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Indoor dust as a mercury reservoir: A case study on indoor microenvironments located in Ernakulam district, Kerala state, India

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ABSTRACT

Introduction: Research on indoor air pollution using settled dust as a medium is limited in India; therefore, this study presents the first comprehensive assessment of Total mercury (THg) in settled indoor dust across various indoor microenvironments in the Ernakulam district of Kerala state, located in southwestern India.

Materials and methods: Sampling was conducted in the third week of February and the first week of March 2022 (n=32) in seven types of indoor microenvironments. Passive sampling was employed for the collection of settled dust samples, and THg in the dust samples was analysed using a Direct Mercury Analyser (Milestone DMA-80, USA).

Results: The average THg concentration across all sampled environments was 0.90±0.66 mg/kg. Correlation analysis revealed a moderate (r=0.48) but statistically significant relationship ($p<0.05$) between THg levels and population density, likely due to contaminants brought to the indoor spaces by the people. Health risk evaluation based on hazard quotient (HQ) for ingestion and dermal exposures suggested that ingestion is the primary route of mercury exposure, with museums posing a high HQing value (0.0295) and furniture making shops posing a low HQing value (0.0001).

Conclusion: This study highlights the need for mercury monitoring in urban built environments and the possible sources of mercury contamination in various indoor microenvironments. The study suggests protective measures for personal protection from dust exposure. Finally, the study concludes by suggesting the requirement for broader surveillance of mercury in various built environments in India.

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Introduction

Mercury (Hg) is a toxic metal and an emerging inorganic contaminant, ranked among the top 20 hazardous substances by the United States Environmental Protection Agency (US EPA) and the Agency for Toxic Substances and Disease Registry (ATSDR) [1-3]. Hg emissions originate from both natural and anthropogenic sources, with about 80% released into the atmosphere, 15% deposited on land, and 5% entering aquatic systems [4].

Globally, Hg emissions are categorized as upstream (e.g., mining, fossil fuel combustion), downstream (e.g., production of consumer goods), and consumption-based emissions (e.g., use of mercury-containing goods) [5]. The distribution of emissions varies by country. China leads in both upstream and downstream emissions, while developed countries such as the United States contribute significantly to consumption-based emissions. In India, mercury emissions were estimated at 310 tonnes in 2010 [6], largely due to coal combustion and metal production [7,8].

Hg exists in several forms in the environment—elemental (Hg^0), monovalent (Hg^+), and divalent (Hg^{2+}) - and may be transformed into toxic organometallic compounds such as methylmercury and phenylmercury depending on the source and conditions [9]. Various industries including electronics, healthcare, and cosmetics are known to use or generate Hg in different chemical forms, many of which can persist in indoor environments.

Accumulated indoor dust in houses, a known predictable indicator of indoor microenvironment pollution from studies carried out mainly in affluent countries, is considered as a reliable parameter for evaluating indoor environments, especially in the Indian scenario which has a specific climatic and infrastructural profile. In several urban and semi-urban areas of India, bad ventilation, high levels of outdoor particulates, and also frequent entry of traffic-and-construction related pollutants assist in indoor dust build up [10]. Poor cleaning habits and minimal utilization of air filtration systems also permit fine particles and related contaminants to settle on indoor contact surfaces [11]. Therefore, accumulated dust also serves as a historical archive of trace metals, organic pollutants and other toxicants reflecting the combined effects of multiple sources operating over time. Consequently, settled indoor dust allows for a holistic assessment of general aspects of building environment quality and is an appropriate medium to estimate human exposure risk through ingestion and dermal contact [12].

International studies have recognized indoor dust as an important pathway for mercury exposure—especially via ingestion, inhalation, and dermal contact[13, 14]. Studies conducted in Europe, North America and East Asia has established indoor dust as a sink and a secondary source of mercury with possible sources such as damaged compact fluorescent lamps, old switches and batteries along with outdoor infiltration [15]. These internationally established exposure routes find significance to indoor microenvironments in India as most of the Indian indoor microenvironments have poor ventilation, lacks regular cleaning and have mercury sources such as compact fluorescent lamps, old switches, wires and batteries, all of which enhance dust deposition. So, when international evidence highlights the toxic effects of mercury in indoor dusts, no such investigations have been conducted in India. Most Indian air pollution studies have focused on outdoor air or household emissions related to solid fuel combustion in rural settings [16, 17].

Recent literatures have reported Total mercury (THg) levels in indoor dust from museums (150–200 ng/m³)[18], educational institutions (0.15–10.59 mg/kg; [19]), and antique shops. Other indoor microenvironments such as electrical

and electronics shops, bakehouses, textile manufacturing units, and furniture workshops are also considered potential sources of indoor mercury, though data on their contamination levels remain limited [20].

Given the increasing concern over chronic mercury exposure and its health implications—ranging from neurotoxicity and nephrotoxicity to immunotoxicity and developmental effects [21]. A comprehensive investigation into indoor dust THg levels is urgently needed. This need is particularly acute in Indian settings, where indoor environments are shaped by unique architectural, cultural, and regulatory contexts that influence pollutant and human exposure patterns [16].

In this context, the present study offers the first comprehensive assessment of Total mercury (THg) in settled indoor dust across a diverse array of indoor microenvironments in India. The studied indoor microenvironments include museums, antique shops, pharmacy cum clinics, educational institutions, furniture making shops, electrical and electronics shops, a bakehouse, a textile unit, a hardware store and a warehouse. These environments were selected based on their potential for mercury use and accumulation in dust via indoor materials and activities.

Materials and methods

Study area

The study was conducted in the Ernakulam district, located on the southwest coast of India (Fig. 1). This district serves as the commercial hub of Kerala, contributing significantly to the state's economy through its diverse industrial and trade-related activities. The region experiences a tropical climate with hot summers, mild winters, and substantial annual rainfall. The average maximum temperature is approximately 32.7 °C, while the average minimum temperature is 22.1 °C. Relative humidity ranges from 23% to 89%, and the average annual rainfall is 3099.1 mm.

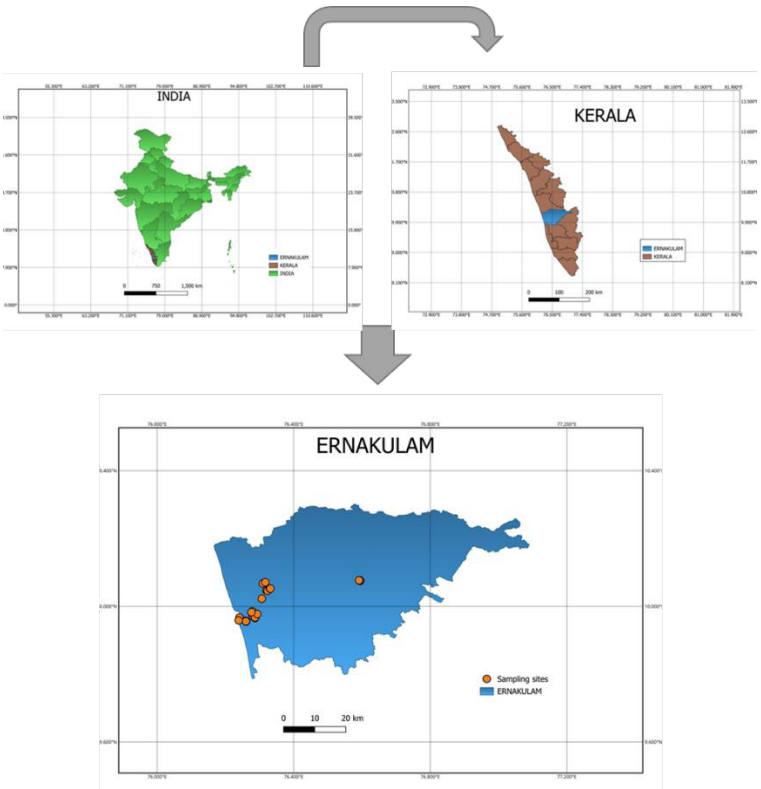

Fig. 1. Study area (from clockwise direction: map of India – map of Kerala state- map of Ernakulam district) depicting the sampling sites

Sample collection, preparation and analysis

A total of 32 indoor dust samples were collected from various microenvironments, including furniture-making shops (F, n = 6), educational institutions (EI, n = 6), electrical and electronics shops (EL, n = 4), pharmacies (PH, n = 3), with PH2 and PH3 representing combined pharmacy-cum-clinic setups, antique shops (AS, n = 5), museums (MU, n = 4), and others (OT, n = 4), comprising a hardware shop, a textile manufacturing unit, a bakery, and a warehouse. Sampling was carried out during the summer season (February–March 2022). The geographic coordinates (latitude and longitude) of each sampling location were recorded using a GPS device and are provided in Table 1.

The dimensions of the indoor spaces were measured using a laser distometer (BOSCH GLM 40). Additional parameters, including the number of occupants, cleaning frequency, average distance from nearby roads/traffic, and distance from parking areas, were also recorded for each site.

Approximately 50–100 g of dust was collected by sweeping surfaces such as floors, window sills, fans, tables, and cupboards using a clean brush. The swept dust was transferred into a paper bag, wrapped in aluminium foil, sealed in a zip-lock bag, and transported to the laboratory at 4 °C. After each sampling collection, the brush was rinsed thoroughly with acetone to prevent cross-contamination. In the laboratory, samples from locations with similar characteristics were homogenised and treated as a single composite sample. The dust samples were then air-dried and subsequently heated in a hot-air oven at 30 °C [22], for a few hours to facilitate drying and ease of sieving. The temperature was set at 30 ºC in order to prevent the volatilisation of mercury. The dried dust was then sieved using a mesh sieve with a cut of size of 200 µm to obtain the fine fraction. About 0.1 g of the sieved dust was subjected to total mercury (THg) analysis using a Direct Mercury Analyser (DMA-80, Milestone) based on US EPA Method 7473.

Quality assurance

Validation of the mercury analysis was performed using a certified reference material, Estuarine Sediment (ERM-CC580). The recovery rate of total mercury was found to be 98.07 ± 0.21%, confirming the reliability of the method. The detection limit for mercury using this method was 0.5 ng.

Statistical analysis

All statistical analyses were performed using IBM SPSS version 22.0. The normality of the dataset was evaluated using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Spearman's correlation was used to assess associations between THg concentrations and parameters such as room volume, cleaning frequency, and number of inhabitants. The Kruskal–Wallis test was conducted to determine differences in THg concentrations and indoor parameters across different microenvironments. Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) were further performed to link the sites based on similarities in mercury contamination profiles.

Contamination factor

The contamination factor analysis was estimated for each sampling location using Eq. 1 [23].

$$CF = \frac{Cn}{Bn} \quad (1)$$

Where CF = Contamination factor

C_n = concentration of THg in a particular

indoor microenvironment (mg/kg)

B_n= background concentration of THg in Indian soil

B_n= 0.05 mg/kg for Indian soils [24].

The classification of contamination factors according to pollution is shown in Table 1.

Human exposure sssessment

The exposure assessment was estimated using equations 2-5, which include Average Daily Dose (ADD), Hazard Quotient (HQ), and Hazard Index (HI) [23, 24].

$$ADD_{ing}=(C*IngR*CF*EF*ED)/(BW*AT) \quad (2)$$

$$ADD_{dermal}=(C*ESA*CF*AF*DAF*EF*ED)/(BW*AT) \quad (3)$$

Where ADD_{ing} represents the average daily dose intake through ingestion, ADD_{dermal} signifies the average daily dose exposure through dermal contact, C = THg concentration in indoor dust (mg/kg), IngR= Ingestion rate (mg/day), EF= Exposure frequency (days/year), ED = Exposure duration (years), BW= Average body weight (kg), AT= Average time (days), CF= Conversion factor (kg/mg), ESA= Exposed skin area (cm^2), AF= Skin adherence factor (mg/cm^2), DAF= Dermal absorption factor (unitless). The values utilised for the variables in Eqs. 2 and 3 are presented in Table 2. Inhalation exposure for the samples was omitted due to the size of sieved dust sample considered for analysis. Inhalation exposure could only be computed if the size of sieved dust samples is < 100 µm [26], where particles <200 µm were used in this study.

$$HQ_{ing}=\frac{ADD_{ing}}{RfD_{ing}} \quad (4)$$

$$HQ_{dermal}=\frac{AD_{Ddermal}}{Rf_{Ddermal}} \quad (5)$$

Here, HQ_{ing} and HQ_{dermal} represent the hazard quotient through ingestion and dermal contact, respectively. RfD stands for Reference Dose. The reference dose for mercury in the case of ingestion (RfD_{ing}) is 3.0 x 10^{-4}, and the reference dose for mercury in the case of dermal exposure (RfD_{dermal}) is 2.10 x 10^{-5} [25]. The Hazard Index (HI) can be derived from the HQ of both ingestion (HQ_{ing}) and dermal exposure (HQ_{dermal}) by adding them together, as shown in Eq. 6.

$$HI=\Sigma HQ_i \quad (6)$$

Where i = route of exposure (ingestion or dermal exposure)

Results and discussion

Total mercury (THg) levels in different indoor microenvironments

The concentration (Mean ± S.D) of total mercury (THg) in indoor dust exhibited substantial variation across different microenvironments (Table 2). Among the studied sites, museums (MU) had the highest THg levels (3.0 ± 2.75 mg/kg). In contrast, furniture-making shops (F) recorded the lowest contamination, with a mean of 0.011 ± 0.005 mg/kg. The wide variability in THg concentrations likely reflects differences in activity type, building characteristics, and materials used. The increasing urbanisation and commercial activity in Indian cities such as rising vehicular traffic, construction, and population density—may contribute to mercury emissions and resuspension of mercury-laden dust. Vehicular movement, in particular, can introduce

mercury through tire wear, braking, and exhaust emissions. The movement of people can also facilitate the transport of outdoor dust into indoor spaces.

Table 1. Classification of contamination factor [25]

Range	Level of contamination
CF < 1	Low contamination
1< CF ≤ 3	Moderate contamination
3 ≤ CF < 6	Considerable contamination
CF ≥ 6	Very high contamination

Table 2. THg concentration (mg/kg) in the investigated indoor microenvironments

Indoor microenvironments*	Mean ±S.D. (mg/kg)
F	0.011 ± 0.005
EL	0.068 ± 0.063
EI	0.42 ± 0.34
PH	1.14 ± 0.52
AS	1.44 ± 0.67
MU	3.0 ± 2.75
OT	0.20 ± 0.24

* F: furniture-making shops, EL: electrical and electronics shops, EI: educational institutions, PH: pharmacies, AS: antique shops, MU: museums, and OT: others

Median THg levels observed in museums in this study (2.94 mg/kg) were lower than those reported in the National History Museum of Rouen, France (11 mg/kg)[18]. However, the THg levels found in our study were notably higher than levels reported in road dust from industrial zones in India [27]. Due to limited available data, comparison with other indoor environments like antique shops, furniture units, and pharmacies remains scarce.

In educational settings, the THg concentration in this study (median: 0.30 mg/kg) was higher than that reported in kindergartens in Ghana (median: 0.16 mg/kg; [28]). This difference may be due to the presence of laboratories in Indian secondary schools and colleges, which act as sources of mercury. Similarly, retail environments dealing with electrical and electronic goods showed measurable mercury levels. Yet, the research on these spaces remains limited despite growing evidence from e-waste sites globally [20, 29, 30].

Statistical analysis

Statistical analysis revealed that THg concentrations were in non-normal distribution ($p < 0.05$) across the sites, indicating the presence of localized hotspots. High Hg levels in museums and antique shops are likely due to the use of Hg-based preservatives applied to artefacts to prevent degradation. These Hg compounds can evaporate into the air and then attach to airborne particles through a process called gas-particle partitioning. Over time, these particles settle as dust on indoor surfaces, contributing to mercury accumulation in dust [31].

Table 3 shows the reported concentration of Hg present in various indoor microenvironments.

In pharmacies and clinics, damaged or malfunctioning instruments like thermometers and sphygmomanometers could result in Hg spills. In laboratories within educational institutions, the handling of various forms of mercury contributes to contamination. Other microenvironments such as bakeries, textile manufacturing shops, hardware stores, furniture-making units, and storage godowns may release Hg via paints, wires, batteries, electrical equipment, and adhesives.

To investigate differences in THg levels across different types of indoor environments, a Kruskal–Wallis test was conducted ($p < 0.05$), revealing statistically significant variation. This suggests that indoor function and associated activities are key determinants of THg contamination levels.

Spearman's correlation analysis (Fig. 2) showed a significant positive correlation between THg concentration and inhabitant number, as well as with room volume. Higher THg concentrations were observed in more populated indoor environments. For example, museums—where visitor numbers are high and rooms are large—showed elevated THg levels, suggesting that Hg-laden dust could be introduced through human activity, such as tracking in contaminants via footwear [32].

Table 3. Reported concentration of Hg present in various indoor microenvironments

Sl.No	Location		Microenvironment	Concentration (mg/kg)			Reference
	City/District/State	Country		Range	Mean	Median	
1	Ernakulam	India	Museums, Antique shops, Pharmacies, Educational Institutions, Furniture making shops, Bakehouse, Warehouse and Workshop	0.006-5.57	0.90	0.30	Current study

Table 3.Continued

Sl.No	Location		Microenvironment	Concentration (mg/kg)			Reference
1	Wuhan	China	Kindergarten	0.150 – 10.590	1.66	0.58	[19]
2	-	China	Municipal solid waste incinerator (interior)	0.55 – 0.87	-	-	[3]
			Hospital waste incinerator (interior)	1.1			
3	Rouen	France	Museum	-	-	11	[18]
4	Kumasi	Ghana	Kindergarten and nursery	BDL* - 1.38	381.30	357.32	[28]
5	Ahvaz	Irn	Household dust and outdoor settled dust	0.040-3.95 (household dust)	0.670 (household dust)	0.370 (household dust)	[23]
				0.02-1.06 (outdoor)	0.07 (outdoor)	0.04 (outdoor)	
	Asaluyeh			0.01-0.12 (household dust)	0.05 (household dust)	0.03 (household dust)	
				0.02 -0.26 (outdoor)	0.04 (outdoor)	0.02 (outdoor)	
	Zabol			0.01-0.08 (household dust)	0.04 (household dust)	0.04 (household dust)	
				0- 0.06 (outdoor)	0.03 (outdoor)	0.03 (outdoor)	

* BDL – Below Detection Level

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Fig. 2. Correlation analysis of THg concentration with room volume, cleaning frequency and population number

While cleaning frequency appeared to influence contamination levels (furniture-making shops with frequent cleaning had the lowest THg levels), the correlation was not statistically significant. Nonetheless, a pattern emerged wherein environments with lower cleaning frequency, such as museums and antique shops, tended to exhibit higher Hg contamination.

Together, these results underscore the multifactorial nature of indoor Hg pollution. Factors such as microenvironment type, number of occupants, room volume, and specific usage patterns shape Hg dynamics indoors. In addition to this, environmental factors such as ventilation, flooring materials used and air-conditioned rooms influence the THg concentration in indoor spaces. Indoor spaces with limited ventilation results in increased accumulation of contaminants in indoor dust by restricting the movement of particles from the point of generation to outdoor spaces [33]. In case of flooring materials, porous floors and floors covered with carpets emit mercury [34]. Similarly air conditioner with poor filtration unit redistributes the contaminated particles to indoor spaces which consist of heavy metals including mercury [35].

The indoor spaces of certain sites in the current study had floors covered with carpets and limited ventilation which may have contributed to accumulation of mercury in the settled dust. Air-conditioned rooms were observed in one electrical and electronics shop and a pharmacy-clinic setup, but details about filter units are absent hence cannot confirm the redistribution of particles from the filtration units. This highlights the need for targeted monitoring and source control to reduce potential exposure and support public health protection in indoor spaces.

The Principal Component Analysis (PCA) biplot (Fig. 3) provides a visual representation

of the relationships between different indoor microenvironments and the selected variables: total Hg (THg) levels, room volume, cleaning frequency, and population number. The first principal component (Dim1) accounts for 62.57% of the variance in the dataset, while the second component (Dim2) explains an additional 34.1%, together capturing 96.67% of the total variability. The arrows (vectors) represent the direction and strength of influence of each variable. Variables such as THg levels and room volume are closely aligned along Dim1, suggesting their strong contribution to the first principal component. In contrast, cleaning frequency and population number are more aligned with Dim2, indicating a greater influence on the second principal component.

A negative relationship is evident between cleaning frequency and THg levels, as the vectors point in nearly opposite directions. This suggests that spaces with higher cleaning frequency tend to have lower Hg accumulation. Individual sampling points plotted in the biplot represents the indoor environments. For example, MU4 and MU2 (museums) lie far along the positive side of Dim1, aligning with high THg levels and room volume. On the other hand, sites such as OT3, MU1, and PH2 are more influenced by higher cleaning frequencies and population numbers. Locations clustered near the origin (such as most educational institutions, electrical shops, and furniture workshops) reflect moderate or average values across all measured parameters.

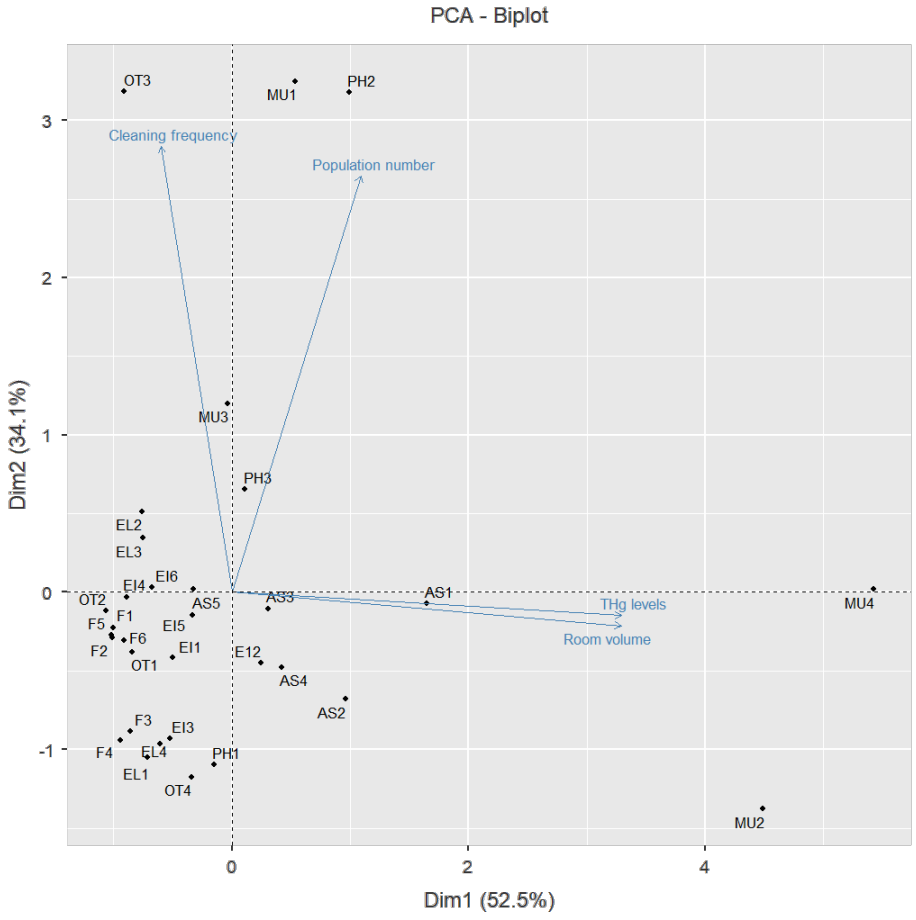

Fig. 3. Principal component analysis (PCA) - biplot chart depicting the relationship between various indoor microenvironments

The Hierarchical Cluster Analysis (HCA) dendrogram (Fig. 4) complements the PCA by grouping the indoor sampling sites based on their similarity in Hg contamination profiles and associated variables. The vertical height of the branches represents the dissimilarity between samples or clusters. MU2 and MU4 are clearly distinct from the rest, forming an isolated cluster at a high linkage distance, which is consistent with their elevated THg concentrations as observed in the PCA. Other museum samples (MU1, MU3), pharmacies (PH2, PH3), and some electrical and electronics shops form clusters at an intermediate level, indicating moderate similarity in indoor Hg contamination characteristics.

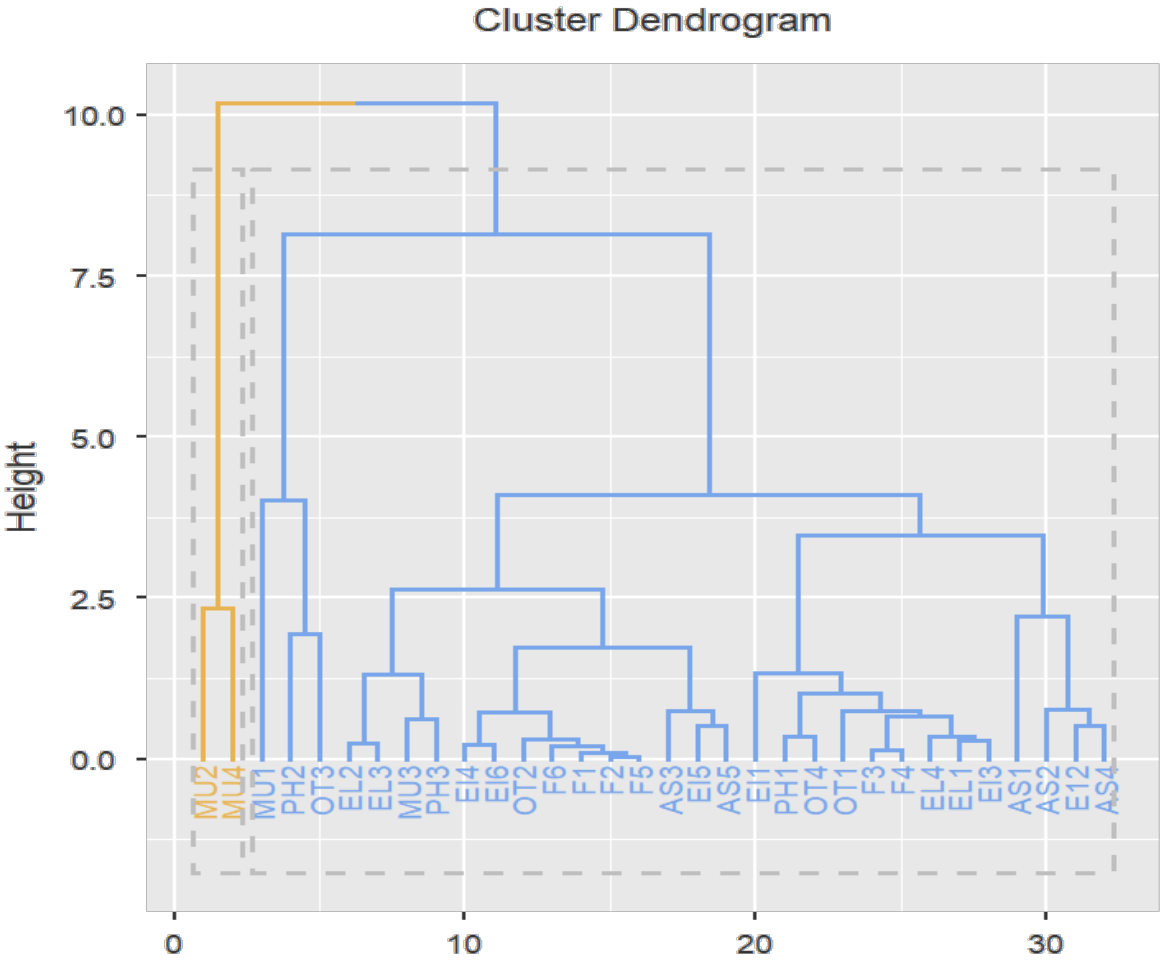

Fig. 4. Cluster dendrogram showing similar and different indoor microenvironment clusters through Hierarchical cluster analysis (HCA)

Clusters formed at lower heights, including various furniture-making shops, educational institutions, and electronics shops, indicate relatively similar indoor conditions and lower levels of Hg contamination.

Contamination factor and human health risk assessment

Building on the findings of THg concentration levels across indoor microenvironments, the Contamination Factor (CF) assessment provided additional insight into the extent of Hg contamination relative to background levels. The CF values, presented in Table 4, illustrate the degree of Hg enrichment in settled dust across different sampling sites and offer a clearer understanding of the contamination severity.

The CF analysis revealed very high levels of Hg contamination in several indoor microenvironments, specifically museums, antique shops, pharmacies, and few educational institutions. These sites exceeded the threshold for "very high contamination" classification, indicating significant anthropogenic Hg input. In comparison, the 'Others' category (OT) and electrical and electronics shops (EL) were classified as moderately contaminated, while furniture-making shops (F) showed very low contamination, suggesting minimal Hg presence.

Table 4. Contamination factors of various indoor microenvironments

Indoor environments*	Contamination factor	Level of contamination**
F1	0.12	LC
F2	0.30	LC
F3	0.41	LC
F4	0.20	LC
F5	0.14	LC
F6	0.19	LC
EL1	0.35	LC
EL2	0.85	LC
EL3	1.18	MC
EI1	3.2	CC
EI2	19.97	VH
EI3	6.03	VH
EI4	2.13	CC
EI5	13.28	VH
EI6	5.86	CC
OT1	0.58	LC
OT2	0.96	LC

Table 4. Continued

Indoor environments*	Contamination factor	Level of contamination**
PH1	15.54	VH
EL4	3.2	CC
PH2	34.77	VH
PH3	18.18	VH
OT3	3.2	CC
OT4	10.91	VH
AS1	49.95	VH
AS2	32.23	VH
AS3	24.97	VH
AS4	20.78	VH
AS5	15.56	VH
MU1	11.56	VH
MU2	104.17	VH
MU3	13.51	VH
MU4	111.37	VH

* F: furniture-making shops, EL: electrical and electronics shops, EI: educational institutions, PH: pharmacies, AS: antique shops, MU: museums, and OT: others

**Low contamination: LC; moderate contamination: MC; considerable contamination: CC; very high contamination: VH

The mean CF values across indoor microenvironments followed the order:

MU (60.15) > AS (28.70) > PH (22.83) > EI (8.41) > OT (3.91) > EL (1.39) > F (0.23). These values highlight that Hg concentrations in museums were approximately 60 times higher than the background level, while antique shops and pharmacies exhibited contamination levels around 20–30 times greater. Educational institutions also showed elevated contamination, albeit to a lesser extent.

The elevated CF values in museums, antique shops, and pharmacies can be directly linked to known sources of Hg within these spaces. In museums, Hg may be introduced through preservative chemicals used for safeguarding biological or historical specimens. Similarly, in pharmacies and clinics, medical devices such as thermometers and sphygmomanometers containing elemental Hg can act as sources, especially when damaged or improperly handled. The accumulation of Hg in indoor dust from these sources contributes to the significantly higher CF values in these environments.

Conversely, electrical and electronics shops, although known to contain Hg in devices

like fluorescent lamps and switches, showed only moderate contamination, possibly due to limited device breakage or better containment. Furniture-making shops demonstrated the lowest CF values, consistent with their low measured THg concentrations, suggesting minimal use or emission of Hg in such environments.

Human exposure to Hg in indoor environments typically occurs through four main pathways: inhalation of dust particles or Hg vapour, ingestion via hand-to-mouth activity, and dermal contact. Given that this study focused on settled dust less than or equal to 200 µm, the primary exposure routes assessed were ingestion and dermal contact [25].

The risk assessments were carried out for all types of indoor spaces using standard indicators such as Average Daily Dose (ADD), Hazard Quotient (HQ), and Hazard Index (HI). These were calculated with a focus on adult populations, as adults were the predominant occupants across the investigated microenvironments (Table 5)

Table 5. Mean average daily dose, hazard quotient and hazard index of various indoor microenvironments

Indoor Microenvironments*	ADD_{ing}	ADD_{dermal}	HQ_{ing}	HQ_{dermal}	HI
F	3.34E-08	5.09E-10	0.0001	2.42E-05	0.0001
EL	2.05E-07	3.12E-09	0.0006	0.0002	0.0008
EI	1.24E-06	1.88E-08	0.0041	0.0009	0.005
PH	1.81E-06	2.76E-08	0.0060	0.0013	0.0073
AS	4.22E-06	6.42E-08	0.0141	0.0031	0.0172
MU	8.84E-06	1.35E-07	0.0295	0.0064	0.0359
OT	5.75E-07	8.75E-09	0.0019	0.0004	0.0023

* F: furniture-making shops, EL: electrical and electronics shops, EI: educational institutions, PH: pharmacies, AS: antique shops, MU: museums, and OT: others

Ingestion exposure (ADD_{ing}) and dermal exposure (ADD_{dermal}) was highest in museum and antique shops. A similar pattern emerged in the hazard quotient analysis. When combining ingestion and dermal exposures into a cumulative hazard index (HI), museums recorded the highest overall value, while furniture-making shops had the lowest. However, none of the indoor microenvironments exhibited an HI value greater than 1, indicating low non-carcinogenic risk under present conditions.

Nonetheless, Hg is a, capable of accumulating in indoor environments over time. This underscores the need for, even in settings where current exposure levels are below concern thresholds. Without intervention, long-term accumulation may elevate future risk, especially in frequently occupied or poorly ventilated spaces. At the biological level, Hg exerts toxicity by binding to sulfhydryl and selenohydryl groups in proteins, disrupting enzyme activity and cellular function across various organs [36]. The form of Hg, exposure concentration, and exposure route all influence its toxicological profile. Hg primarily affects the central nervous system, whereas are more damaging to the gastrointestinal tract and kidneys. Hg, such as methylHg, are distributed systemically and accumulate in critical tissues

including the brain, liver, kidneys, placenta, and fetal organs, contributing to neurodegenerative and developmental effects. Another primary reservoir for inorganic Hg is proximal renal tubules where Hg binds to metallothionein.

Toxic effects may also be influenced by co-existing elements. For instance, Se can interact with Hg, forming complexes that may mitigate or exacerbate toxicity depending on the relative concentrations. Other co-contaminants commonly found in indoor environments—such as Pb, Cd, and As- can also interact with Hg, resulting in additive or synergistic toxic effects. For example, both lead and Hg target the nervous system, while Cd and Hg collectively increase renal burden [36, 37].The combined presence of these elements in dust can magnify risks to human health, particularly with chronic exposure.

These findings collectively highlight the critical need for proactive management of Hg contamination in indoor environments. Regular surveillance, adequate ventilation, reduced use of Hg-containing materials, and occupational safeguards such as personal protective equipment (PPE) for cleaning and maintenance staff are essential for minimizing long-term health impacts. Given the persistent nature and cumulative toxicity of Hg, even low-level exposures should not be overlooked in public health assessments.

Conclusion

This study presents the first comprehensive assessment of THg concentrations in indoor settled dust across a range of microenvironments in Ernakulam district, Kerala state located in south-western India. The results revealed substantial variability in Hg levels among the sampled sites, with particularly elevated concentrations observed in antique shops and museums. Low cleaning frequencies, especially in museums, appeared to exacerbate Hg accumulation, indicating that regular and thorough cleaning practices could be an effective strategy for reducing exposure. Increasing the volume of indoor spaces relative to occupancy may also aid in pollutant dilution. Use of Personal Protective Equipment (PPE) such as gloves and masks is advisable for cleaning personnel and others who may be regularly exposed to dust in these settings.

Furthermore, the study highlights the need for broader surveillance of Hg in indoor environments across different building types in India. Omission of inhalation exposure in computation of non-carcinogenic human health risk assessment is one of the limitations of the present study. So human health risk assessment including these three routes of exposure should be considered in the future studies. The present study also limits mercury speciation which is also to be addressed in the future studies. Comprehensive monitoring would help identify sources and patterns of contamination, inform exposure assessments, and support the development of strategies to reduce indoor Hg levels and safeguard public health.

Since indoor settled dust acts as a sink for heavy metals including mercury, step by step phase out of this element should be implemented. As India has become a member of Minamata convention since 2018, which aids in regulating mercury, implementation of certain policies replacing the older products and equipments with mercury can be done. Furthur establishment of permissible limit or standard threshold value should be implemented likewise indoor air mercury. Also a mercury spill protocol and phase out of mercury containing older instruments can be implemented at institutional level as a beginning stage. Integrating indoor air mercury with India's National Clean Air Programme (NCAP) and developing indoor air mercury standards finds significance in countering health risk thereby improving public health.

So in general, This study provides a baseline

for assessing indoor mercury exposure in Indian urban settings. However, future studies should incorporate inhalation exposure pathways and vulnerable populations such as children. Establishing standardized indoor mercury monitoring protocols and regulatory guidelines is urgently recommended.

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Competing interests

The authors declare no conflicts of interest.

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Ethical considerations

Ethical issues (Including plagiarism, misconduct, data fabrication and/or falsification, double publication and/ or submission, redundancy, etc.) have been completely observed by the authors. Permissions were taken from owners of the indoor microenvironments subjected to sampling.

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