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Evidence of turmeric adulteration with lead chromate across South Asia

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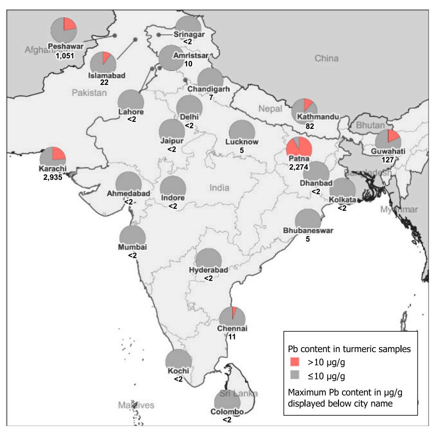
HIGHLIGHTS

- Pb and Cr concentrations of turmeric across South Asia
- Pb:Cr molar ratio indicates $PbCrO_4$ adulteration versus environmental contamination
- Pb levels >500 times higher than regulatory limit in India, Pakistan, and Nepal
- Projected blood lead levels exceed reference levels by >10-fold due to turmeric
- Spices represent an understudied source of lead poisoning globally

GRAPHICAL ABSTRACT



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ABSTRACT

Food adulteration with toxic chemicals is a global public health threat. Lead chromate adulterated spices have been linked with lead poisoning in many countries, from Bangladesh to the United States. This study systematically assessed lead chromate adulteration in turmeric, a spice that is consumed daily across South Asia. Our study focused on four understudied countries that produce >80 % of the world's turmeric and collectively include 1.7 billion people, 22 % of the world's population. Turmeric samples were collected from wholesale and retail bazaars from 23 major cities across India, Pakistan, Sri Lanka, and Nepal between December 2020 and March 2021. Turmeric samples were analyzed for lead and chromium concentrations and maximum child blood lead levels were modeled in regions where samples had detectable lead. A total of 356 turmeric samples were collected, including 180 samples of dried turmeric roots and 176 samples of turmeric powder. In total, 14 % of the samples ($n = 51$) had detectable lead above 2 μg/g. Turmeric samples with lead levels greater than or equal to 18 μg/g had molar ratios of lead to chromium near 1:1, suggestive of lead chromate adulteration. Turmeric lead levels exceeded 1000 μg/g in Patna (Bihar, India) as well as Karachi and Peshawar (Pakistan), resulting in projected child blood lead levels up to 10 times higher than the CDC's threshold of concern. Given the

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overwhelmingly elevated lead levels in turmeric from these locations, urgent action is needed to halt the practice of lead chromate addition in the turmeric supply chain.

1. Introduction

Turmeric, commonly referred to as Indian saffron or "the golden spice", is consumed daily in many households across South Asia. Turmeric roots belong to the *Zingiberaceae* family and owe their yellow-orange hue to curcumin, a natural polyphenol pigment found in turmeric (Prasad and Aggarwal, 2011). Turmeric, thanks to the anti-oxidant and anti-inflammatory properties of curcumin, has been used as a natural medicine in South Asian countries for thousands of years (Babaei et al., 2020). Recently, clinical trials have begun to test the viability of turmeric and curcumin to ameliorate wide-ranging conditions from cancers to COVID-19 (Babaei et al., 2020).

India is the primary producer, exporter, and consumer of turmeric worldwide. India produces 80 % of the world's turmeric supply, predominantly in the states of Andhra Pradesh, Tamil Nadu, and Karnataka. To a lesser extent, turmeric is also cultivated in other South Asian countries, including Bangladesh, Pakistan, Sri Lanka, and Nepal. (Jadhav et al., 2022)

Adulteration of turmeric and other spices is a public health threat globally, especially in countries lacking sufficient regulatory capacity and large informal food industries (Forsyth et al., 2023; Hore et al., 2019; Ericson et al., 2020; Forsyth et al., 2024). Spices are particularly prone to adulteration as they are a high value commodity often sold in processed forms (Moore et al., 2012). Turmeric adulteration can be harmless – the addition of starchy edible compounds – or toxic with the addition of industrial pigments (Forsyth et al., 2019a). The health threat of adulterants may not always be clear. For example, metanil yellow is an azo dye added to turmeric with suspected carcinogenic effects (Dixit et al., 2009; Combes and Haveland-Smith, 1982). Other pigments, like lead chromate, have severe and well-documented toxic effects stemming from chromium and lead exposure (Singh et al., 1999).

Lead is a particularly troubling toxicant, harming nearly every system in the body, including the circulatory, endocrine, renal, immune, reproductive, and nervous systems (Mishra, 2009; Needleman, 1991). Exposure to lead during early childhood has a negative, irreversible, and long-term effect, hampering brain development and reducing IQ (Bellinger, 2013). The combined economic losses from lead-related IQ deficits are estimated to amount to more than $293 billion per year in the South Asian countries of India, Pakistan, Nepal, Sri Lanka, and Bangladesh (Attina and Trasande, 2013).

Turmeric has been identified as a source of lead poisoning, especially among South Asians. Studies linking turmeric with elevated blood lead levels have included women and children living in Bangladesh and India (Forsyth et al., 2019b; Brown et al., 2022), as well as those living in the U.S. who have unknowingly transported lead-tainted turmeric back from South Asia (Tan et al., 2023). Investigations into the turmeric supply chain in Bangladesh revealed the widespread practice of adding lead chromate to turmeric roots to enhance appearances and to facilitate the sale of poor quality roots, a practice dating back to the 1980s (Forsyth et al., 2019a).

Although the current evidence suggests that turmeric may be an overlooked source of lead poisoning globally, little is known about the geographic extent of lead-tainted turmeric across South Asia beyond Bangladesh. The primary aim of this study was to assess lead and chromium levels of turmeric sold at major bazaars across the South Asian countries of India, Sri Lanka, Pakistan, and Nepal, countries with a combined population of >1.7 billion people. Secondary aims for the study were to i) estimate the theoretical contribution of turmeric lead levels to children's blood lead levels, and ii) assess evidence of other types of turmeric adulteration (e.g., metanil yellow, starchy fillers) in relation to quality attributes like curcumin concentration.

2. Materials and methods

2.1. Turmeric sample collection

Turmeric samples were collected from 23 major cities across India, Pakistan, Sri Lanka, and Nepal between December 2020 and March 2021, the main turmeric growing season in the region. The country of Bangladesh was excluded from sampling due to the extensive study of lead in turmeric and the successful reduction of lead-tainted turmeric by 2020 (Forsyth et al., 2023). In India, 17 focal states were selected based on geographic spread and population size. The number of states selected in each region was proportional to population. For example, since the Northern region of India comprises 30 % of India's population, we aimed to sample from at least 5 states or 30 % of the total sample size. Within a geographic region, the states with the largest populations were preferentially selected. In each state, we selected the largest city for sampling.

In Pakistan, the largest city from each province was selected for sampling along with Islamabad in the Islamabad Capital Territory. It was not feasible to sample from a city in Balochistan due to safety concerns. In Sri Lanka and Nepal, samples were collected from the capital cities of Colombo and Kathmandu, respectively.

Local sample collectors from each city were trained to follow a mystery shopping protocol. They visited the largest wholesale market and the largest retail bazaar in the city. At each location, the sample collector purchased at least 50 g of each unique type of turmeric from at least two vendors. Sample collectors asked vendors about the turmeric variety and harvest region of the turmeric to maximize sampling diversity and minimize duplicate samples. Unique types included loose powder, packaged powder, polished roots, and unpolished roots from different harvest regions or varieties. Samples were stored in lead-free polyethylene bags, double-bagged to prevent cross contamination.

2.2. Turmeric sample analysis

Samples from India, Nepal, and Sri Lanka were sent to Pure Earth India's office located in Delhi where a trained analyst measured lead concentrations with a portable x-ray fluorescence analyzer (XRF, Olympus Delta DCC-4000). The XRF has been shown to be accurate within 5 % of laboratory results for lead in powdered spices, with a limit of detection of 2 μg/g (Lopez et al., 2022). A subset of samples from India, Nepal, and Sri Lanka that were above the limit of detection for lead were sent to an accredited laboratory (Eurofins, Delhi) for lead and chromium analysis via inductively coupled plasma mass spectrometry (ICP-MS) with a limit of detection of 0.01 μg/g. A calibration curve was developed for turmeric roots and powder separately to correct XRF values.

A random selection of 75 root and powder samples from India were also analyzed for metanil yellow concentrations via liquid chromatography mass spectrometry (LC-MS) (Lim et al., 2020), percent starch content following the American Spice Trade Association Method 8, and percent curcumin content using high performance liquid chromatography (HPLC) (Tønnesen and Karlsen, 1983) at the Eurofins Laboratory. All analyses were conducted at the Eurofins Laboratory.

Samples from Pakistan were not allowed to be shipped to India for analyses and were therefore analyzed for lead and chromium concentrations in country using inductively coupled plasma optical emissions spectrometry (ICP-OES) at the National Textiles University's accredited laboratory where the limit of detection was 0.5 μg/g.

To assess the likelihood that lead chromate was the source of lead in the turmeric samples containing lead above the detection limit, the molar ratio of lead to chromium was calculated using the molar mass of lead (207.2 g/mol), chromium (51.9961 g/mol). A molar ratio of lead to chromium close to 1:1 is suggestive of lead chromate (Forsyth et al., 2019b).

2.3. Estimating the theoretical maximum child blood lead level increase from turmeric

The maximum contribution of turmeric lead levels to child blood lead levels was estimated via two approaches. The first approach utilized linear calculations based on data from this and other studies (see equation below). For each city with detectable lead in turmeric, the maximum turmeric lead concentration found in the present study was used as an input (*MaxTurmPb*). The fraction of bioaccessible lead in turmeric (the amount of lead capable of being absorbed by the body) was estimated using the average turmeric lead bioaccessibility of 42.9 % from a study of Bangladeshi turmeric (Gleason et al., 2014). Household-level turmeric consumption data was estimated from the latest expenditure survey conducted by the National Sample Survey Organization of India (Srivastava, 2013). Turmeric consumption (*TurmCons*) was reported in terms of grams of turmeric consumed per household per month per region, averaging estimates for urban and rural households. The amount of turmeric consumed per person was estimated by dividing the household-based consumption data by the average household size, utilizing survey data from 2018 in Pakistan and 2019 in India (Average Household Size, Global Data Lab, n.d.) and 2022 in Nepal (2022 Nepal DHS Summary Report, 2023). The resulting turmeric quantity (in grams per person per month) was divided by the average number of days in a month then divided in half to acquire a turmeric intake for children based on the assumption that turmeric consumption would be proportional to caloric consumption and that the caloric needs for 24–36 months old is roughly one half the caloric needs of adults (Faizan and Rouster, 2020). The contribution of ingested lead to blood lead levels was estimated as 0.52 μg/L per 1 μg of lead ingested per day based on the Glasgow Duplicate Diet Study assessing the concentration of lead consumed and resulting blood lead levels among 131 Scottish infants between 1979 and 1980 (World Health Organization, 2011; Lacey et al., 1985; Sherlock and Quinn, 1986). The measured intake lead levels among the Scottish children ranged from approximately 6 to 429 micrograms per day, which is similar to the range in estimated intake from lead-tainted turmeric from this study (Table 3).

The calculation was set as:

$$\Delta BLL = TurmCons\left(\frac{g}{day}\right) x\ MaxTurmPb\left(\frac{\mu g}{g}\right) x\ 0.429\ x\ \frac{0.52\left(\frac{\mu g}{L}\right)}{1\left(\frac{\mu g}{day}\right)}$$

where:

ΔBLL is the change in child blood lead level.

TurmCons is the estimated grams of turmeric consumed per child per day.

MaxTurmPb is the maximum turmeric lead concentration from the particular region within the present study.

The second approach utilized the All Ages Lead Model (AALM) version 3.0 developed by the U.S. Environmental Protection Agency to estimate blood lead levels among adults and children of all ages (All Ages Lead Model (AALM), n.d.). This model requires inputs related to consumption patterns and makes assumptions based on age and sex. We predicted blood lead levels separately for a male child at age 36 months and a female child at age 36 months and averaged these. All exposure sources were set to zero for ages 0–24 months old. Between 24 and 36 months, a consistent daily intake of lead from turmeric was included in the model. This daily intake was calculated using *MaxTurmPb* and *TurmCons,* accounting for the average 42.9 % bioaccessibility of lead in turmeric as described above.

3. Results

3.1. Turmeric sample results

A total of 356 turmeric samples were taken from 23 cities across South Asia. By turmeric type, this included 180 samples of dried turmeric roots and 176 samples of turmeric powder. In total, 14 % of the samples ($n = 51$) had detectable lead above 2 μg/g and 7 % of the samples ($n = 24$) had lead above the Indian standard of 10 μg/g (*Food Safety and Standards Authority of India*, 2011) (Table 1). Turmeric lead levels exceeded 10 μg/g from seven cities in total: Patna, Guwahati, and Chennai in India, Kathmandu in Nepal, and Karachi, Islamabad, and Peshawar in Pakistan (Fig. 1a). Turmeric lead levels exceed 1000 μg/g from three cities: Patna, Karachi and Peshawar. Notably, every sample of turmeric from Patna contained detectable lead, with a median of 1232 μg/g and a maximum of 2274 μg/g. In Karachi, 50 % of turmeric samples contained detectable lead, with a median of 3 μg/g and a maximum of 2936 μg/g.

Turmeric samples with levels above 10 μg/g were primarily polished turmeric roots ($n = 14$) but included loose powder ($n = 5$), packaged branded powder ($n = 3$) and unpolished roots ($n = 2$). One of these unpolished root samples contained 18 μg/g lead and a molar ratio of lead to chromium of 0.8 while the other sample contained 15 μg/g and no detectable chromium. Polished roots and loose powder were the only forms of turmeric with lead levels above 1000 μg/g. (Table 2).

Within India, turmeric was reported to be predominantly sourced from the state of Tamil Nadu (22 %), followed by Maharashtra (14 %), although the source of the turmeric was unknown for 32 % of samples. Turmeric samples with elevated lead levels from Bihar were also reported to be harvested in Bihar and the sample of turmeric with elevated lead from Guwahati was also reported to be from Bihar. Within Pakistan, more than half of the turmeric samples were reported to be sourced from Punjab province (68 %) and within Nepal and Sri Lanka origins were reported as being local or unknown. Overall, 29 % of the turmeric samples were reported to be sourced locally and 35 % were reported to be sourced from elsewhere (outside the state for India or outside the province for Pakistan). (Fig. 1b, Supplemental Table S1).

Turmeric samples with lead levels greater than or equal to 18 μg/g had molar ratios of lead to chromium near 1:1, suggestive of lead chromate adulteration (average 0.92; SD 0.30). On the other hand, turmeric samples with lead levels equal to or <15 μg/g had lower molar ratios of lead to chromium (average 0.44; SD 0.30), suggestive of natural lead contamination from soil or dust. (Fig. 2).

Overall, turmeric samples contained low levels of curcumin (average 1.45 %; SD 0.67), less than the standard of 2 % set by the Food Safety Standards of India (*Food Safety and Standards Authority of India*, 2011). If lead chromate pigments are added to compensate for less vibrant, poorer quality turmeric roots, then we would expect lead and curcumin levels to be inversely related. (Supplemental Table S2, Fig. S1) There was no apparent association between turmeric lead levels and curcumin content among the 44 samples assessed. However, this should be repeated in another study due to the small sample size.

Similarly, there was no association between starch levels and curcumin levels nor excessive starch levels beyond what would be considered natural. All starch levels were less than the 60 % maximum set by the Food Safety and Standards Authority of India (Supplemental Table S2, Fig. S2).

Of the random subset of 40 turmeric root samples and 35 powder samples tested for metanil yellow adulteration, 8 % ($n = 6$) contained detectable levels above 0.05 mg/kg metanil yellow and 3 % ($n = 2$) contained excessive concentrations >70 times higher than the maximum of 100 mg/kg set by the Food Safety and Standards Authority of India (*Food Safety and Standards Authority of India*, 2011). The two samples of loose turmeric powder above the limit were collected from West Bengal and contained 7500 and 8300 mg/kg metanil yellow. Due to the low overall prevalence of elevated lead levels in turmeric, conclusions

Table 1
Turmeric lead concentrations by location of sampling (n = 356). LOD = limit of detection (2 μg/g).

Country	Region	City	State/Province	Samples (n)	Lead Concentration (μg/g)	
					n (%) above 10 μg/g	Maximum
India	North	Lucknow	Uttar Pradesh	11	0 (0)	5
		Chandigarh	Chandigarh	21	0 (0)	7
		Amritsar	Punjab	15	0 (0)	10
		Delhi	Delhi	15	0 (0)	<LOD
		Srinagar	Jammu and Kashmir	25	0 (0)	<LOD
	Northeast	Guwahati	Assam	11	2 (18)	127
	East	Kolkata	West Bengal	11	0 (0)	<LOD
		Patna	Bihar	12	11 (92)	2274
		Bhubaneswar	Odisha	16	0 (0)	5
		Dhanbad	Jharkhand	26	0 (0)	<LOD
	South	Chennai	Tamil Nadu	19	1 (5)	11
		Hyderabad	Telangana	15	0 (0)	<LOD
		Kochi	Kerala	18	0 (0)	<LOD
	West	Ahmedabad	Gujarat	8	0 (0)	<LOD
		Indore	Madhya Pradesh	10	0 (0)	<LOD
		Jaipur	Rajasthan	15	0 (0)	<LOD
		Mumbai	Maharashtra	21	0 (0)	<LOD
Pakistan		Islamabad	Islamabad Capital Territory	10	1 (10)	22
		Karachi	Sindh	21	5 (24)	2935
		Lahore	Punjab	16	0 (0)	<LOD
		Peshawar	Khyber Pakhtunkhwa	9	2 (22)	1051
Nepal		Kathmandu	Bagmati	17	2 (12)	82
Sri Lanka		Colombo	Western Province	14	0 (0)	<LOD
	TOTAL			**356**	**24 (7)**	**2935**

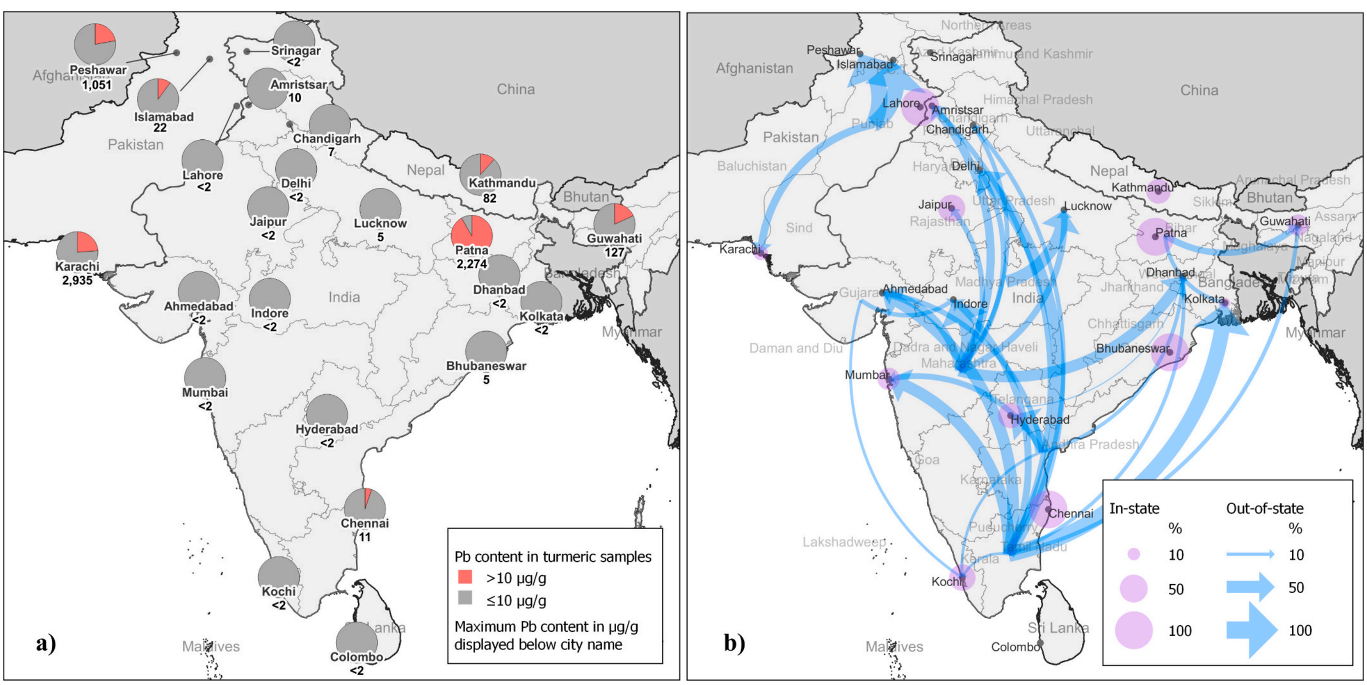

Fig. 1. Map of lead concentrations in turmeric (a) and map indicating dominant sourcing patterns (b). In Fig. 1b, the arrows represent turmeric sourced from another state (or province) and the circles represent turmeric sourced from within the state (or province), with relative size corresponding to the percent of samples meeting those criteria. Overall, 36 % of samples were of unknown origin, not represented on the map.

cannot be drawn about whether or not samples with metanil yellow were less likely to be adulterated with lead chromate (Supplemental Table S3). We cannot say whether metanil yellow is being used as a substitute coloring agent for lead chromate, though none of the samples with metanil yellow contained detectable lead.

3.2. Modeling lead exposure risk from turmeric

There is considerable variability in the estimates of the theoretical maximum blood lead level increase from lead in turmeric based on turmeric consumption patterns. The combination of extremely elevated turmeric lead levels in Patna, India, as well as the highest estimated per capita consumption of turmeric across the South Asian region, result in an estimated daily intake of up to 663 μg of lead from turmeric that we would expect to increase child blood lead level between 345 and 790 μg/L. In Pakistan, child blood lead levels were estimated to increase between 55 and 126 μg/L in Peshawar and 173–396 μg/L in Karachi from turmeric alone. The two approaches to modeling turmeric's contribution to blood lead levels yielded different results, with basic assumption calculations resulting in lower estimates and AALM modeling resulting

Table 2
Turmeric lead concentration and price for all samples from India, Pakistan, Sri Lanka, and Nepal (n = 356).

Turmeric Type	n	Lead Concentration				Price per Kg (Indian Rupees)[1]		
		n (%) < 10 μg/g	n (%) 10–100 μg/g	n (%) > 100 μg/g	Maximum (μg/g)	Mean (SD)	Median	IQR
Polished roots	143	129 (90)	1 (1)	13 (9)	2935	157 (83)	130	100, 175
Unpolished roots	37	35 (95)	2 (6)	0 (0)	18	211 (123)	180	110, 220
Loose powder	90	85 (94)	1 (1)	4 (4)	1665	191 (105)	160	139, 220
Packaged powder	28	28 (100)	0 (0)	0 (0)	5	153 (62)	140	120, 173
Branded powder	58	55 (95)	3 (6)	0 (0)	82	242 (58)	240	207, 280

[1] Price noted in Indian rupees using exchange rates from July 15, 2023 (1 Pakistani rupee = 0.28 Indian rupees; 1 Nepalese rupee = 0.63 Indian rupees; 1 Sri Lankan rupee = 0.26 Indian rupees).

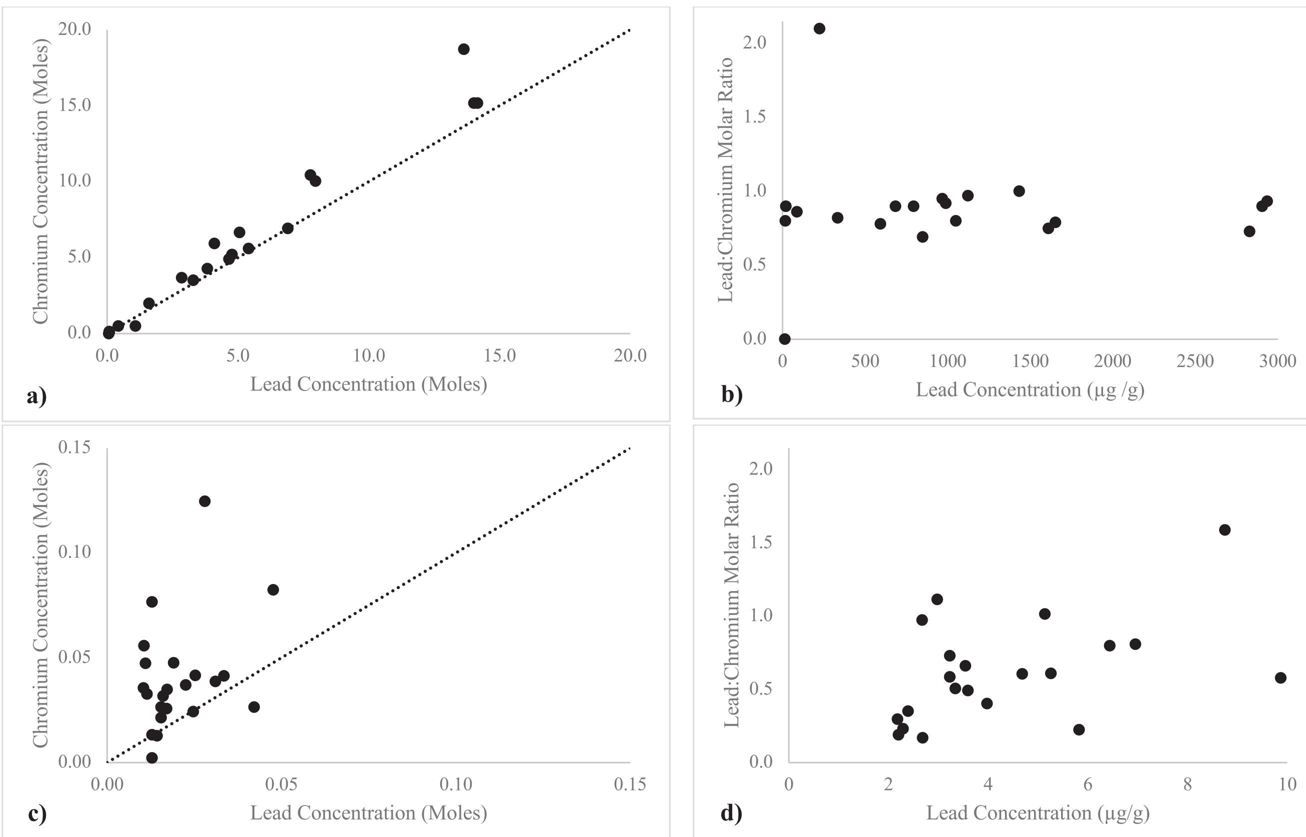

Fig. 2. Molar ratios and concentrations of lead and chromium for 20 turmeric samples with laboratory lead levels above 10 μg/g (a, b) and 22 turmeric samples with laboratory lead levels between 2 and 10 μg/g (c, d). The threshold of 10 μg/g was used per the limit set by the Food Safety Standards Authority of India. Note that the left panel differs from the right panel in terms of the x and y axes.

in higher estimates due to assumptions of linearity versus non-linearity in toxicokinetics as well as the impact of age and sex (Table 3). The basic assumption calculations may underestimate blood lead levels because the relationship between lead intake and blood lead level was based on a study of younger children. Nonetheless, evidence from pediatric case studies of lead poisoned children indicate that the basic assumption calculations and the AALM model provide realistic bounds on likely blood lead levels (Supplemental Fig. S3).

4. Discussion

This study evaluates the extent of lead chromate turmeric adulteration across four understudied South Asian countries– India, Pakistan, Sri Lanka, and Nepal. Although other forms of adulteration were investigated, from metanil yellow dyes to added starch, lead chromate adulteration was detected with a higher prevalence, in multiple locations, and poses a more profound public health risk. In total, 14 % of turmeric samples contained detectable lead (above 2 μg/g). Turmeric samples with molar lead to chromium ratios indicative of lead chromate adulteration were identified in several cities, particularly in major cities of India and Pakistan. In India, lead chromate adulterated turmeric was most prominent in Patna in the state of Bihar, in addition to one sample from Guwahati in the state of Assam. Elsewhere, a number of lead chromate adulterated turmeric samples were collected from Karachi and Peshawar in Pakistan, as well as one sample from Kathmandu, Nepal. Notably, the turmeric samples with elevated lead from both Patna and Guwahati were reportedly sourced from Bihar. On the other hand, turmeric from Karachi and Peshawar had been sourced from Punjab province of Pakistan and turmeric from Kathmandu was sourced locally from Nepal, suggesting multiple points of lead chromate adulteration across South Asia. This study intended to identify areas of greatest concern, but it is not exhaustive. Although additional studies might better clarify the breadth of exposed populations, the current findings highlight the importance of further investigation into where and why

Table 3
Estimates of the theoretical maximum blood lead level (BLL) increase for children 24–36 months old from turmeric in locations with turmeric lead levels above the LOD.

Country	Region	City	State	Maximum turmeric lead concentration (μg/g)	Turmeric consumption per household per month (g)[1]	Average household size (n)	Estimated lead intake from turmeric μg/day	Estimated child BLL increase - basic assumptions (μg/L)	Estimated child BLL increase - AALM (μg/L)
India	North	Lucknow	Uttar Pradesh	5	204	5.3	1	1	2
		Chandigarh	Chandigarh	7	204	4.5	2	1	2
		Amritsar	Punjab	10	204	4.7	3	2	4
	Northeast	Guwahati	Assam	127	183	4.4	38	20	45
	East	Patna	Bihar	2274	206	5.0	663	345	790
		Bhubaneswar	Odisha	5	206	4.1	2	1	2
	South	Chennai	Tamil Nadu	11	80	3.5	2	1	2
Pakistan		Islamabad	Islamabad Capital Territory	22	139	7.1	3	2	4
		Karachi	Sindh	2935	139	8.6	333	173	396
		Peshawar	Khyber Pakhtunkhwa	1051	139	9.7	105	55	125
Nepal		Kathmandu	Bagmati	82	139	3.9	21	11	25

lead chromate turmeric adulteration is occurring, especially in the state of Bihar, across Pakistan, and to a lesser extent in Nepal.

The results from this study highlight how different forms of the spices pose different health risks, with polished turmeric roots and loose turmeric powder having the highest lead levels. Consistent with other studies, the loose, under-regulated spices were more likely to be adulterated than packaged turmeric (Forsyth et al., 2019a; Dixit et al., 2009). In India and Pakistan, the permissible levels of lead are the same for loose and packaged turmeric and the national food safety authorities are responsible for lead testing. However, packaged turmeric may undergo additional scrutiny and lead testing by foreign regulatory agents if exported. Investigations in Bangladesh indicated that lead chromate was being added to turmeric roots during the polishing process, whereby roots are tumbled in a large drum to remove excess dirt and rub away the outer turmeric skin to reveal the inner yellow hue of the root (Forsyth et al., 2019a). From the present study, polished dried turmeric roots and loose turmeric powder had higher lead and chromium levels compared to unpolished roots and packaged branded turmeric powder. However, three packaged branded samples in this study contained elevated lead, along with one sample of unpolished roots that contained elevated lead and chromium suggestive of lead chromate. It is possible that the elevated lead and chromium levels in the sample of unpolished roots was due to cross contamination from storage bags previously containing lead chromate adulterated polished roots.

We report lead levels in polished turmeric roots up to 2935 μg/g, >200 times higher than the 10 μg/g limit set by the Food Safety Standards Authority of India. Consuming turmeric with lead at these levels would likely contribute to lead poisoning across the region, particularly for children. Indeed, a recent study indicated that turmeric was one of the most likely sources of lead exposure among children in Patna, Bihar (Brown et al., 2022). The modeled assessment of the contribution of turmeric lead to the human lead burden within this study suggests that turmeric could be raising blood lead levels considerably throughout the region. In Bihar, theoretical maximum child blood lead levels between 345 and 790 μg/L were estimated from consuming typical amounts of turmeric with 2274 μg/g lead. And for those children in Bihar consuming turmeric with median lead levels of 1232 μg/g, resulting child blood lead levels could range from 190 to 428 μg/L. The CDC Blood Lead Reference Value is currently set at 35 μg/L (Ruckart et al., 2021). The potential harm to health and development from turmeric-related lead exposure is alarming. Although lead is toxic across all body systems, considering only the cognitive deficits from lead-tainted turmeric in Bihar, resulting IQ would be 7 points lower per child and expected lifetime earnings 14 % lower compared to other parts of South Asia where turmeric lead levels remain below 10 μg/g (Trasande and Liu, 2011; Murray et al., 2020). This does not consider the other adverse effects from lead exposure including mortality from cardiovascular disease which resulted in an estimated 5.5 million premature adult deaths in 2019 (Larsen and Sánchez-Triana, 2023).

The limited scientific data available, primarily from pediatric assessments of children of South Asian descent living in the U.S., suggest that these estimates of turmeric's maximum contribution to blood lead levels are reasonable. For example, a 24-month old child from North Carolina whose blood lead level was 480 μg/L had been consuming turmeric with 2000 μg/g lead with no other known sources of lead exposure (Kappel et al., 2021). Meanwhile, several other children of similar ages with blood lead levels ranging from 100 to 160 μg/L were found to be consuming turmeric with lead concentrations between 390 and 1600 μg/g (Tan et al., 2023). Notably, the turmeric consumed by these children was reported to have been hand carried back from the Indian states of Uttar Pradesh, Madhya Pradesh, and Andhra Pradesh. Although turmeric from Lucknow, Uttar Pradesh and Indore, Madhya Pradesh was assessed in the present study and not found to contain lead, further investigation is warranted to better understand the geographic extent and frequency of lead chromate adulteration of turmeric.

Importantly, lead in turmeric seems to come from the intentional adulteration of turmeric with toxic lead chromate pigments and not from the unintentional contamination of turmeric with polluted dust or soil at other points in the supply chain (i.e., through processing, storing, or transporting). The molar ratios of lead and chromium in turmeric provide a clue as to the source of lead. The molar ratio of lead to chromium is typically <0.8 if attributable to soil, dust, or other environmental pollution (Forsyth et al., 2018). Whereas the molar ratios of lead chromate pigments in our samples typically hover around 1, though can exceed 1 if the lead chromate pigments themselves are not pure and contain other forms of lead compounds like lead carbonates (Forsyth et al., 2019b). This study suggests that lead levels at and below 15 μg/g could be attributed to natural contamination whereas higher lead levels, from 18 to 2935 μg/g, resulted from lead chromate due to adulteration, as evidenced by the nearly 1:1 M ratio of lead to chromium.

The lead limits that governments set for commodities typically take several factors into account, including the public health risk, the feasibility of detection, and the feasibility of achieving these limits based on manufacturing processes and natural contamination levels. Given that there is no safe level of lead ingestion, governments aim to set regulatory limits as low as possible. For spices including turmeric, the Food Safety and Standards Association of India has set a limit of 10 μg/g lead which appears to be reasonable based on the molar lead:chromium ratio data from this study. In Pakistan, however, the limit of lead in turmeric has been set at 5 μg/g, which may be too low to be feasible given the evidence of elevated turmeric lead levels up to 15 μg/g likely from background contamination (Agriculture and Food Division., n.d.). In order to achieve this standard, improvements in general environmental pollution levels may be needed. At present, there is no lead limit for turmeric set by the governments of Nepal or Sri Lanka.

This study's limitations relate primarily to the non-random cross-sectional sampling strategy. Since certain types of turmeric are more likely than others to be adulterated with lead chromate (e.g., bulb roots or poor quality varieties (Forsyth et al., 2019a)), our aim was to use a criterion-based non-random approach to maximize the diversity of turmeric types sampled in order to have the best chance of detecting a problem of lead chromate adulteration if it exists. The descriptive statistics are meant to be suggestive of the magnitude of the potential problem. However, since the samples were not taken proportional to market share, we cannot draw direct conclusions about the proportion of people in each city procuring lead-tainted turmeric. Additionally, given that lead chromate adulteration may vary seasonally or temporally, obtaining a null result from a single cross-sectional sampling effort (turmeric season of 2020–2021) does not mean that turmeric sampled from those locations at other times would be consistently lead-free. Evidence from other parts of South Asia indicate that lead chromate has been added to turmeric since at least the 1980s and the practice ebbs and flows based on climate and macroeconomic factors (Forsyth et al., 2019a; Syed et al., 1987).

5. Conclusions

Lead is a dangerous toxicant that harms hundreds of millions of people and has been estimated to cause nearly 6 trillion dollars in harm from lost productivity and premature death from cardiovascular disease in low- and middle-income countries in 2019. This study provides a novel and effective approach for assessing lead-based food adulteration at scale, an approach that can also be applied to other food supply chains. Specifically, this study analyzed lead concentrations in turmeric sampled across wholesale markets in South Asia, where the majority of the world's turmeric is produced. Given the overwhelmingly elevated lead levels in turmeric from Bihar and Pakistan, there is an urgent need to intervene to halt the practice of lead chromate adulteration. Recent success in Bangladesh to reduce lead in turmeric via a combination of food safety policy enforcement, improved tools for rapid lead detection (Lopez et al., 2022), and broad awareness-raising efforts provides a model for other countries in South Asia to consider (Forsyth et al., 2023). Subsequent efforts should explore the turmeric supply chain in these regions to understand the scope of the problem, where lead chromate is entering the turmeric supply chain, as well as the incentives driving the practice.

CRediT authorship contribution statement

Jenna E. Forsyth: Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dinsha Mistree:** Writing – review & editing, Project administration, Conceptualization. **Emily Nash:** Writing – review & editing, Formal analysis. **Manyu Angrish:** Validation, Supervision, Project administration, Methodology, Investigation. **Stephen P. Luby:** Writing – review & editing, Methodology, Funding acquisition, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175003.

References

2022 Nepal DHS Summary Report. Kathmandu, Nepal: Ministry of Health and Population: Ministry of Health and Population [Nepal], New ERA, and ICF 2023.
Agriculture and Food Division.
All Ages Lead Model (AALM).
Attina, T.M., Trasande, L., 2013. Economic costs of childhood Lead exposure in low- and middle-income countries. Environ. Health Perspect. 121, 1097–1102. https://doi.org/10.1289/ehp.1206424.
Average Household Size, Global Data Lab. https://globaldatalab.org/areadata/table/hhsize/.
Babaei, F., Nassiri-Asl, M., Hosseinzadeh, H., 2020. Curcumin (a constituent of turmeric): new treatment option against COVID-19. Food Sci. Nutr. 8, 5215–5227.
Bellinger DC. Prenatal exposures to environmental chemicals and Children's neurodevelopment: an update. Saf. Health Work 2013;4:1–11. doi: https://doi.org/https://doi.org/10.5491/SHAW.2013.4.1.1.
Brown, M., Patel, P., Nash, E., et al., 2022. Prevalence of elevated blood lead levels and risk factors among children living in Patna, Bihar, India 2020. PLOS Global Public Health. 2, e0000743.
Combes, R., Haveland-Smith, R., 1982. A review of the genotoxicity of food, drug and cosmetic colours and other azo, triphenylmethane and xanthene dyes. Mutation Research/Reviews in genetic toxicology. 98, 101–243.
Dixit, S., Purshottam, S.K., Khanna, S.K., et al., 2009. Surveillance of the quality of turmeric powders from city markets of India on the basis of curcumin content and the presence of extraneous colours. Food Additives & Contaminants: Part A. 26, 1227–1231. https://doi.org/10.1080/02652030903016586.
Ericson, B., Gabelaia, L., Keith, J., et al., 2020. Elevated levels of Lead (Pb) identified in Georgian spices. *Annals of.* Glob. Health 86.
Faizan, U., Rouster, A.S., 2020. Nutrition and Hydration Requirements in Children and Adults.
Food safety and standards (food products standards and food additives) regulations. Food Safety and Standards Authority of India, 2011.
Forsyth, J.E., Akhalaia, K., Jintcharadze, M., et al., 2024. Reductions in spice lead levels in the republic of Georgia: 2020–2022. Environ. Res. 118504.
Forsyth, J.E., Baker, M., Nurunnahar, S., et al., 2023. Food safety policy enforcement and associated actions reduce turmeric lead chromate adulteration across Bangladesh. Environ. Res. 116328.
Forsyth JE, Nurunnahar S, Islam SS, *et al.* Turmeric means "yellow" in Bengali: Lead chromate pigments added to turmeric threaten public health across Bangladesh. Environ. Res. 2019a;179:108722. doi: https://doi.org/https://doi.org/10.1016/j.envres.2019.108722.
Forsyth JE, Saiful Islam M, Parvez SM, *et al.* Prevalence of elevated blood lead levels among pregnant women and sources of lead exposure in rural Bangladesh: a case control study. Environ. Res. 2018;166:1–9. doi: https://doi.org/https://doi.org/10.1016/j.envres.2018.04.019.
Forsyth, J.E., Weaver, K.L., Maher, K., et al., 2019b. Sources of blood Lead exposure in rural Bangladesh. Environ. Sci. Technol. 53, 11429–11436. https://doi.org/10.1021/acs.est.9b00744.
Gleason, K., Shine, J.P., Shobnam, N., et al., 2014. Contaminated turmeric is a potential source of lead exposure for children in rural Bangladesh. J. Environ. Public Health 2014, 730636. https://doi.org/10.1155/2014/730636.
Hore, P., Alex-Oni, K., Sedlar, S., et al., 2019. A spoonful of Lead: a 10-year look at spices as a potential source of Lead exposure. J. Public Health Manag. Pract. 25, S63–S70.
Jadhav, V., Baviskar, P., Waghmare, S., et al., 2022. Export Performance of Turmeric in India.
Kappel, M., Kraushaar, V., Mehretu, A., et al., 2021. Notes from the field: childhood Lead poisoning associated with turmeric spices—Las Vegas, 2019. Morb. Mortal. Wkly Rep. 70, 1584.
Lacey, R., Moore, M., Richards, W., 1985. Lead in water, infant diet and blood: the Glasgow duplicate diet study. Sci. Total Environ. 41, 235–257.
Larsen, B., Sánchez-Triana, E., 2023. Global health burden and cost of lead exposure in children and adults: a health impact and economic modelling analysis. The Lancet Planetary Health. 7, e831–e840.

Lim, H.S., Choi, E., Lee, J.-H., et al., 2020. Analysis of illegal colourants (citrus red II, diethyl yellow, dimethyl yellow, metanil yellow and rhodamine B) in foods by LC-UV and LC-MS/MS. Food Additives & Contaminants: Part A. 37, 895–904.
Lopez, A.M., Nicolini, C.M., Aeppli, M., et al., 2022. Assessing analytical methods for the rapid detection of Lead adulteration in the global spice market. Environ. Sci. Technol. 56, 16996–17006.
Mishra, K.P., 2009. Lead exposure and its impact on immune system: a review. Toxicol. in Vitro 23, 969–972.
Moore, J.C., Spink, J., Lipp, M., 2012. Development and application of a database of food ingredient fraud and economically motivated adulteration from 1980 to 2010. J. Food Sci. 77, R118–R126.
Murray, C.J., Aravkin, A.Y., Zheng, P., et al., 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the global burden of disease study 2019. Lancet 396, 1223–1249.
Needleman, H.L., 1991. Human lead exposure. CRC Press.
Prasad, S., Aggarwal, B.B., 2011. Turmeric, the Golden Spice. *Herbal Medicine: Biomolecular and Clinical Aspects*, 2nd edition. CRC Press/Taylor & Francis.
Ruckart, P.Z., Jones, R.L., Courtney, J.G., et al., 2021. Update of the blood lead reference value—United States, 2021. Morb. Mortal. Wkly Rep. 70, 1509.
Sherlock, J., Quinn, M., 1986. Relationship between blood lead concentrations and dietary lead intake in infants: the Glasgow duplicate diet study 1979–1980. Food Addit. Contam. 3, 167–176.
Singh, J., Pritchard, D.E., Carlisle, D.L., et al., 1999. Internalization of carcinogenic lead chromate particles by cultured normal human lung epithelial cells: formation of intracellular lead-inclusion bodies and induction of apoptosis. Toxicol. Appl. Pharmacol. 161, 240–248.
Srivastava, S., 2013. KRISHI publication and data inventory repository. Journal of Spices and Aromatic Crops 22, 47–54.
Syed, A.M., Qadiruddin, M., Khan, A., 1987. Detection and estimation of Lead in curcuma longa bulbs (turmeric) by atomic absorption spectrophotometry. J. Chem. Soc. Pak. 9, 387.
Tan, S.W., Cohen, S.G., Wilson, M.A., et al., 2023. Lead poisoning from home-prepared indian spices in 3 families. Clin. Pediatr. 00099228221150158.
Tønnesen, H.H., Karlsen, J., 1983. High-performance liquid chromatography of curcumin and related compounds. J. Chromatogr. A 259, 367–371.
Trasande, L., Liu, Y., 2011. Reducing the staggering costs of environmental disease in children, estimated at $76.6 billion in 2008. Health Aff. 30, 863–870.
World Health Organization, 2011. Evaluation of certain food additive and contaminants. World Health Organ. Tech. Rep. Ser. 1.