Published by
NIGERIAN SOCIETY OF PHYSICAL SCIENCES
Available online @ https://asr.nsps.org.ng/index.php/asr

African Scientific Reports 5 (2026) 439

African Scientific Reports

Environmental exposure and health risk assessment of particulate-associated heavy metals from medical waste incineration

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Abstract

Incineration, a widely adopted waste-management strategy, poses significant health and environmental risks because of the continuous emission of heavy metals (HMs). In this study, the levels of ten HMs (Zn, Fe, Cu, Cr, Cd, As, Ni, Co, Pb, and Hg) were determined in particulate matter around a hospital incineration facility using flame atomic absorption spectrometry (FAAS). HM concentrations ranged from 0.059 to 0.330 mg kg^{-1} in the descending order Zn > Fe > Cu > Cr > Cd > As > Ni > Co > Pb > Hg. Statistical analysis confirmed significant differences between the exposed sites and the control baseline ($p < 0.05$). The mean levels of Ni, As, Cd, Hg, Pb, and Cr (0.120, 0.1216, 0.1440, 0.0592, 0.0704, and 0.2192 mg kg^{-1}, respectively) exceeded World Health Organization limits, indicating potential ecological and public health risks. Strong positive correlations ($p < 0.01$) were obtained between specific metal pairs (As–Pb: $r = 0.864$; Hg–Cd: $r = 0.517$; Ni–Pb: $r = 0.670$; Pb–Cr: $r = 0.983$), suggesting common emission sources and synergistic environmental effects. Several other metals also exhibited strong positive correlations, including Cr–Co, Cr–Pb, Cd–Ni, As–Ni, Cu–Co, and Pb–Co ($r > 0.70$). These associations reiterate multiple common exposure pathways among workers occupationally exposed to the hospital incinerator. These findings highlight the need for enhanced regulatory frameworks and mitigation strategies to address pollution, safeguard public health, and promote sustainable waste management in this environment.

DOI:10.46481/asr.2026.5.2.439

Keywords: Particulate-associated heavy metals, Medical waste incineration, Environmental exposure, FAAS

Article history:
Received: 08 January 2026
Received in revised form: 13 March 2026
Accepted for publication: 22 March 2026
Available online: 10 June 2026

1. Introduction

The rapid expansion of urban populations, intensified industrial activities, and the acceleration of global economic development have collectively exacerbated environmental challenges, particularly air pollution [1]. Among environmental hazards, air pollution is a dominant contributor to premature mortality worldwide and has been consistently linked to various health burdens [2, 3].

Within this environmental matrix, heavy-metal pollution has emerged as a critical concern, driven predominantly by anthropogenic sources such as mining operations, industrial emissions, vehicular exhaust, landfill leachate, municipal and hospital waste

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disposal, and indiscriminate open burning [4]. Secondary contributors, including agricultural activities involving pesticides and fertilizers, further amplify heavy-metal contamination in the ecosystem [5].

Medical waste incineration, a widely used disposal technique for hospital refuse in low- and middle-income countries, has been identified as a significant source of environmental contamination [6]. Inadequately controlled incineration processes release a complex mixture of pollutants into the atmosphere, including fine particulate matter and hazardous HMs such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), nickel (Ni), and copper (Cu), among others [7]. These emissions also contain acid gases and organic compounds, which pose additional risks to air quality and public health [2]. Although international guidelines advocate pollution-abatement technologies such as gas scrubbers and flue-gas cleaning systems, these technologies are rarely implemented or effectively maintained in many incineration facilities in developing nations [8]. Consequently, nearby communities and healthcare workers are frequently exposed to harmful emissions, with epidemiological studies suggesting associations between long-term proximity to incinerators and elevated risks of cancer, leukemia, and congenital anomalies [9].

Heavy metals released through incineration are particularly alarming because of their chemical persistence, environmental mobility, and bioaccumulative potential [10]. Unlike organic pollutants, HMs do not degrade over time and can accumulate in biological tissues, leading to both acute and chronic toxicity [11]. They have been implicated in damage to major organ systems, including the liver, kidneys, lungs, and nervous system, and are known to cause developmental, reproductive, and neurobehavioral disorders [12]. For instance, chronic lead exposure is linked to cognitive deficits, neurodevelopmental delays, and a spectrum of neurodegenerative conditions such as Parkinson's disease and Alzheimer's disease [13]. Similarly, arsenic toxicity may result in gastrointestinal, cardiovascular, and dermal complications and is strongly associated with malignancies of the skin, bladder, liver, and lungs [14]. Cadmium exposure has been correlated with respiratory dysfunction, renal impairment, bone demineralization, and hematologic malignancies such as leukemia [15].

Global and regional studies provide mounting evidence of the health implications of particulate-bound HMs in incinerator emissions [7]. For example, a risk assessment in Wuhan, China, identified cadmium and nickel as leading carcinogenic agents in airborne particulate matter [16]. Likewise, in the United Kingdom, maternal exposure to emissions from medical waste incinerators was associated with congenital abnormalities, including spina bifida and cardiac defects [3]. These findings have prompted policy shifts in high-income countries such as the Netherlands, Germany, and the United States, where incineration facilities have been phased out or subjected to stringent emission controls [17]. However, in sub-Saharan Africa, many healthcare facilities continue to rely on poorly regulated incineration practices, resulting in the unchecked release of hazardous pollutants [18]. This circumstance highlights the critical need for regular environmental monitoring and health-risk assessments, as advised by the World Health Organization (WHO) and other international organizations [19].

In response to these challenges, this study investigated the levels of HMs in particulate-bound emissions from a medical waste incinerator using FAAS. The study quantified the concentrations of ten HMs (Zn, Fe, Cu, Cr, Cd, As, Ni, Co, Pb, and Hg) captured using glass-slide samplers. It further compared the metal levels with WHO guidelines and regional background levels, thereby offering a contextual risk profile. By evaluating exposure pathways for healthcare workers, patients, and neighbouring residents, the study aimed to fill critical knowledge gaps in environmental health-risk assessment within tropical healthcare settings. Ultimately, the findings are expected to inform evidence-based waste-management policies, guide the development of pollution-control strategies, and provide a replicable framework for environmental monitoring across similar institutions.

2. Materials and methods

2.1. Study area

Federal Teaching Hospital, Ido-Ekiti (FETHI), Ekiti State, Nigeria, is located in the Ido-Osi Local Government Area of Ekiti State at latitude 7.8434°N and longitude 5.1877°E. It has residency training programs in eight departments, an accredited School of Nursing, 22 clinical departments, and four non-clinical departments. The hospital has a bed capacity of 450. The medical waste generated per bed per day is 0.73 kg [20]. The generated waste is burnt using an incineration plant [20].

2.2. Sample collection

Glass slides of size 2.54×4.54 cm^2 each were cleaned in ethanol and deionized water and placed close to the hospital incinerator. The slides were also placed at some departments between 100 and 300 m from the same incinerator, where its fumes diffuse. Measurements were taken at the incinerator and three different departments/units (labelled B–E) in the hospital to determine the levels of exposure or vulnerability. The control location, Location A, was about 23000 m away from the incinerator and outside the main wind-dispersion channel. The area has minimal human activity, no combustion sources, and minimal car traffic. The site was selected to represent the hospital's background particle-deposition level without being directly affected by emissions from the incinerator. After two months of exposure, the slides were carefully removed from their locations, and the particulate matter (PM) was rinsed into a container using diluted hydrochloric acid. The samples were kept in new vials (five for each department and blank slides), labelled, and taken to the laboratory at the Centre for Energy and Research Development (CERD), Obafemi Awolowo University, Ile-Ife, for heavy-metal analyses.

2.3. Sample preparation and analysis

Twenty millilitres (20 mL) of freshly prepared concentrated nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) were added to each sample in a 2:1 ratio, slowly digested for 10 min, and heated at 48°C for about 5 min. After cooling, the resulting solution was dissolved in 5 mL nitric acid (0.1 M), transferred, and filled with double-distilled water to the 20 mL measuring-cylinder mark. The digested sample was transferred into a labelled clean sample bottle and kept for analysis. Blanks and standards were prepared using the same procedure.

The concentrations of ten HMs (Cr, Cd, As, Cu, Fe, Hg, Zn, Pb, Co, and Ni) in the digested samples, blanks, and standards were analyzed with a PG990 atomic absorption spectrometer (AAS) by flame atomization, using an air-acetylene flame and single-element hollow cathode lamp. All samples and standards were run in triplicate. The high correlation (r = 0.9997–0.9999) obtained between absorbance and HM concentration indicated the reliability and precision of the results presented in this study.

2.4. Risk-assessment equations

Environmental and health-risk assessments of particulate-bound HMs were conducted using established quantitative indices:

$$\text{Contamination factor (CF)} = \frac{C_{\text{exposed}}}{C_{\text{non-exposed}}}. \tag{1}$$

Here, C_{exposed} is the concentration of the metal in the exposed area (μg m^{-3}), and $C_{\text{non-exposed}}$ is the background concentration (μg m^{-3}).

$$\text{Percentage increase (\%)} = \frac{C_{\text{exposed}} - C_{\text{non-exposed}}}{C_{\text{non-exposed}}} \times 100. \tag{2}$$

$$\text{Pollution load index (PLI)} = (CF_1 \times CF_2 \times CF_3 \times \cdots \times CF_n)^{1/n}, \tag{3}$$

where n is the number of metals analyzed. A PLI > 1 indicates pollution.

$$\text{Average daily dose via inhalation } (ADD_{\text{inh}}) = \frac{C \times IR \times EF \times ED}{BW \times AT}, \tag{4}$$

where C is the metal concentration (μg m^{-3}), IR is the inhalation rate (m^3 day^{-1}), EF is the exposure frequency (days year^{-1}), ED is the exposure duration (years), BW is the body weight (kg), and AT is the averaging time (days).

$$\text{Hazard quotient (HQ)} = \frac{ADD_{\text{inh}}}{RfD}, \tag{5}$$

where RfD is the reference dose for inhalation exposure.

$$\text{Hazard index (HI)} = \sum_i HQ_i. \tag{6}$$

An HI > 1 indicates a potential non-carcinogenic health risk.

$$\text{Lifetime cancer risk (LCR)} = ADD_{\text{inh}} \times IUR, \tag{7}$$

where IUR is the inhalation unit risk (μg m^{-3})$^{-1}$. The acceptable cancer-risk range is 10^{-6} to 10^{-4}.

Because PM was collected using passive glass-slide deposition samplers, the detected amounts of HMs represent particles deposited from the atmosphere during the exposure period. The relationship in equation (8) was used to convert the deposited particle mass into an equivalent airborne concentration to evaluate inhalation exposure:

$$C_{\text{air}} = \frac{M}{A \times t \times V_d}. \tag{8}$$

Here, C_{air} represents the airborne PM concentration (μg m^{-3}), M is the mass of PM collected on the deposition surface (μg), A is the glass-slide sampler surface area (m^2), t is the exposure time, and V_d is the deposition velocity (m s^{-1}). Previous environmental exposure studies have used passive deposition samplers to measure the relative quantities of airborne contaminants [21]. The deposited particle load was considered to reflect spatial variations in airborne concentrations due to gravity settling and atmospheric diffusion processes around emission sources.

Table 1: Descriptive statistics for the levels of heavy metals in particulate matter at different units/departments around the incinerator.

Group	Cr	Cd	As	Cu	Fe	Hg	Zn	Pb	Co	Ni	Description
A	0.160	0.120	0.088	0.200	0.264	0.032	0.264	0.048	0.080	0.096	Mean (non-exposed)
B	0.232	0.136	0.120	0.272	0.320	0.056	0.360	0.080	0.080	0.136	Exposed Dept B
C	0.272	0.160	0.144	0.320	0.352	0.088	0.400	0.088	0.128	0.136	Exposed Dept C
D	0.208	0.160	0.128	0.296	0.296	0.056	0.320	0.064	0.112	0.120	Exposed Dept D
E	0.224	0.144	0.128	0.288	0.328	0.064	0.304	0.072	0.104	0.088	Exposed Dept E
Overall exposed	0.234	0.150	0.130	0.244	0.324	0.066	0.346	0.076	0.106	0.120	Overall mean (exposed)
Mean (all)	0.219	0.144	0.122	0.235	0.312	0.059	0.330	0.070	0.101	0.115	Combined mean
SD	0.036	0.015	0.019	0.084	0.030	0.018	0.047	0.014	0.019	0.020	Standard deviation
Max (exposed)	0.272	0.160	0.144	0.320	0.352	0.088	0.400	0.088	0.128	0.136	Maximum
Min (exposed)	0.160	0.120	0.088	0.088	0.264	0.032	0.264	0.048	0.080	0.088	Minimum

Note: A = control (non-exposed); B = at the incinerator; C = Mental Health Department; D = Intensive Care Unit (ICU) Department; E = crèche.

3. Results and discussion

The concentrations of ten HMs in the PM at the various units or departments around the incinerator in the study area are presented in Table 1, while the comparison of the observed levels with recommended limits is given in Table 2. The levels of HMs ranged from 0.056 to 0.400 mg kg^{-1} at the exposed sites in the order Zn > Fe > Cu > Cr > Cd > As > Ni > Co > Pb > Hg and from 0.032 to 0.264 mg kg^{-1} in the control, following the order Fe = Zn > Cu > Cr > Cd > Ni > As > Co > Pb > Hg. Mercury had the least concentration, followed by lead, while zinc had the highest concentration, followed by iron and copper, aligning with Ref. [22]. On a departmental/unit basis, in most cases, PM in the mental health care unit had the highest levels of all the HMs (Cr, Cd, As, Cu, Fe, Hg, Zn, Pb, Co, and Ni). This could be due to its proximity to the incinerator plant compared with the other departments. For As, Cu, Zn, Co, and Ni, this was followed by the intensive care unit and the crèche, respectively (Table 1). Elevated levels of zinc were observed in all departments, possibly because of high levels of this metal in the composition of the medical waste being incinerated. These levels could also be attributed to the closeness of the sampling points to the source of the incinerator fumes, as posited by Ref. [23]. The rate of diffusion decreases with distance, which agrees with a similar report by Ref. [24]. Using a *t*-test, a significant difference existed between the levels of these HMs at the exposed sites and the control ($p < 0.05$). This was an indication of pollution arising from this anthropogenic activity, as reported by Ref. [25]. The differences in HM concentrations between the exposed and control locations were assessed using statistical analysis. Each sampling location employed five replicate samples ($n = 5$) for the *t*-test. The levels of HMs at the exposed areas and the control location differed statistically significantly ($p < 0.05$), indicating that the contamination was caused by emissions from the medical waste incinerator.

From Table 2, the Cd and Fe levels in this study (0.144 ± 0.0152 and 0.312 ± 0.0299, respectively) were relatively higher than the values reported in a similar study by Uwem [26] but lower for Co, Ni, and Zn. Also, the mean Cd level in this study was higher than the value (0.019 ± 0.012 mg kg^{-1}) reported by Ref. [27] but lower for Cr (0.348 ± 0.161 mg L^{-1}) and Pb (0.677 ± 0.499). Most of these studies, including Ref. [28], were carried out using bottom ash from hospital waste incinerators. Despite this, the results obtained were above the recommended limits for most metals, as discovered in this study. Likewise, in this study, the levels of these HMs were above the recommended limits (Table 2).

The heatmap (Figure 1) illustrating the inter-elemental correlation analysis offers important information on possible common sources of particulate-associated HM emissions from the medical waste incinerator. Strong, statistically significant positive correlations were found in the matrix between several metallic species, including Cr and Pb ($r = 0.98$) and As and Pb ($r = 0.86$). These high correlation values point to a shared cause, most likely related to the combustion chamber's thermal destruction of particular types of medical waste, such as plastics, electronic components, and pigments containing HMs [35]. Additionally, the moderate to significant correlations found among Pb, Cd, and Hg ($r = 0.52$–0.61) demonstrate the synergistic nature of these pollutants, suggesting that similar incineration conditions control the mobilization of these metals into the atmosphere [36]. These results, which are corroborated by the heatmap's clustered intensities, highlight that environmental contamination is caused by a complex, integrated multi-elemental emission profile rather than by discrete metal emissions. This suggests that a multi-elemental strategy should be prioritized in monitoring programs, because the removal of one major contributor may greatly reduce the total atmospheric burden of several dangerous HMs.

3.1. Heavy-metal risk assessment

For the health risk assessment models, mass concentrations (mg/kg) from Table 1 were converted to equivalent airborne concentrations (ug/m^3) using Equation 8.

The pollution load index (PLI) was 1.399. Table 3 provides the CF and percentage increase associated with contamination linked to the medical waste incinerator. All ten HMs under analysis had CF values greater than 1, indicating that exposed locations

Table 2: Comparison of the levels of heavy metals with recommended limits.

Element	Mean ± SD (mg/kg)	Range (mg/kg)	Recommended limit (mg/kg)	Reference
Cr	0.2192 ± 0.0363	0.160–0.272	5×10^{-6}–0.01	OSHA; NIOSH [29, 30]
Cd	0.1440 ± 0.0152	0.120–0.160	5×10^{-9}; 5×10^{-6}	WHO; OSHA [29, 31]
As	0.1216 ± 0.0185	0.088–0.144	1×10^{-6}; 1×10^{-5}	WHO; OSHA [29, 31]
Cu	0.2352 ± 0.0838	0.088–0.320	1×10^{-4}	OSHA [32]
Fe	0.3120 ± 0.0299	0.264–0.352	0.3	WHO [31]
Hg	0.0592 ± 0.0180	0.032–0.088	5×10^{-5}; 1×10^{-4}	OSHA; NIOSH [30, 33]
Zn	0.3296 ± 0.0468	0.264–0.400	0.00; 0.005	OSHA; NIOSH [30, 33]
Pb	0.0704 ± 0.0138	0.048–0.088	5×10^{-5}; 7.5×10^{-5}	NIOSH; OSHA [30, 34]
Co	0.1008 ± 0.0187	0.080–0.128	1×10^{-4}	OSHA [32]
Ni	0.1152 ± 0.0200	0.088–0.136	3.8×10^{-10}; 0.001	WHO; OSHA [29, 31]

WHO = World Health Organization; OSHA = Occupational Safety and Health Administration; NIOSH = National Institute for Occupational Safety and Health.

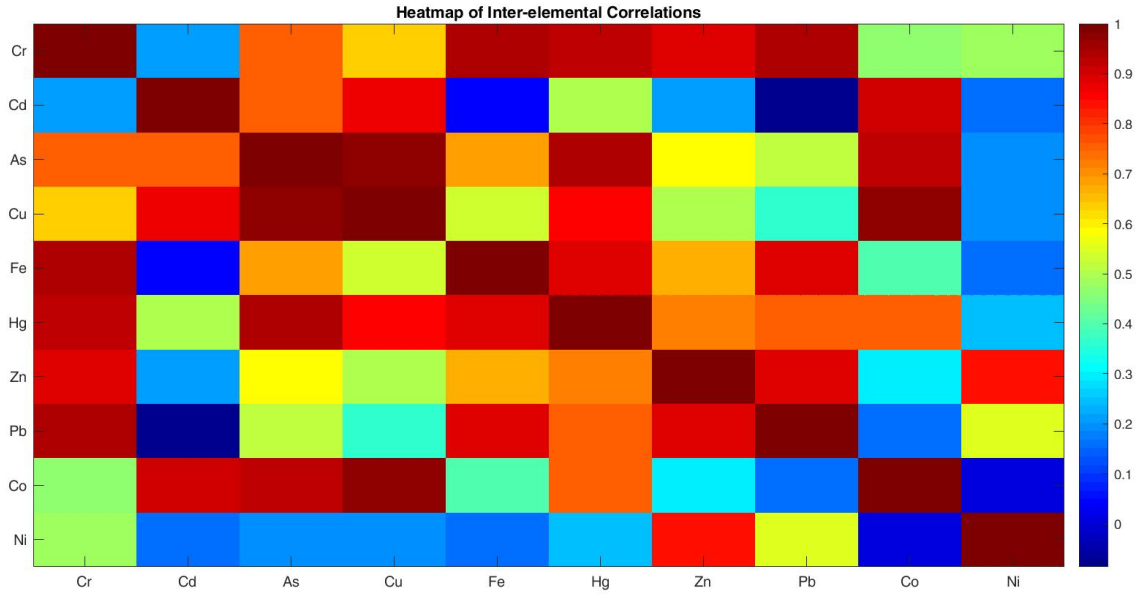

Figure 1: Heatmap of inter-elemental correlations.

had higher concentrations than the non-exposed control location. Notably, Hg showed the greatest CF (2.063), equivalent to a concentration increase of 106.3%. This was followed by Pb, with a CF of 1.583 (58.3% increase), and As, with a CF of 1.477 (47.7% increase). In line with the observed overall PLI of 1.399, which verifies the existence of pollution (PLI > 1), these results identify the incinerator as the main source of HM enrichment in the surrounding hospital environment [37, 38].

The hazard index (HI) was 2.56. The non-carcinogenic and carcinogenic risks from inhaling these particulate-bound HMs are evaluated in Table 4. Because the computed HI of 2.56 is higher than the safety threshold of 1, it suggests a possible non-carcinogenic health risk for individuals nearby [39, 40]. With an HQ of 2.34, which is significantly higher than the allowable limit, Cr appeared as a major contributor to this risk. Mercury also contributed to the non-carcinogenic burden [41], but its individual HQ was still less than unity. In terms of carcinogenic hazards, Table 4 shows that As (5.6×10^{-4}), Cd (2.7×10^{-4}), and Ni (5.8×10^{-5}) had elevated LCR values. These values, especially for As and Cd, are outside the generally acceptable range of 10^{-6} to 10^{-4}, indicating a long-term carcinogenic risk that calls for prompt attention and the adoption of stricter emission-control measures to protect the health of hospital employees and surrounding residents [14, 42].

Table 3: Contamination factor (CF) and percentage increase.

Metal	Non-exposed (μg m^{-3})	Exposed (μg m^{-3})	CF	Increase (%)
Cr	0.160	0.234	1.463	46.3
Cd	0.120	0.150	1.250	25.0
As	0.088	0.130	1.477	47.7
Cu	0.200	0.244	1.220	22.0
Fe	0.264	0.324	1.227	22.7
Hg	0.032	0.066	2.063	106.3
Zn	0.264	0.346	1.311	31.1
Pb	0.048	0.076	1.583	58.3
Co	0.080	0.106	1.325	32.5
Ni	0.096	0.120	1.250	25.0

Table 4: Hazard quotient (HQ), hazard-index (HI) contribution, and lifetime cancer risk (LCR).

Metal	HQ	HI contribution	LCR
Cr	2.34	2.34	N/A
Hg	0.22	0.22	N/A
As	N/A	N/A	5.6×10^{-4}
Cd	N/A	N/A	2.7×10^{-4}
Ni	N/A	N/A	5.8×10^{-5}

4. Conclusion

This study employed FAAS to assess ten HMs (As, Pb, Ni, Zn, Cr, Cu, Hg, Fe, Cd, and Co) in PM collected from the incinerator and three distinct units at Federal Teaching Hospital, Ido-Ekiti, Nigeria. The concentrations ranged from 0.08 to 0.352 mg kg^{-1} at the incinerator site and from 0.08 to 0.264 mg kg^{-1} at the control site, with a mean distribution order of Zn > Fe > Cu > Cr > Cd > As > Ni > Co > Pb > Hg. Statistical analysis revealed significant differences ($p < 0.05$) between the levels of these HMs and the control levels. The levels of these metals were also found to be above the maximum permissible limits. The reportedly high levels of HMs in this study could be attributed to the use of the incinerator, because no other anthropogenic activity that could result in environmental pollution occurred in the neighbourhood during the study period. This could result in a high risk of exposure of waste-management workers, community health workers, and residents near the incineration plant to harmful toxins or pollutants. It is therefore recommended that such plants should be situated far from residential areas and that the chimney fumes should be appropriately channelled. Biological samples from health workers and residents in the vicinity should also be analyzed for HMs. Environmental monitoring and impact assessment should be carried out regularly or periodically at the site, with strict adherence to safety rules by regulatory bodies.

Data availability

The quantitative datasets are available from the corresponding author upon request.

Declaration of competing interest

The authors affirm that the work described in this publication was not influenced by any known competing financial interests or personal ties.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgments

The authors acknowledge the Department of Physics, Federal University Oye-Ekiti, and the Federal Teaching Hospital, Ido-Ekiti (FETHI), Ekiti State, for providing institutional support.

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