

Bhutan, a small Himalayan kingdom celebrated for its unique Gross National Happiness (GNH) philosophy, has embarked on a strategic path of economic diversification and industrialization over the past few decades. This development trajectory, which includes the expansion of key sectors like hydropower generation, cement production, ferrosilicon manufacturing, and various manufacturing industries, aims to drive economic growth, create employment opportunities, and enhance living standards across the nation (Asian Development Bank, 2013; World Bank, 2022).

However, this rapid industrial expansion has concurrently introduced new and evolving challenges in occupational health and safety (OHS). Early industrial ventures, particularly concentrated in regions such as the Pasakha Industrial Estate in Chukha Dzongkhag, have experienced growth that often outpaced the establishment of robust OHS management systems. Workers in these burgeoning sectors face exposure to a range of hazards, including physical, chemical, and ergonomic risks, as evidenced by studies indicating issues from silica dust and chemical fumes to high noise levels and poorly designed workstations (Dendup, 2021; Dukpa & Dendup, 2018). Despite Bhutan's commitment to sustainable development, the OHS framework has struggled to keep pace, exhibiting limitations in regulatory enforcement, trained OHS professionals, adequate workplace inspections, and widespread awareness among both employers and employees (Dukpa & Dendup, 2018).

Among these pressing OHS concerns, exposure to airborne hazards represents a particularly insidious threat to worker health. Industrial processes generate a variety of airborne pollutants, including particulate matter (PM), volatile organic compounds (VOCs), heavy metals, and various gaseous contaminants. Prolonged exposure to these substances can lead to severe acute and chronic health conditions such as chronic respiratory illnesses, cardiovascular diseases, neurological disorders, and various forms of cancer (Nishida & Yatera, 2022; Ratajczak, Badyda et al., 2021; Rückerl, Schneider et al., 2011).

Crucially, the ramifications of these airborne hazards extend far beyond individual worker health, imposing significant burdens on Bhutan's broader socio-economic development. Unchecked occupational exposures diminish human capital by contributing to reduced life expectancy, premature mortality, and impaired well-being among the workforce (Dorman, 2020). This in turn directly impacts national economic productivity, leading to increased absenteeism, presenteeism (reduced productivity while at work), and lower industrial efficiency, with global estimates indicating economic losses from occupational diseases can account for up to 4% of GDP(Akram, 2015; Dorman, 2012). Furthermore, the substantial costs associated with treating chronic occupational diseases strain public health systems and impose considerable financial hardship on individual households, potentially pushing vulnerable families into poverty (Dorman, 2020; Yokoyama, Iijima et al., 2013). Ultimately, inadequate OHS undermines the principles of inclusive and sustainable industrial growth, impeding Bhutan's progress towards critical Sustainable Development Goals (SDGs), notably SDG 3 (Good Health and Well-being) and SDG 8 (Decent Work and Economic Growth), by failing to ensure that economic gains are achieved without compromising worker welfare (Ali, 2004; Kavouras, Vardopoulos et al., 2022).

Despite the critical importance of understanding and mitigating these widespread risks, there is a significant and notable lack of comprehensive, localized data on airborne hazard exposure levels in Bhutanese industries. Existing global literature largely focuses on developed countries, leaving a substantial gap in knowledge specific to the unique challenges faced by workers in rapidly industrializing nations like Bhutan (Ahmad, Sattar et al., 2016; Christiani, Durvasula et al., 1990). This scarcity of information poses a considerable barrier to developing and implementing targeted, evidence-based OHS policies and interventions.

This issue is highly relevant to the strategic priorities of the Asian Development Bank (ADB), aligning with its commitment to fostering human capital development, promoting inclusive growth, and supporting sustainable infrastructure across its developing member countries. By addressing occupational airborne hazards, Bhutan can significantly enhance worker health and productivity, thereby strengthening its human capital and contributing to a more resilient and sustainably developed industrial sector in line with regional development goals.

Therefore, this study aims to fill this critical data gap by conducting a comprehensive assessment of airborne hazard exposure levels in selected industrial in Passakha within Chukha Dzongkhag, Bhutan. By identifying specific hazardous substances and evaluating worker exposure against national and international Permissible Exposure Limits (PELs), this research provides vital, localized insights to inform the development of effective government policies and a robust National Occupational Health and Safety strategy, ensuring a safer and healthier working environment for Bhutanese industries.

Methods

Sample Size

A total of 27 samples from 14 companies were collected and analyzed for volatile organic compounds (VOCs), heavy metals, silica, and total and respirable dust from Pasakha and Phuentsholing area under Chhukha Dzongkhag.

Sampling Methods

Due to time and financial constraints, a practical 30-minute grab sampling method was employed. The testing methods employed for assessing various airborne hazards include the EPA Compendium Method IP-10 for measuring PM10 and PM2.5 particulate matter. Sulfur dioxide (SO2) and nitrogen dioxide (NO2) are analyzed using the IS: 5182 standards (Parts 2 and 6, respectively), while carbon monoxide (CO) is assessed under Part 10 of the same standard. Total dust is measured according to IS: 5182 (Part 4), and benzene and volatile organic compounds (VOCs) are evaluated using IS: 5182 (Part 11). Silica is tested following OSHA D-142 guidelines, and heavy metals are analyzed according to IS: 5182 (Parts 22 and 26). Additionally, formaldehyde (HCHO) is assessed using the APHA method, and ozone (O3) is measured according to ASTM D5149-02

Airborne Hazads Sampling

The sampling parameters were established based on industry types and include total dust (total particulate matter suspended in the air), respirable dust (inhalable dust affecting the respiratory system), sulfur dioxide (SO2), formaldehyde (HCHO), silica (silicon dioxide), and heavy metals (lead, nickel, chromium, mercury, arsenic, and cadmium). Additionally, volatile organic compounds (VOCs) such as benzene and xylene, ozone (O3), total volatile organic compounds (TVOC), and nitrogen dioxide (NO2) were also included in the assessment.

Sampling Instruments

For the sampling of airborne hazards, the equipment used included the Benzene/VOC Sampler, Personal Sampler, Indoor Air Sampler, Indoor Air Quality Monitor, Charcoal, Charcoal Tube, Tedlar Bag, EPM-2000, and Filter Paper (37mm and 25mm), along with Absorbing Reagents.

Sample Analysis

Samples were analyzed in an internationally accredited laboratory compliant with ISO/IEC 17025:2017 standards, ensuring precision and reliability. Advanced analytical techniques, including gas chromatography and inductively coupled plasma mass spectrometry (ICP-MS), were employed to detect and quantify hazardous substances.

Finding And Discussion

Company profile

The comprehensive assessment of airborne hazards in [14] workplaces across seven industrial sectors in Chukha Dzongkhag, Bhutan, revealed significant findings concerning worker exposure to various hazardous substances. The analysis, covering [16] parameters and conducted against national (ROHSW 2022) and international (OSHA, NIOSH, ACGIH) permissible exposure limits (PELs), highlights critical areas where immediate intervention is required to safeguard worker health and ensure sustainable industrial operations

Particulate Matter (Pm10 And Pm2.5)

Monitoring of particulate matter indicated concerning concentrations in several key industrial areas. The highest concentrations of PM10 and PM2.5 were recorded in the Crushing & Screening Section of a metal company (IAQ-04), with levels of 1,165 μg/m³ and 913 μg/m³, respectively. While these values are below Bhutan's national PELs (10,000 μg/m³ for PM10 and 5,000 μg/m³ for PM2.5), they significantly exceed the more stringent international benchmarks from OSHA (5,000 μg/m³ for both) and ACGIH (3,000 μg/m³ for PM2.5). Similarly, the Welding Section of a Ferro Alloys company (IAQ-05) recorded elevated levels of 943 μg/m³ for PM10 and 546 μg/m³ for PM2.5. These findings, particularly in metal and ferroalloy operations, underscore a critical risk for chronic respiratory diseases (e.g., COPD, lung cancer) and cardiovascular issues among workers. Such health impacts directly contribute to reduced productivity, increased absenteeism, and long-term healthcare burdens for affected individuals and the national health system. Therefore, enhanced dust control measures, including improved ventilation systems and process enclosures, are urgently needed in these high-exposure zones.

Formaldehyde (Hcho)

Formaldehyde concentrations presented significant concerns, with several locations exceeding established PELs and Threshold Limit Values (TLVs). Most notably, the Feeding Section of a Plastic Industry (IAQ-09) recorded a concentration of 1.11 PPM, which surpasses the ROHSW 2022 PEL, OSHA-TWA, and ACGIH-TLV of 1.0 PPM. Elevated levels were also observed in the Printing Section of a printing press (0.952 PPM) and the Production Section of a ferro alloy plant (0.91 PPM), both exceeding ACGIH-TLVs. Exposure to formaldehyde, a probable human carcinogen, can lead to severe respiratory irritation, asthma exacerbation, and increased cancer risk. These exceedances highlight an immediate need for targeted interventions, including source control, enhanced local exhaust ventilation, and stringent personal protective equipment protocols, to mitigate serious health risks for workers in these specific industries. The details of observation of formaldehyde are illustrated in Table 2.

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Table 1.Particulate Matter Exposure level

Sl #	Code	Name of Location	Area of Location	PM $_{10}$ (µg /m^3)	PM $_{2.5}$ (µg /m^3)
1	IAQ-01	Fuel distribution A	Diesel Counter	248	139
2	IAQ-01	Fuel distribution B	Petrol Counter	171	95
3	IAQ-02	Fuel distribution C	Drivers Waiting Shead	198	136
4	IAQ-03	Fuel distribution D	Cash Counter	211	78
5	IAQ-04	Metals	Welding Section	575	294
6	IAQ-04	Metals	Furnace Section	757	552
7	IAQ-04	Metals	Crushing & Screening Section	1165	913
8	IAQ-05	Ferro Alloys	Welding Section	813	688
9	IAQ-05	Ferro Alloys	Furnace Section	943	546
10	IAQ-05	Ferro Alloys	Crushing & Screening Section	924	494
11	IAQ-06	Steels & Rolling Mills	Furnace Section	1054	793
12	IAQ-07	Ceramic Metals	Furnace Section	918	636
13	IAQ-07	Ceramic Metals	Coke Area	1179	736
14	IAQ-07	Ceramic Metals	Raw Material Section	597	263
15	IAQ-08	Metals	Furnace Section	969	628
16	IAQ-08	Metals	Raw Material Section	684	276
17	IAQ-09	Plastic Industry	Feeding Section	376	196
18	IAQ-09	Plastic Industry	Production Section	114	76
19	IAQ-10	Printing Press	Printing Section	197	103
20	IAQ-10	Printing Press	Binding Section	281	91
21	IAQ-11	Furniture Manufacturing	Production Section	912	527
22	IAQ-12	Construction	Road Works	291	107
23	IAQ-13	Ferro Alloys	Furnace Section	441	173
24	IAQ-13	Ferro Alloys	Production Section	571	290
25	IAQ-14	Ferro Alloys	Furnace Section	705	413
26	IAQ-14	Ferro Alloys	Production Section	645	344

Table 2.Observation level of Formaldehyde (HCHO)

Sl#	Code	Tyes of companies	Area of Location	Observation (PEL in PPM)
1	IAQ-01	Fuel distribution A	Diesel Counter	0.57
2	IAQ-01	Fuel distribution B	Petrol Counter	0.89
3	IAQ-02	Fuel distribution C	Drivers Waiting Shed	0.11
4	IAQ-03	Fuel distribution D	Cash Counter	0.61
5	IAQ-04	Metals	Welding Section	0.14
6	IAQ-04	Metals	Furnace Section	0.21
7	IAQ-09	Plastic Industry	Feeding Section	1.11
8	IAQ-09	Plastic Industry	Production Section	0.58
9	IAQ-10	Printing Press	Printing Section	0.95
10	IAQ-10	Printing Press	Binding Section	0.52
11	IAQ-11	Furniture Manufacturing	Production Section	0.32

12	IAQ-13	Ferro alloy	Furnace Section	0.53
13	IAQ-13	Ferro alloy	Production Section	0.91

Heavy Metals (Lead, Arsenic, Chromium, Nickel, Cadmium)

The assessment of heavy metals revealed widespread and concerning exceedances, particularly in the Ceramic Metals and Ferro Alloys sectors. These substances are known for their severe toxic effects on multiple organ systems.

- **Lead (Pb)**: Concentrations of 76 µg/m³ in the Furnace Section and 91 µg/m³ in the Coke Area of Ceramic Metals (IAQ-07) significantly exceed the OSHA and ACGIH TWA of 50 µg/m³. Elevated lead exposure is associated with neurological damage, kidney dysfunction, and reproductive issues, directly impacting worker cognitive function and long-term employability.
- **Arsenic (As)**: A concerning level of 86 µg/m³ was detected in the Furnace Section of a Metals company (IAQ-08), substantially exceeding the ACGIH TWA of 10 µg/m³. Arsenic is a known carcinogen, and such levels pose a high risk of various cancers and skin lesions.
- **Chromium (Cr)**: The highest level of 81 µg/m³ in the Furnace Section of a Ferro Alloys company (IAQ-05) exceeded the ROHSW 2022 PEL of 50 µg/m³. Chromium exposure is linked to lung cancer and respiratory problems.
- **Nickel (Ni)**: The Welding Section of Ferro Alloys (IAQ-05) recorded 97 µg/m³, far exceeding the OSHA TWA of 7 µg/m³ and the ACGIH TWA of 10 µg/m³. High nickel exposure can cause respiratory irritation and increase cancer risk.
- **Cadmium (Cd)**: The Furnace Section of Ceramic Metals (IAQ-07) showed 55 µg/m³, a severe exceedance of the OSHA and ACGIH TWA of 5 µg/m³. Cadmium is a potent kidney toxin and carcinogen.

These widespread exceedances of heavy metals point to a systemic issue in metallurgical industries, demanding immediate and comprehensive control measures, including engineering controls, improved waste management, and mandatory health surveillance programs for exposedworkers. The recommended levels (Table 3) andobservation levels of the heavy metal are given in table 4.

Silica (Sio2)

Silica exposure also presented significant risks, particularly in crushing and material handling operations. The Coke Area of Ceramic Metals (IAQ-07) recorded a concerning 84.7 µg/m³, substantially exceeding OSHA and NIOSH limits of 50 µg/m³. Similarly, the Crushing & Screening Section of Metals (IAQ-04) at 34.8 µg/m³, and Ferro Alloys furnace (69.9 µg/m³) and production (61.8 µg/m³) sections, all exceeded the ACGIH TLV of 25 µg/m³ (Table 5). Prolonged exposure to respirable crystalline silica causes silicosis, a severe and often fatal lung disease, and increases the risk of lung cancer. These findings necessitate immediate implementation of effective dust suppression, localized ventilation, and stringent respiratory protection programs in all operations involving silica-generating processes.

Table 3.Recommendation and Legal values of heavy metals

Metal	OSHA (PEL) [µg/m	NIOSH (REL) [µg/m3	ACGIH (TLV) [µg/m3	ROHSW2022 (PEL) [µg/m3
Pb	TWA - 50	TWA - 50	TWA - 50	TWA - 150
As	TWA - 10	TWA - 1 STEL - 2 CEL - 15	TWA - 10	TWA - 200
Cr	TWA 100	TWA - 7	C - 349	TWA - 50
Ni	TWA - 7	TWA - 10 STEL - 30	TWA - 10	TWA - 50
Hg	TWA - 10	TWA - 10 STEL - 30	TWA - 10	TWA - 350
Cd	TWA - 5	TWA - 40 (10 hrs)	TWA - 50	TWA - 50

Table 4.Observation level of Heavy metalsls

Sl#	Code	Tyes of Company	Area of Location	Pb (µg/m³)	As (µg/m³)	Cr (µg/m³)	Ni (µg/m³)	Hg (µg/m³)	Cd (µg/m³)
1	IAQ-01	Fuel Station	Diesel Counter					10	

7	IAQ-04	Metals	Crushing & Screening Section	11		25	17	ND	
8	IAQ-05	Ferro Alloys	Welding Section	ND	9	50	65		
9	IAQ-05	Ferro Alloys	Furnace Section	24	64	81	97		
10	IAQ-05	Ferro Alloys	Crushing & Screening Section	4	7	17	20		
12	IAQ-07	Ceramic Metals	Furnace Section	76	52	29		10	55
13	IAQ-07	Ceramic Metals	Coke Area	91	76	36		12	79
14	IAQ-07	Ceramic Metals	Raw Material Section	10	4	18		7	
15	IAQ-08	Metals	Furnace Section	15	86	68		16	
16	IAQ-08	Metals	Raw Material Section	4	12	17		5	
26	IAQ-14	Ferro Alloys	Production Section	8	16	29		ND	

Table 5.Observation Level of Silica (SiO2)

Sl.#	Code	Types of Company	Area of Location	Observation (µg /m3)
1	IAQ-04	Metals	Welding Section	5.6
2	IAQ-04	Metals	Furnace Section	10.4
3	IAQ-04	Metals	Crushing & Screening Section	34.8
4	IAQ-07	Ceramic Metals	Furnace Section	14.6
5	IAQ-07	Ceramic Metals	Coke Area	84.7
6	IAQ-07	Ceramic Metals	Raw Material Section	39.7
7	IAQ-13	Ferro Alloys	Furnace Section	69.9
8	IAQ-13	Ferro Alloys	Production Section	61.8

Other Gaseous Pollutants (So2, No2, O3) And Volatile Organic Compounds (Vocs)

While individual analyses of Benzene, Toluene, and Xylene generally showed concentrations below established limits, the assessment of Total Volatile Organic Compounds (TVOCs) revealed concerning levels. The Feeding Section of the Plastic Industry recorded a high concentration of 1.41 mg/m^3, exceeding the ACGIH TWA (1.62 mg/m^3) and NIOSH REL (0.32 mg/m^3). The Printing Section of the Printing Press (1.11 mg/m^3) and the Production Section of Ferro Alloys (1.06 mg/m^3) also showed elevated TVOCs, indicating the presence of a complex mixture of organic chemicals that pose potential long-term health risks. For other gaseous pollutants like Sulfur Dioxide (SO2) and Nitrogen Dioxide (NO2), while mostly within national PELs, elevated readings were observed in specific furnace sections (e.g., Steels & Rolling Mills, Ferro Alloys). Ozone (O3) levels in the Feeding Section of the Plastic Industry (0.15 ppm) exceeded all major TWA limits (Table 6). Although not always exceeding the highest permissible limits, these elevated concentrations necessitate continuous monitoring and a proactive approach to prevent cumulative exposure effects and ensure worker well-being.

Table 6.Gaseous Pollutants Observation Levels (SO2, NO2, O3)

Sl #	Code	Type of Company	Area of Location	SO2 (µg/m³)	NO2 (µg/m³)	O3 (ppm)
1	IAQ-04	Metals	Welding Section	46.7	73.8	-
2	IAQ-04	Metals	Furnace Section	75.4	91.1	-
3	IAQ-04	Metals	Crushing & Screening Section	22.1	37	-
4	IAQ-05	Ferro Alloys	Welding Section	64.2	75.1	-
5	IAQ-05	Ferro Alloys	Furnace Section	109.1	89.4	-
6	IAQ-05	Ferro Alloys	Crushing & Screening Section	24.9	32.2	-

7	IAQ-06	Steels & Rolling	Furnace Section	152.8	179	-
8	IAQ-08	Metals	Furnace Section	96.9	-	-
9	IAQ-08	Metals	Raw Material Section	19.6	-	-
10	IAQ-08	Ferro Alloys	Furnace Section	-	127.8	-
11	IAQ-08	Ferro Alloys	Raw Material Section	-	39.1	-
12	IAQ-09	Plastic	Feeding Section	-	-	0.15
13	IAQ-09	Plastic	Feeding Section	-	-	0.08
14	IAQ-10	Printing Press	Printing Section	-	-	0.06
15	IAQ-10	Printing Press	Printing Section	-	-	0.04
16	IAQ-12	Construction	Road Works	-	-	0.05
17	IAQ-14	Ferro Alloys	Furnace Section	79.3	108.6	-

Table 7.Volatile Organic Compounds (VOCs) Observation Levels (Benzene, Toluene, Xylene, TVOCs)

Sl #	Code	Type of Company	Area of Location	Benzene (mg/m^3)	Toluene (mg/m^3)	Xylene (mg/m^3)	TVOCs (mg/m^3)
1	IAQ-01	Fuel distribution station	Diesel Counter	0.03	0.11	0.07	-
2	IAQ-01	Fuel distribution station	Petrol Counter	0.07	0.17	0.14	-
3	IAQ-02	Fuel distribution station	Drivers Waiting Shed	0.02	0.03	0.07	-
4	IAQ-03	Fuel distribution station	Cash Counter	0.161	0.56	0.3	-
5	IAQ-07	Ceramic Metals	Furnace Section	0	0.56	0	0.56
6	IAQ-07	Ceramic Metals	Coke Area	0	0.42	0	0.42
7	IAQ-07	Ceramic Metals	Raw Material Section	0	0.3	0	0.3
8	IAQ-09	Plastic Industry	Feeding Section	-	-	-	1.41
9	IAQ-09	Plastic Industry	Production Section	-	-	-	0.89
10	IAQ-10	Printing Press	Printing Section	-	-	-	1.11
11	IAQ-10	Printing Press	Binding Section	-	-	-	0.73
12	IAQ-11	Furniture Manufacturing	Production Section	-	-	-	0.96
13	IAQ-13	Ferro Alloys	Furnace Section	-	-	-	0.62
14	IAQ-13	Ferro Alloys	Production Section	-	-	-	1.06

Limitations Of The Study

This study has some limitations that should be acknowledged. Firstly, the short duration of sample collection, specifically the 30-minute intervals, may not adequately capture the temporal variability in pollutant concentrations, which can fluctuate due to factors such as industrial activities, and changing weather conditions. This brief sampling window may miss critical peaks or troughs in exposure levels, leading to an incomplete understanding of actual risks faced by workers.

The study's focus on specific pollutants limits its scope, potentially overlooking other relevant contaminants present in the work environment. Furthermore, the selection of sampling locations and times may introduce bias, as some workplaces were not operating at full capacity during sampling, affecting the representativeness of the data.

Lastly, the findings are based on concentrations measured during the sampling periods, which may not reflect long-term exposure levels experienced by workers. Chronic exposure assessments require longer sampling durations for a more accurate evaluation of health risks. At the same time, occupational disease surveillance system may be established to corelate specific pollutant concentration with disease occurrence. Thus, future research should aim for longer sampling periods, a broader range of pollutants, and a comprehensive approach to better capture the dynamic nature of workplace exposures.

Recommendations

The assessment of airborne hazards in selected industries in Passakha, under Chukha Dzongkhag, Bhutan, unequivocally reveals several critical issues that necessitate immediate and concerted policy interventions. Notably, numerous workplaces, particularly within the plastic, metals, ceramic, and ferro alloys sectors, have recorded airborne concentrations of hazardous substances, such as formaldehyde, particulate matter (PM10 and PM2.5), and heavy metals, that significantly exceed both national and international permissible exposure limits (PELs). This pervasive exposure poses severe health risks to workers, ranging from chronic respiratory diseases and neurological disorders to various cancers, directly impacting the human capital vital for Bhutan's growth. Compounding these concerns is the evident lack of comprehensive and consistent data on airborne hazards in Bhutanese industries, which currently hinders effective policy making, robust enforcement, and proactive occupational health management.

The unaddressed burden of these occupational hazards poses a significant impediment to Bhutan's socio-economic development. It directly impacts worker productivity, strains public healthcare resources, and fundamentally undermines the nation's journey towards inclusive and sustainable industrialization. Addressing these challenges is not merely a health imperative but a crucial investment in national prosperity and the well-being of its citizens, aligning perfectly with Bhutan's Gross National Happiness philosophy and the strategic objectives of development partners like the Asian Development Bank.

Therefore, to mitigate these critical risks and foster a healthier, more productive industrial workforce, the following policy recommendations are crucial:

Immediate Action Plans And Targeted Interventions

Develop and implement urgent action plans for workplaces identified with hazardous substance exceedances. This includes enforcing stricter controls, such as improved ventilation systems, process modifications to reduce emissions at the source, and mandatory use of appropriate personal protective equipment (PPE) where engineering controls are insufficient.

Strengthening Regulatory Framework and Enforcement

Review and update the "Regulation on Occupational Health, Safety and Welfare, 2022" to incorporate findings from this and future studies, ensuring PELs are regularly updated and align with international best practices. Enhance the capacity and authority of regulatory bodies for more frequent, thorough, and effective workplace inspections and compliance enforcement.

National Monitoring and Data Management System

Establish a robust national system for continuous monitoring of airborne hazards across all industrial sectors. This includes investing in laboratory infrastructure, trained personnel, periodic monitoing by the companies and reporting, and a centralized database for OHS data, which will enable evidence based policy formulation and track progress over time.

Capacity Building and Awareness Programs

Implement comprehensive training and awareness programs for workers, supervisors, and management across industries. These programs should focus on hazard identification, risk assessment, safe work practices, the proper use and maintenance of control measures (including PPE), and the socio-economic importance of OHS.

Promoting Engineering Controls and Best Practices

Incentivize and support industries in adopting primary engineering controls (e.g., local exhaust ventilation, enclosure of hazardous processes, automation) over administrative controls and PPE. Promote the integration of robust occupational health and safety management systems (OHSMS) within all industrial enterprises including AI driven technologies.

Multi-Stakeholder Collaboration

Foster stronger collaboration among government agencies, industry associations, labor unions, and international development partners to collectively address OHS challenges, share best practices, and mobilize resources for effective implementation of OHS policies.

Conclusion

In conclusion, it is imperative to prioritize occupational health and safety through these comprehensive interventions, Bhutan can effectively safeguard its vital workforce, enhance industrial competitiveness, and ensure that its economic development is both inclusive and truly sustainable, laying a strong foundation for the nation's long-term prosperity.

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