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Assessment of prevalence of elevated blood lead levels and risk factors among children and pregnant women in Bihar, India

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ABSTRACT

Background: While modeled estimates and studies in contaminated areas indicate high lead exposure among children in Bihar, India, local data on lead exposure in the child population is limited.
Objectives: To characterize lead exposure, and assess potential sources of lead exposure among a state-representative sample of children and their pregnant mothers residing in Bihar.
Methods: Blood samples were collected from 697 children under five and 55 pregnant women from eight districts in Bihar. Blood lead levels were determined using capillary blood and a portable lead analyzer. Household demographics, home environment, behavior, and nutrition information were collected through computer-assisted personal interviews with primary caregivers. Logistic regression was used to assess associations between potential risk factors and elevated blood lead levels.
Results: More than 90% of children and 80% of pregnant women reported blood lead levels ≥5 μg/dL. Living near a lead-related industry and pica behavior of eating soil were significantly associated with increased odds of having elevated blood lead levels. Additional risk factors for having a blood level ≥5 μg/dL included the use of skin lightning cream (aOR = 5.11, 95%CI: 1.62, 16.16) and the use of eyeliners (aOR = 2.81, 95%CI: 1.14, 6.93). Having blood lead levels ≥10 μg/dL was also significantly associated with the household member who had an occupation or hobby involving the use of lead (aOR = 1.75, 95%CI: 1.13, 2.72).
Discussion: Elevated blood lead levels were prevalent among children and pregnant women in Bihar, indicating the urgent need for a comprehensive lead poisoning prevention strategy.

1. Introduction

Lead is an environmental toxicant that affects virtually every system in the body. Lead exposure can cause anemia, hypertension, renal impairment, immunotoxicity, and toxicity to the reproductive organs (Tchounwou et al., 2012). Young children are particularly susceptible to lead poisoning because they absorb far more lead from their environments than adults, and because their central nervous systems are still developing (Schwartz, 1994). Lead can affect children's brain development even at low levels of exposure. Lead exposure can result in reduced intelligence quotient (IQ), behavioral changes, and reduced educational attainment and lifetime earnings (Budtz-Jørgensen et al., 2013; Lanphear et al., 2005; Nevin, 2007; Wright et al., 2008; Bellinger et al., 2005; Palaniappan et al., 2011; Heng et al., 2022; Galiciolli et al., 2022). Pregnant women with high blood lead levels may suffer from adverse birth outcomes and the fetus can be exposed as lead can easily cross the placenta to the fetus (Flora et al., 2012; Cantor et al., 2019).

According to the Institute for Health Metrics and Evaluation (IHME) global model estimates, over 275 million Indian children had blood lead levels (BLLs) exceeding 5 μg/dL, a threshold above which clinical intervention is generally recommended (Rees and Fuller, 2020). A recent report that modeled statewide BLLs based on data from IHME estimated the highest average BLL in Bihar among all Indian states (Kumar, 2022). However, there are several important gaps in

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understanding and characterizing lead exposure among children in Bihar. Apart from the modeled estimate and highly localized studies with small sample sizes,(Ansari et al., 2020; Brown et al., 2022) no local data has been previously collected using a representative sample of the state to understand the distribution of BLL in the general child population.

There is also a lack of understanding of sources of lead exposure and predictors of BLLs among general communities. Studies assessing BLL among young children in Bihar previously focused on children living near informal used lead-acid (ULAB) battery recycling sites (Ansari et al., 2020; Brown et al., 2022). A 2013 study measured lead levels in paint samples and found that over 45% of samples reported lead levels exceeding the international best practice standard of 90 parts per million and some decorative paint samples reported very high lead content (over 80,000 ppm) (Mohanty et al., 2013). There is also accumulating evidence of lead exposure through the use of unsafe consumer products adulterated or contaminated with lead, (Rees and Fuller, 2020) including spices, (Lin et al., 2010; Goswami and Mazumdar, 2014) cookware or dinnerware, jewelry, (Patil et al., 2006) toys, packaged food, (Singhal, 2016) cosmetics, (Goswami, 2013) and traditional medicines (Raviraja et al., 2010). A recent screening of consumer products purchased in markets from three Indian states found lead levels exceeding recommended standards in ceramic and metal food wares, cosmetics, toys, and spices (Lead in Consumer Goods, 2023). There is an urgent need to understand sources of lead exposure through improved collection of local data and a systematic assessment of the relationship between these sources and BLLs.

In the present study, we explored the distribution of blood lead levels and the prevalence of elevated BLLs among children under the age of 5 using a state-wide representative sample. BLLs among pregnant women who are mothers of participating children were also assessed and the relationship between maternal and child blood lead levels was explored. Moreover, the prevalence of potential risk factors of lead exposure and their association with elevated blood lead levels among children were also evaluated.

2. Material and methods

2.1. Study population and sampling design

This cross-sectional study was conducted in children aged 13 months–60 months and their pregnant mothers living in Bihar. We calculated the sample size using the formula $n = Z^2 \frac{P(1-P)}{e^2}$, setting the level of confidence (Z) to 1.96, the margin of error (e) to 0.05, and the proportion of children with BLL $\geq$5 μg/dL (P) to 0.54 based on the 2019 GBD estimate for India (Rees and Fuller, 2020). Taking a design effect (accounting for intercorrelation within clusters) of 1.5 and an expected response rate of 85% into account, the final sample size was targeted at 700. A multi-stage sampling design was used to select a state-representative sample of children and a convenience sample of pregnant women who are also mothers of participating children (Fig. S1). We first divided all districts in Bihar into four geographic regions (south, north, east, and west regions) and then randomly selected 2 districts from each region (8 districts in total) to ensure geographic representation. In the selected districts, 2–4 wards or villages were randomly selected using probability proportional to size based on the population reported in the 2011 Census (India Ministry of Home Affairs, 2011). Urban areas were intentionally oversampled by selecting 4 urban wards from districts in the state's most populous city, Patna. Within these wards/villages, households were selected using the random walk sampling approach. Screening questions based on inclusion and exclusion criteria were used to ensure that the blood lead level of a participant is relevant to their current residency, their general health allows their participation, and they are willing to participate in this study. Inclusion criteria for children included, 1) age 13 months–60 months; 2) living in the current household for at least 2 months and spending not more than 1 month outside the area during the last 2 months; and 3) the child's caregiver is capable and willing to provide written consent. Inclusion criteria for pregnant women included, 1) age 18–49 years with a normal pregnancy course; 2) mother of a participating child; 3) living in the current household for at least 2 months; and 4) being capable and willing to provide written consent. Exclusion criteria for children and pregnant women included, 1) having parent/guardian/self-reported acute or terminal illness; and 2) having any other significant disease, disorder, or finding which may significantly impose a risk to the volunteer because of participation, affect the ability of the volunteer to participate, or impair interpretation of the study data.

2.2. Data and sample collection

The study was conducted after obtaining approval from the BRANY (Biomedical Research Alliance of New York) Institutional review board located in the U.S. (Protocol Number: 22-176-522) and the ethics committee of the Indian Council of Medical Research- Rajendra Memorial Research Institute of Medical Sciences located in Patna, Bihar (Approval letter no. RMRI/EC/54/2022, dated September 21, 2022). The field visits were conducted by personnel certified in human subjects research ethics and on the study protocol between December 2022 and February 2023. Each participant was visited at their home and written informed consent was obtained from the parents of participating children and the pregnant women by researchers who were native Hindi speakers. A copy of the consent form was provided to the participants. Computer-assisted personal interview was conducted with the primary caregiver or the pregnant mother to collect information on factors that may be related to a child's lead exposure at home. This included take-home exposure (e.g., parental occupation or hobby), home environment (e.g., source of drinking water, chipping paint), use of consumer products that may contain lead (e.g., spice, cosmetics), behavioral and nutritional factors that may modify the exposure (e.g., pica behavior, nutrition, household and personal hygiene), and demographics (e.g., age, sex, primary caregiver's educational attainment) (Table S2). If a below-poverty-line (BPL) certificate was issued by the Indian government, the household was considered economically disadvantaged and used as an indicator of economic status. A clean area was identified in the home to conduct the blood collection and testing to reduce the potential for sample contamination. The field team shared BLL results with the family along with recommendations tailored to the child's BLL to reduce lead exposure and if relevant, to seek further assessment with a clinician.

2.3. Blood lead measurements

The blood lead levels of participants were determined using capillary blood and analyzed using a point-of-care analyzer (i.e., LeadCare II). The LeadCare analyzer has been approved by the U.S. FDA for blood lead screening and reported comparable results to the laboratory approaches in previous verification studies, including some conducted in India (Jain and Hu, 2006; Nakata et al., 2021; Pineau et al., 2002; Taylor et al., 2001). After cleaning the child's hand and finger, a few drops of blood were obtained from a finger prick using a capillary tube and added to the treatment reagent. The mixture was then added to a sensor and analyzed, with results provided in a few minutes. Two levels of kit controls were analyzed at the beginning of each sampling day. To further validate the LeadCare measurements, we also collected venous blood samples from 5% of pregnant women (n = 32). These samples were analyzed by a nationally accredited laboratory using Inductively coupled plasma mass spectrometry (ICP-MS). LeadCare analyzer has a reportable range of 3.3–65 μg/dL and results below the detection limit were assigned a value of 2.3 following the formula of $\frac{Detection\ Limit}{\sqrt{2}}$. Only 6 children reported values below the detection limit.

2.4. Statistical analysis

Sampling weights were calculated and applied in the analysis using srvyr package in R software to account for the complex sampling design. Analyses of pregnant women were conducted using unweighted data. Both geometric and arithmetic means were reported for subgroups of interest due to the skewed distribution of BLL and the common use of arithmetic means in producing pooled estimates in systematic reviews (Ericson et al., 2018; Iyer et al., 2015). Kruskal Wallis test was conducted to compare the distributions of BLL across different demographic groups. The prevalence of participants with elevated BLLs was also assessed using two different thresholds. BLL ≥5 μg/dL was reported as this is the threshold that WHO recommended initiating clinical intervention for children and pregnant women. BLL ≥10 μg/dL was also reported as this exposure level may contribute to anemia (Organization WH, 2021). The Spearman correlation coefficient (R) was calculated to assess the correlation between maternal and child BLL.

We developed associative models rather than predictive models, as we aim to explore the associations between each risk factor and BLL while controlling for important confounders. Generalized logistic regression analyses were used to calculate odds ratios (ORs) and 95% confidence intervals (CIs) for associations between risk factors and the probability of a child's BLL exceeding either 5 or 10 μg/dL. In the multivariate regression analyses, we adjusted for potential confounders known to be associated with childhood BLL based on previous literature. The final model adjusted for children's age, sex, primary caregiver's education, and socio-economic status indicated by possession of a BPL certification.

3. Results

3.1. Study population

The final sample consisted of 697 children and 55 pregnant women from eight Bihar districts. The average age of the children in our sample was 38 months with a slightly higher proportion of male children (55%). An estimated 86% of children were from rural households. The majority of primary caregivers in the household had some school education - 28% with primary school education, 33% with middle school education, and 11 % with high school education. More than half of the children (61%) in our sample were from households below the poverty line. The average age of pregnant women in the sample was 25 years, and the average gestational age was 22 weeks.

3.2. Blood lead levels among children

The weighted geometric mean of BLL was 7.6 μg/dL. Almost 90% of children had BLL ≥5 μg/dL and 20% of children had BLL ≥10 μg/dL (Table 1). The full distribution of BLL among sampled children is shown in Fig. 1. We found significant differences in median BLLs across districts ($p < 0.01$). While Patna (GM = 9.8 μg/dL, 95%CI: 8.7, 11.0) and Gaya (GM = 9.7 μg/dL, 95%CI: 8.3, 11.2) reported the highest geometric means of BLL, all districts had a large proportion of children reporting BLL ≥5 μg/dL (79%–96%). We observed an increasing trend of geometric mean BLL across age groups with children aged 49–60 months reporting the highest mean (GM = 8.1 μg/dL, 95%CI: 7.3, 9.0). When assessing the association between demographic factors and elevated blood lead levels, we found that living in urban areas (OR = 6.09, 95% CI: 1.54, 24.06) was associated with higher odds of BLL ≥5 μg/dL and older age (OR = 1.03, 95%CI: 1.01, 1.04) was associated with higher odds of BLL ≥10 μg/dL (Table S1).

Table 1
BLL distribution and prevalence of children with BLL ≥5 and ≥ 10 μg/dL in Bihar, India overall and by demographic characteristics.

Characteristic	Weighted %	GM (95% CI) (μg/dL)	AM (95% CI) (μg/dL)	Min	Max	P90	P95	% ≥ 5 μg/dL	% ≥ 10 μg/dL
All		7.6 (7.3, 8.0)	8.2 (7.7, 8.6)	2.3	40.5	11.9	14.1	89.7	20.2
District[a]									
Patna	7.6	9.8 (8.7, 11.0)	10.7 (9.2, 12.1)	2.3	40.5	16.2	18.2	96.2	47.3
Muzaffarpur	17.9	7.2 (6.9, 7.5)	7.3 (7.0, 7.7)	4.0	13.6	9.8	10.4	95.7	8.5
Gaya	16.0	9.7 (8.3, 11.2)	10.7 (8.9, 12.4)	2.3	32.5	16.3	19.6	92.9	51.2
Nawada	8.3	8.0 (6.9, 9.4)	8.6 (7.9, 9.2)	2.3	15.5	11.9	13.2	91.7	22.2
Bhagalpur	11.0	7.4 (6.7, 8.1)	7.6 (6.8, 8.4)	3.6	11.1	9.8	10.3	89.6	8.6
West Champaran	14.7	6.9 (6.5, 7.4)	7.2 (6.6, 7.9)	3.5	14.9	9.9	13.1	88.1	9.9
Vaishali	13.0	7.0 (5.3, 9.2)	7.4 (4.9, 9.9)	3.8	15.5	11.3	13.1	83.6	18.8
Purnea	11.5	6.4 (5.6, 7.2)	6.7 (5.8, 7.5)	3.4	11.5	9.1	9.5	79.2	1.7
Sex									
Female	44.4	7.6 (7.1, 8)	8.0 (7.4, 8.6)	2.3	31.1	11.6	13.1	91.5	18.2
Male	55.2	7.7 (7.3, 8.1)	8.3 (7.8, 8.8)	2.3	40.5	12.5	14.8	88.3	21.6
Missing	0.4								
Age group									
12–24 months	22.3	7.0 (6.6, 7.5)	7.4 (6.8, 8.0)	2.3	33.7	9.7	11.0	85.9	9.2
25–36 months	24.0	7.6 (6.9, 8.3)	8.0 (7.3, 8.8)	2.3	21.5	11.9	13.4	92.6	20.1
37–48 months	23.8	7.7 (7.4, 8.0)	8.1 (7.8, 8.5)	2.3	24.5	12.0	14.0	91.4	21.0
49–60 months	29.9	8.1 (7.3, 9.0)	8.9 (7.8, 10.0)	2.3	40.5	13.2	16.9	88.8	27.8
Urbanicity									
Urban	13.6	8.4 (6.8, 10.4)	9.1 (6.6, 11.6)	2.3	40.5	14.3	16.4	97.9	32.0
Rural	86.4	7.5 (7.1, 8.0)	8.0 (7.5, 8.6)	2.3	32.5	11.6	13.2	88.4	18.3
Caregiver's Education									
Illiterate	15.9	8.3 (7.6, 9)	8.9 (7.9, 9.8)	4.0	23.4	13.1	15.5	87.9	28.7
Primary school (Grade 1 to 5)	31.9	7.6 (6.7, 8.3)	8.1 (7.3, 8.9)	2.3	33.7	13.1	12.6	91.8	18.3
Middle school (Grade 6 to 8)	31.5	7.5 (6.8, 8.2)	8.1 (7.3, 8.8)	2.3	23.9	10.9	14.5	89.3	20.7
High school (Grade 9 to 12)	11.7	7.6 (7.0, 8.3)	8.2 (7.4, 9.0)	2.3	40.5	12.4	15.1	90.5	15.4
Higher education	8.8	7.2 (6.4, 8.1)	7.7 (6.6, 8.8)	3.5	17.5	11.5	13.6	86.0	16.5
Missing	0.1								
Socio-economic status									
Low (BPL card)	61.6	7.5 (7.2, 7.9)	8.0 (7.6, 8.4)	2.3	32.5	11.3	13.1	91.4	17.7
Not low (No BPL card)	38.3	7.8 (7.2, 8.4)	8.5 (7.7, 9.3)	2.3	40.5	13.2	15.6	87.0	24.1
Missing	0.1								

[a] P value of Kruskal Wallis test ≤0.01.

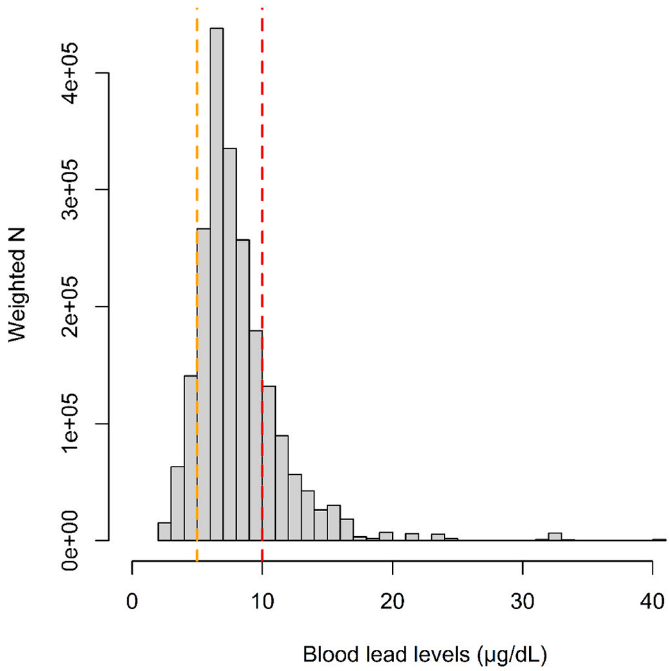

Fig. 1. Histogram of BLL distribution among children in Bihar, India (orange line indicates 5 μg/dL and red line indicates 10 μg/dL).

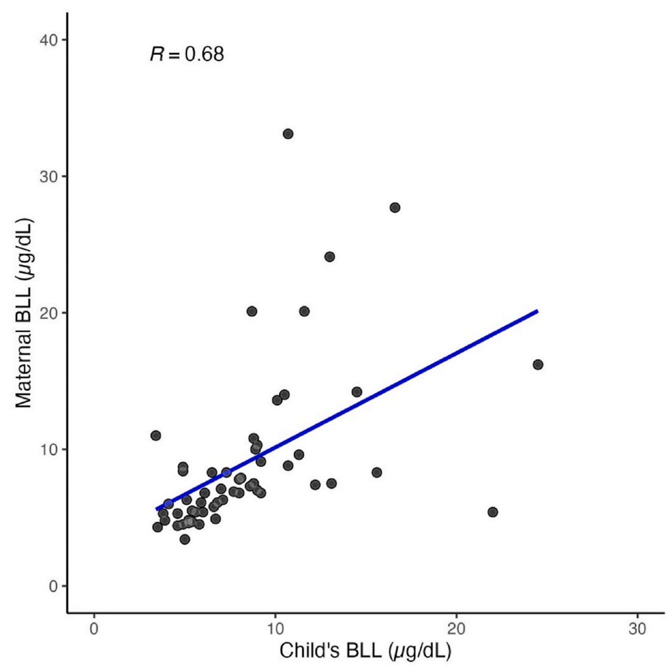

Fig. 2. Scatter plot representing the correlation between BLLs of children and their pregnant mothers.

3.3. Blood lead levels among pregnant women

The geometric mean of BLL among sampled pregnant women was 7.8 μg/dL (Table 2). Over 81% of pregnant women had BLL ≥5 μg/dL and 22% had BLL ≥10 μg/dL. The average BLL of pregnant women living in urban areas (GM = 14.9 μg/dL, 95%CI: 11.0, 20.3) was significantly higher than those living in rural areas (GM = 6.5 μg/dL, 95%CI: 6.0, 7.1). There is a moderate correlation observed between maternal BLL and their young children (R = 0.68) (Fig. 2).

3.4. Risk factors of lead exposure

Table 3 presents the prevalence of potential risk factors and their association with the odds of a child having blood lead levels ≥5 and ≥ 10 μg/dL. More than half of the children (56%) were in a household with a member who had an occupation or hobby that may involve lead and 46% of households were located within 1 km of potentially lead-related industrial activities. The most common job or hobby with potential lead exposure reported by participating households is building renovation/ repair (27%), followed by building demolition (12%), and car repair (8%). Fig. S2 shows the prevalence of any lead-related occupation or hobby with the list of the top five responses from the study. The most common types of potential lead-related industrial site within 1 km of sampled households were mining (42%), followed by manufacturing plants (6%), and smelters (2%) (Fig. S3). Drinking water from hand pumps (76%) and dirt floors (60%) were prevalent in participating homes. Metal cookware (96%), loose spice from a local shop (87%), and eyeliners (i.e., Kohl/Surma/Kajal) (87%) were common in the households while the use of traditional medicine was rare (4%). Skin lightning cream was also used on children in 35% of households. Only a third of homes reported using wet methods to clean the house (33%). Pica behavior, including eating soil and paint chips, was reported in 16% and 31% of children, respectively. Breastfeeding was reported for 28% of children and the use of vitamins was rare (7%).

After controlling for children's age in months, sex, urbanicity, primary caregiver's education, and poverty, the factors significantly

Table 2
BLL distribution and prevalence of pregnant women with BLL ≥5 and ≥ 10 μg/dL in Bihar, India overall, by trimester and by demographic characteristics.

Characteristic	N	%	GM (95% CI) (μg/dL)	AM (95% CI) (μg/dL)	Min	Max	P90	P95	% ≥ 5 μg/dL	% ≥ 10 μg/dL
All	55	100	7.8 (6.8, 8.9)	9.0 (7.4, 10.6)	3.4	33.1	15.4	21.3	81.8	21.8
Trimester										
1st	14	25.5	7.4 (5.6, 9.8)	8.7 (5.5, 11.8)	3.4	24.1	16.8	21.5	78.6	14.3
2nd	17	30.9	7.2 (6.2, 8.3)	7.5 (6.4, 8.6)	4.4	13.6	10.1	11	82.4	11.8
3rd	24	43.6	8.5 (6.8, 10.8)	10.3 (7.3, 13.2)	4.3	33.1	18.9	26.6	83.3	33.3
Urbanicity[a]										
Urban	12	21.8	14.9 (11.0, 20.3)	16.9 (12.2, 21.7)	5.4	33.1	27.3	30.1	100	83.3
Rural	43	78.2	6.5 (6.0, 7.1)	6.8 (6.2, 7.4)	3.4	13.6	9.0	10.0	76.7	4.7
Education										
illiterate	5	9.1	8.9 (6.9, 11.5)	9.2 (6.7, 11.8)	6.8	14	12.4	13.2	100	20.0
Primary school (Grade 1 to 5)	15	27.3	7.2 (5.6, 9.3)	8.4 (5.3, 11.5)	4.4	27.7	13.4	19.6	80.0	13.3
Middle school (Grade 6 to 8)	28	50.9	8.7 (7.2, 10.5)	10.1 (7.6, 12.6)	4.6	33.1	20.1	22.7	89.3	28.6
High school (Grade 9 to 12)	3	5.5	5.6 (4.3, 7.3)	5.7 (4.1, 7.3)	4.8	7.3	6.8	7.1	33.3	0.0
Higher education	4	7.3	5.4 (3.3, 8.8)	6.0 (2.7, 9.2)	3.4	10.8	9.2	10.0	50.0	25.0
Socio-economic status										
Low (BPL card)	32	58.2	7.3 (6.2, 8.7)	8.5 (6.4, 10.5)	3.4	33.1	13.3	20.1	78.1	15.6
Not low (No BPL card)	23	41.8	8.5 (6.9, 10.4)	9.7 (7.3, 12.2)	4.4	27.7	15.8	23.3	87.0	30.4

[a] P value of Kruskal Wallis test ≤0.01.

Table 3
Associations between potential sources of lead exposure at home and child BLL.

		BLL ≥5 μg/dL				BLL ≥10 μg/dL			
Variable	Weighted %	Crude OR (95% CI)	p-value	Adjusted OR[a] (95% CI)	p-value	Crude OR (95% CI)	p-value	Adjusted OR[a] (95% CI)	p-value
Take-home exposure									
Lead-related occupation or hobby									
Yes	56.0	0.78 (0.54, 1.13)	0.17	1.00 (0.64, 1.58)	0.98	1.44 (0.95, 2.16)	0.08	1.75 (1.13, 2.72)	0.02
No	44.0	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Home environment									
Living near lead-related industries									
Yes	45.5	3.12 (1.28, 7.60)	0.017	4.56 (1.84, 11.32)	0.006	2.14 (1.03, 4.45)	0.04	3.25 (1.28, 8.23)	0.02
No	54.5	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Drinking water from handpump									
Yes	76.8	0.65 (0.25, 1.70)	0.35	0.77 (0.26, 2.29)	0.58	0.59 (0.26, 1.33)	0.18	0.67 (0.28, 1.6)	0.3
No	23.2	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Drinking water from municipal supply									
Yes	28.5	1.59 (0.63, 4.05)	0.30	1.65 (0.55, 4.99)	0.31	0.58 (0.26, 1.28)	0.16	0.62 (0.27, 1.43)	0.21
No	71.5	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Presence of chipping paint									
Yes	13.6	0.65 (0.32, 1.31)	0.21	0.60 (0.26, 1.39)	0.18	1.04 (0.44, 2.48)	0.92	0.94 (0.34, 2.62)	0.9
No	86.4	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Floor type									
Concrete	39.1	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Dirt	59.5	0.60 (0.22, 1.60)	0.28	0.72 (0.27, 1.92)	0.43	0.73 (0.39, 1.37)	0.29	0.87 (0.4, 1.91)	0.67
Other	0.6	0.12 (0.02, 0.77)	0.03	0.10 (0.01, 1.14)	0.06	1.44 (0.11, 18.49)	0.76	1.73 (0.03, 98.03)	0.74
Missing	0.8								
Consumer Products									
Use of metal cookware									
Yes	96.3	2.29 (0.52, 10.15)	0.25	1.82 (0.3, 10.85)	0.45	0.19 (0.08, 0.44)	0.00	0.2 (0.07, 0.55)	0.01
No	3.7	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Use of spice from local shops									
Yes	87.1	0.22 (0.05, 1.03)	0.05	0.24 (0.04, 1.44)	0.10	1.95 (0.92, 4.13)	0.08	1.97 (0.96, 4.07)	0.06
No	12.9	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Use of skin lightning cream for the child									
Yes	34.5	4.41 (1.79, 10.87)	0.00	5.11 (1.62, 16.16)	0.01	1.05 (0.35, 3.12)	0.92	1.41 (0.38, 5.29)	0.55
No	65.5	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Use of Kohl/Surma/Kajal for the child or in the household									
Yes	86.5	2.317 (1.12, 4.78)	0.03	2.81 (1.14, 6.93)	0.03	0.63 (0.2, 2)	0.41	0.79 (0.2, 3.21)	0.7
No	13.5	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Use of traditional/herbal medicine for the child and in the household									
Yes	4.1	0.647 (0.15, 2.73)	0.52	0.69 (0.1, 4.61)	0.65	1.22 (0.32, 4.65)	0.75	0.87 (0.29, 2.67)	0.78
No	95.9	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Behavior & Nutrition									
Eating soil									
Yes	16.4	4.47 (1.68, 11.91)	0.01	5.39 (1.77, 16.38)	0.01	2.08 (0.96, 4.53)	0.06	2.45 (1.12, 5.38)	0.03
No	83.6	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Eating paint chips									
Yes	30.6	1.62 (0.54, 4.88)	0.36	1.91 (0.54, 6.78)	0.26	1.94 (0.77, 4.93)	0.15	2.29 (0.87, 6.03)	0.08
No	69.4	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Household cleaning method									
Wet wipe	33.0	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Dry wipe	66.8	0.61 (0.22, 1.67)	0.30	0.82 (0.29, 2.31)	0.65	0.9 (0.5, 1.61)	0.70	1.16 (0.56, 2.37)	0.64
Other	0.2								
Breastfeeding									
Yes	27.7	0.78 (0.48, 1.26)	0.28	0.85 (0.41, 1.79)	0.62	0.61 (0.40, 0.92)	0.02	0.92 (0.43, 1.98)	0.8
No	72.3	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Use of Vitamins									
Yes	6.7	2.60 (0.59, 11.48)	0.19	1.97 (0.36, 10.7)	0.37	2.99 (1.05, 8.5)	0.04	2.25 (0.67, 7.56)	0.15
No	93.3	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref

[a] Adjusted for a child's age in months, sex, maternal education, and household ownership of the below-poverty-line certification.

associated with the odds of having BLL ≥5 μg/dL were living near a lead-related industry (aOR = 4.56, 95%CI: 1.84, 11.32), using skin lightning cream on the child (aOR = 5.11, 95%CI: 1.62, 16.16), use of eyeliners in the household (aOR = 2.81, 95%CI: 1.14, 6.93), and pica behavior of eating soil (aOR = 5.39, 95%CI: 1.77, 16.38). Although using loose spices from the local shop and having a floor other than dirt or concrete were significantly associated with BLL ≥5 μg/dL in the crude analysis, their effects attenuated and were not significant in multivariate analysis.

Living near a lead-related industry (aOR = 3.25, 95%CI: 1.28, 8.23), living with a household member who had an occupation or hobby involving lead (aOR = 1.75, 95%CI: 1.13, 2.72), and pica behavior of eating soil (aOR = 2.45, 95%CI = 1.12, 5.38) were significantly associated with increased odds of having BLL ≥10 μg/dL in the final model. Unexpectedly, an inverse relationship was observed between the use of metal cookware (aOR = 0.19, 95%CI: 0.08, 0.44) and having BLL ≥10 μg/dL. It is noteworthy that the use of metal cookware was extremely prevalent (96%) among studied households and therefore the effect may be driven by outliers. In the crude analysis, breastfeeding and use of vitamins were significantly associated with the odds of having BLL ≥10 μg/dL but the effects were mostly accounted for after adjusting for demographic factors.

4. Discussion

Our study found high average BLLs among a representative sample of children under the age of five living in Bihar and a high proportion of children with elevated BLL. The average BLL among Bihar children (AM = 8.2 μg/dL, GM = 7.6 μg/dL) found in our study was higher than the average BLL estimates for Indian children reported by Ericson et al. (6.9 μg/dL)(Ericson et al., 2018), Iyer et al. (age <2 years old: 4.9 μg/dL; 2–10 years old: 4.2 μg/dL), (Iyer et al., 2015) and IHME (6.2 μg/dL) (Rees and Fuller, 2020). Blood lead levels among pregnant women in our study were also high and showed a strong correlation with their young child's BLL. The average BLL of Bihar pregnant women (AM = 9.0 μg/dL, GM = 7.8 μg/dL) was higher than estimates for adult women in India reported by Ericson et al. (2018) (4.3 μg/dL) and Iyer et al. (2015) (3.7 μg/dL).

As per the literature review, the present study is the first to characterize the distribution of BLL among Bihar children using a statewide representative sample. While the average BLL reported in our study was slightly lower than the averages reported in previous Bihar studies, these previous studies took small samples from communities near known sources of lead pollution or included older children. Ansari et al. reported a mean BLL of 24.4 μg/dL among children aged 3–12 years old living near a ULAB site in Patna, with 91% of children having BLL exceeding 5 μg/dL (Ansari et al., 2020). Brown et al. assessed children under the age of six and living in communities near ULAB activities and found a mean BLL of 11.6 μg/dL and 87% of children had BLL exceeding 5 μg/dL (Brown et al., 2022). A study that assessed school-age children in 10 cities in India reported a median BLL of 9.7 among children aged 6–16 years old in Patna (Kumar et al., 2023). NITI Aayog's report showed the modeled estimates of statewide average BLL in the Bihar population (including both children and adults) was 10.4 μg/dL based on 2017 GBD data (Kumar, 2022). While the average BLL of children in our study was lower likely due to the use of a population-based sample rather than one with a known source of lead exposure, all studies found similarly high proportions of children with elevated BLL. Among children under the age of 5, we also observed higher average BLL among the older age groups. This observation is consistent with what has been observed previously in Indian children and other child populations in Asia (Jain and Hu, 2006; Li et al., 2020). This trend is different from what has been observed in the U.S. where BLL tends to peak in children aged 12–24 months and is likely associated with more active hand-to-mouth behavior and ingestion of non-food items like soil or paint chips (Egan et al., 2021). This later peak of lead exposure among Bihar children needs further investigation and may suggest other important exposure routes through non-pica behavior such as diet, use of consumer products, and chronic cumulative exposure. We also observed some variation in the BLL of children in different districts. This may be related to the large variation in the percentage of children living near an industrial site across different districts in our data and the different demographic compositions of the households.

Living near an industrial site that may involve lead was an important risk factor for elevated BLL among Bihar children. The most common industrial site reported near our participating households was mining followed by manufacturing plants and smelters. Previous studies conducted in India also found high BLL among children living in highly industrialized areas (Roy et al., 2009; Niranjan and Madhusudana, 2006), ULAB sites, (Ansari et al., 2020), and smelters (Hegde et al., 2010). Communities living near lead-related industrial activities were likely exposed to lead through being in primary or tracked contact with contaminated soil as high levels of lead were found in the soil surrounding these sites across India (Vishwanath et al., 2012; Clark et al., 2005). In Bihar, a 2018 study found lead levels exceeding Indian standard limits in soil sampled from multiple blocks across Patna and the heavy metal profile indicated that traffic pollution and industrial emissions were major sources of contamination (Devi and Yadav, 2018). Another study that evaluated soil and dust samples also found higher lead concentrations in these samples collected from homes near a ULAB site in Patna than those collected from homes far away from the site (Brown et al., 2022).

We found that children with a pica behavior of eating soil are more likely to have elevated BLLs. Pica behavior, particularly eating soil and paint chips, has long been identified as a risk factor for lead poisoning among children, particularly for those living in areas with lead contamination (De la Burdé and Reames, 1973; Leung and Hon). Ingesting lead-contaminated soil is a major route of lead exposure among young children due to their hand-to-mouth behavior and pica behavior can further magnify a child's soil intake (World Health Organization, 2010). Similarly, a study of 253 Delhi children found significantly higher BLL among children with pica behavior than those without pica behavior (Gogte et al., 1991).

We also found that children living with family members with lead-related occupations were more likely to have BLL≥ 10 μg/dL. The most common occupation/hobby reported in our sample was construction work (i.e., remodeling or demolishing buildings) followed by automobile repair and paint removal. It has been well-established in previous studies that children of parents working in these sectors were likely to report elevated BLL due to take-home exposure (Baker et al., 1977; Dolcourt et al., 1978; Piacitelli et al., 1997; Roscoe et al., 1999). Children may be exposed to lead-contaminated dust brought from the workplace back home by their parents on their clothing, shoes, hair, and hands.

The use of cosmetics that may contain lead including eyeliners and lightning creams was also positively associated with having BLL ≥5 μg/dL among Bihar children. High concentrations of lead have been detected in some eye cosmetics (e.g., kohl, surma, kajal) produced in South Asia, the Middle East, and Africa as lead sulfide was commonly used in their production when not regulated (Lead in Consumer Goods, 2023; Al-Ashban et al., 2004; Tiffany-Castiglioni et al., 2012). A few severe lead poisoning cases have been linked to the use of lead-containing eyeliner in India and elsewhere (Goswami, 2013; Tiffany-Castiglioni et al., 2012). Several Indian studies have found children and infants living in households with the use of these eye cosmetics are more likely to report elevated BLLs (Gogte et al., 1991; Patel et al., 2001, 2011; Sharma et al., 2021). While mercury poisoning is a more common concern related to skin-lightning products, (McKelvey et al., 2011; Pramanik et al., 2021) two studies in India have also detected considerable levels of lead in these products when assessing a range of heavy metals (Saidalavi et al., 2017; Jose et al., 2018).

The strengths of our study include using a large and representative sample and assessing a wide range of factors associated with lead exposure in homes. However, there are a few limitations to be aware of. Our study measured BLLs using capillary blood and a portable analyzer which may be more vulnerable to contamination. We took several measures to minimize field contamination and validate the measurements obtained by the analyzer. A detailed protocol was developed and used in field team training to direct that samples be collected in a clean and undisturbed environment and require the thorough cleaning of fingers before samples were taken. Quality control materials were tested at the beginning of each sampling day to ensure the instrument was performing properly. Our validation study using a subset of venous blood samples also showed comparable results. There was a strong correlation between LeadCare and ICP-MS measurements (R = 0.70) and the difference in medians was comparable with previous validation studies (difference = 2.18 μg/dL) (Nakata et al., 2021; Taylor et al., 2001). In general, LeadCare reported slightly higher values than the ICP-MS measurements so there is a possibility of overestimation. However, previous validation studies found a higher agreement between LeadCare and laboratory based assessments for BLL below 10 μg/dL which accounts for almost 80% of our samples (Nakata et al., 2021). While our study was designed to provide a state-wide estimate of BLL among Bihar children, it was not powered to provide district-level estimates. Therefore, the district-level estimates reported in this study should be seen as indicative rather than definitive. Our findings for pregnant women were also preliminary as our sample size was fairly small and was a convenience sample.

5. Conclusion

Using a statewide sample, we found concerningly high lead exposure among the Bihar child population who were at the age most vulnerable to lead poisoning. Our study results indicate the need for a lead poisoning prevention program in Bihar that addresses known sources of lead in industry, manufacturing, and consumer products, further explores suggested sources, educates parents on exposure control methods, builds widespread testing capacity, and facilitates routine BLL screening of populations likely to have high BLL. Local and national government engagement is important to drive improvements in regulatory policies and their enforcement, and greater engagement of the clinical and public health systems.

CRediT authorship contribution statement

Yi Lu: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Formal analysis. **Ambrish Kumar Chandan:** Writing – review & editing, Validation, Project administration, Methodology, Investigation. **Sumi Mehta:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Meenakshi Kushwaha:** Writing – review & editing, Validation, Formal analysis, Data curation. **Arun Kumar:** Writing – review & editing, Project administration, Methodology, Investigation. **Mohammad Ali:** Writing – review & editing, Investigation. **Abhinav Srivastava:** Writing – review & editing, Validation, Project administration, Investigation. **Ashok Kumar Ghosh:** Writing – review & editing, Supervision, Methodology. **Stephan Bose-O'Reilly:** Writing – review & editing. **Lavanya Nambiar:** Writing – review & editing. **Daniel Kass:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

D.K. and S.M. conceptualized the project. D.K., S.M., Y.L., A.C., A.K., A.S., A.K.G. contributed to the methodology. A.C., A.K., and A.S., contributed to data collection. M.K., Y.L., and A.K. completed the analyses and interpretation of data. Y.L. prepared the first draft of the manuscript and D.K., S.M., S.B., and L.N. provided critical review and revision.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.119528.

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