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Turmeric means "yellow" in Bengali: Lead chromate pigments added to turmeric threaten public health across Bangladesh

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ABSTRACT

Adulteration is a growing food safety concern worldwide. Previous studies have implicated turmeric as a source of lead (Pb) exposure due to the addition of lead chromate ($PbCrO_4$), a yellow pigment used to enhance brightness. We aimed to assess the practice of adding yellow pigments to turmeric and producer- consumer- and regulatory-factors affecting this practice across the supply chain in Bangladesh. We identified and visited the nine major turmeric-producing districts of Bangladesh as well as two districts with minimal turmeric production. In each district, we conducted semi-structured interviews and informal observations with individuals involved in the production, consumption, and regulation of turmeric. We explored perceptions of and preferences for turmeric quality. We collected samples of yellow pigments and turmeric from the most-frequented wholesale and retail markets. We collected samples of turmeric, pigments, dust, and soil from turmeric polishing mills to assess evidence of adulteration. Interviews were analyzed through an inductive, thematic coding process, with attention focused on perceptions of and preferences for turmeric quality. Samples were analyzed for Pb and chromium (Cr) concentrations via inductively coupled plasma mass spectrometry and x-ray fluorescence. In total, we interviewed 152 individuals from across the supply chain and collected 524 samples of turmeric, pigments, dust, and soil (Table S3, Table S4). Turmeric Pb and Cr concentrations were highest in Dhaka and Munshiganj districts, with maximum turmeric powder Pb concentrations of 1152 μg/g, compared to 690 μg/g in the 9 major turmeric-producing districts. We found evidence of $PbCrO_4$-based yellow pigment adulteration in 7 of the 9 major turmeric-producing districts. Soil samples from polishing mills contained a maximum of 4257 μg/g Pb and yellow pigments contained 2–10% Pb by weight with an average Pb:Cr molar ratio of 1.3. Turmeric wholesalers reported that the practice of adding yellow pigments to dried turmeric root during polishing began more than 30 years ago and continues today, primarily driven by consumer preferences for colorful yellow curries. Farmers stated that merchants are able to sell otherwise poor-quality roots and increase their profits by asking polishers to adulterate with yellow pigments. Adulterating turmeric with lead chromate poses significant risks to human health and development. The results from this study indicate that $PbCrO_4$ is being added to turmeric by polishers, who are unaware of its neurotoxic effects, in order to satisfy wholesalers who are driven by consumer demand for yellow roots. We recommend immediate intervention that engages turmeric producers and consumers to address this public health crisis and ensure a future with Pb-free turmeric.

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1. Introduction

Food safety risks are a growing public health concern worldwide, especially in low- and middle-income countries (Grace, 2015). Food adulteration is one class of risk, where, unbeknownst to the consumer, substances are added to artificially augment the quality or quantity of a product in order to lower production costs or increase sales prices (Moore et al., 2012). These additives can be non-toxic, such as in the dilution of milk with water, or extremely toxic, such as in the addition of carcinogenic melamine to milk (Spink and Moyer, 2011). In 2008, melamine-tainted milk from China killed six infants and hospitalized 54,000 (The Lancet. China's food, 2014). Globalization and lengthening supply chains have made food adulteration a global concern (Manning and Soon, 2014; Ellis et al., 2016). Most of the world's food production occurs in low- and middle-income countries with limited regulatory enforcement (Rosegrant et al., 2020). As a result, adulterated foods are often detected only after they have been distributed widely to higher income countries with stringent food safety monitoring (Bansal et al., 2017).

Spices are among the top five most commonly adulterated food types because they are expensive commodities that are processed prior to sale (Petrakis et al., 2017; Hagh-Nazari and Keifi, 2006). Among a database of more than 1000 records of food adulteration worldwide between 1980 and 2010, 11% of scholarly articles and 19% of media reports related to spices, many featuring toxic color additives agents like Sudan dyes (Moore et al., 2012).

Turmeric is an essential culinary spice consumed daily in South Asia, also known as 'the golden spice' or 'Indian saffron' due to its brilliant yellow color (Prasad and Aggarwal, 2011). A relative of the ginger root, turmeric is grown predominantly in India, as well as Bangladesh, Myanmar, China, and Nigeria. For millennia, turmeric has been consumed medicinally as an anti-inflammatory agent and to promote general health in South Asia (Prasad and Aggarwal, 2011). Similarly, across other countries within the past five years, turmeric has been studied and consumed for its healing properties, targeting everything from gastric disorders to cancers (Gupta et al., 2013). Major manufacturers worldwide have also started using turmeric as a natural coloring agent in foods ranging from macaroni and cheese to yogurt and ice cream in response to consumer pressure to reduce the use of artificial coloring agents (Cowell et al., 2017).

Despite its widespread consumption and uses, turmeric has not been extensively examined for adulteration but it has been identified as a source of lead (Pb) exposure in South Asia (Gleason et al., 2014; Lin et al., 2010). Lead is a threat to public health, as even low levels of Pb exposure can lower IQ and disrupt normal cognitive development, especially among children (Lanphear et al., 2005; Budtz-Jorgensen et al., 2013). Thirteen brands of turmeric exported by Bangladesh and India have been recalled worldwide since 2011 due to excessive Pb concentrations (Cowell et al., 2017). A study in rural Munshiganj district of Bangladesh found that 78% of 309 children aged 20–40 months had elevated blood lead levels and that turmeric was the likely exposure route (Gleason et al., 2014). They reported average Pb concentrations of 80 μg/g in turmeric, more than 30 times higher than the national threshold for allowable Pb in turmeric in Bangladesh (Bangladesh Standards and, 2001). Recent population- and isotope-based studies suggest that elevated Pb in turmeric is the dominant contributor to elevated blood lead levels in rural Mymensingh, Kishoreganj, and Tangail districts (Forsyth et al., 2018, 2019). These researchers identified that a lead chromate ($PbCrO_4$)-based yellow pigment was being added to turmeric during processing, possibly to enhance the color of dried turmeric root (Gleason et al., 2014; Forsyth et al., 2019; Syed et al., 1987).

To build on these prior findings, the objectives of our study were to assess the practice of adding yellow pigment to dried turmeric root and to better understand the factors affecting turmeric adulteration across the supply chain in Bangladesh. By identifying why and how people adulterate, we can recommend interventions to reduce this risk.

2. Materials and methods

2.1. Study site selection

In January 2017, we met with governmental officials from Bangladesh's Department of Agricultural Authority to understand patterns in turmeric production and distribution throughout the country. Based on this meeting, as well as informal interviews with wholesalers at the largest turmeric market in Dhaka, the capital city of Bangladesh, we identified major turmeric-producing districts. In those districts, farmers and processors grow, dry, polish, and grind turmeric before distributing it as dry root or ground powder. According to records supplied by the Bangladesh Department of Agriculture in 2016, turmeric was produced in 63 of the 64 districts with a total production area of 42,754 ha. We selected the top eight turmeric-producing districts, which produce nearly 50% of the nation's turmeric, for our study. In addition, although its production volume is low, we included Khulna District in our study sample as turmeric from this region is well-known and numerous processors as well as consumers described Khulna turmeric as the highest quality in Bangladesh (Table S1). These nine major turmeric-producing districts in our sample are clustered geographically into four major regions relative to Dhaka: i) Southwest: Khulna; ii) Northwest: Pabna, Natore, and Rajshahi; iii) North: Mymensingh and Tangail; and iv) Southeast: Khagrachari, Bandarbon, and Rangamati (Fig. 1).

Our study sample also included two districts that are not major turmeric producers: i) Dhaka, the nationwide hub of turmeric distribution, and ii) Munshiganj, a nearby rural district where a prior population-based study suggested that turmeric contributes to human Pb exposure (Gleason et al., 2014). In these districts, turmeric is not grown in significant quantities, nor is it dried, or polished but, rather, turmeric is distributed either as dry root or ground powder for sale (Fig. 1).

2.2. Data collection

In each district, we used a snowball sampling approach to select at least 2 or 3 individuals involved with turmeric production, processing, distribution, sale, and consumption (Coyne, 1997; Patton, 1990; Teddlie and Yu, 2007). We conducted semi-structured interviews and informal observations with these individuals who were laborers, farmers, manual and machine polishers, grinders, wholesalers, retailers, corporate representatives, and consumers. We interviewed merchants selling turmeric, as well as others selling yellow pigments, for both retail and wholesale. We interviewed two types of consumers: those purchasing turmeric for household purposes and individuals from restaurants and hotels purchasing larger volumes of turmeric. At factories and company offices, we visited corporate representatives who were involved with turmeric purchasing or with quality assurance and control. We obtained written informed consent from all study participants. The protocol was reviewed and approved by the ethical review committee at icddr,b and Stanford University.

The interviews explored factors associated with adulteration of turmeric with yellow pigments, with questions probing perceptions of and preferences for turmeric quality. We explored the quality attributes of turmeric by displaying nine dried turmeric root samples representing a range in quality and color from 5 districts and asking respondents to rank them by quality (Fig. S1). We further explored respondents' perceptions of color by presenting an adapted version of the World Color Survey chart as an aid (Kay et al., 2009) (Fig. S2).

To understand the role of regulation, we conducted semi-structured interviews with food safety inspectors and law enforcement officers involved with the monitoring and enforcement of food safety priorities. We used an interview protocol that focused on daily operations, food

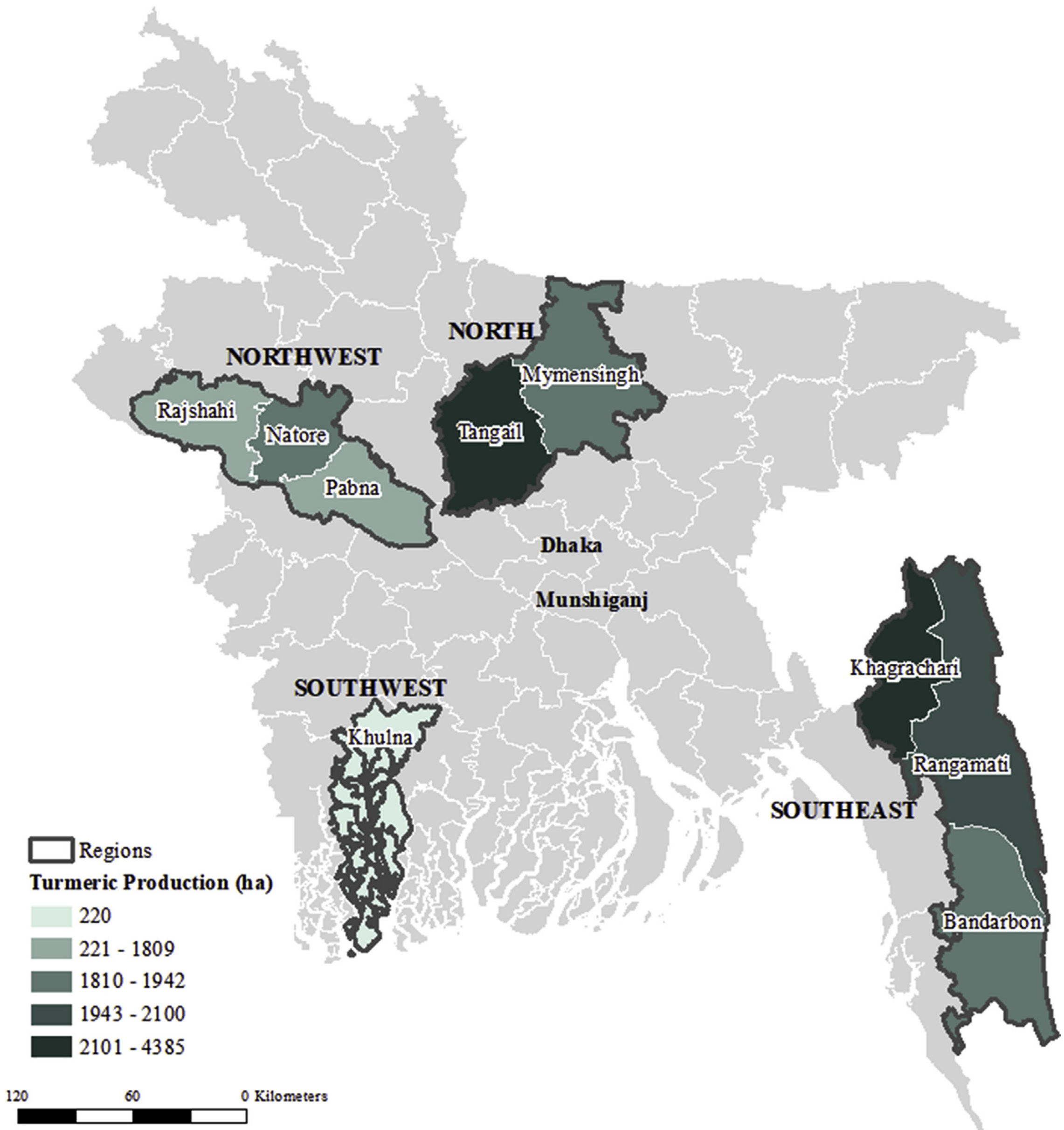

Fig. 1. Turmeric production (ha) among the nine major turmeric-producing districts in Bangladesh included in this study.

safety priorities, and inspectors' knowledge of turmeric adulteration.

Across all study districts, we collected samples of pigments and each type of turmeric available at major wholesale and retail markets. Turmeric types included loose powdered turmeric and packaged (branded) powdered turmeric, as well as polished and unpolished dried turmeric root. Within a given market, we inquired with each merchant about the production and distribution history of the turmeric for sale to ensure that we maximized sample variety and did not collect duplicate samples. As multiple merchants sold the same brand of turmeric, we only collected additional samples if the lot numbers printed on the packaged turmeric differed.

In each turmeric-producing district, we collected samples from the largest polishing mills, as well as smaller mills, when possible. We collected samples of turmeric powder, unpolished and polished dried turmeric root, and pigments. We also sampled dust inside and below polishing machines to assess how recently $PbCrO_4$-based pigments had been added, as well as three soil samples from a 5-to-50-m radius around the mills to determine how far the Pb contamination may have spread into the surrounding environment.

2.3. Data analysis

Interviews were conducted in Bengali by trained qualitative researchers with backgrounds in anthropology and sociology. The same researchers transcribed the audio-recorded interviews in Bengali then translated them into English. We coded the interview data using *a priori* (deductive) and emergent (inductive) coding processes guided by our interest in overall turmeric quality as well as pressures to adulterate.

We analyzed samples for Pb and chromium (Cr) concentrations at Stanford's Environmental Measurements Facility (em1.stanford.edu) using inductively coupled plasma mass spectrometry (Thermo Scientific XSERIES 2 ICP-MS) for turmeric samples and x-ray fluorescence (Spectro XEPOS HE XRF, XLab Pro 5.1 software) for the minimally soluble pigment, dust, and soil samples. Turmeric samples were dissolved in concentrated HNO_3 and digested via microwave digestion (MarsXpress, CEM corporation) prior to being aspirated in 2% HNO_3 for ICP-MS analysis. Blanks were analyzed every 20 samples and an internal standard solution was measured every 40 samples to correct for instrumental drift. A sub-set of 20% of samples were analyzed in

Table 1
Interviews conducted and samples collected across the supply chain in Bangladesh. Individuals often carried out multiple activities (*e.g.,* individuals who polished turmeric also raised turmeric).

Role	Interviews	Samples	Sample types
Farmers/polishers	55	263	turmeric, yellow pigment, yellow pigment waste bags, polishing dust, floor dust, soil
Companies selling packaged turmeric	4	27	turmeric
Color merchants	4	7	yellow pigment
Grinders/wholesalers/retailers	34	227	turmeric
Household consumers	34		
Restaurant consumers	13		
Food safety inspectors/law enforcement officers	8		

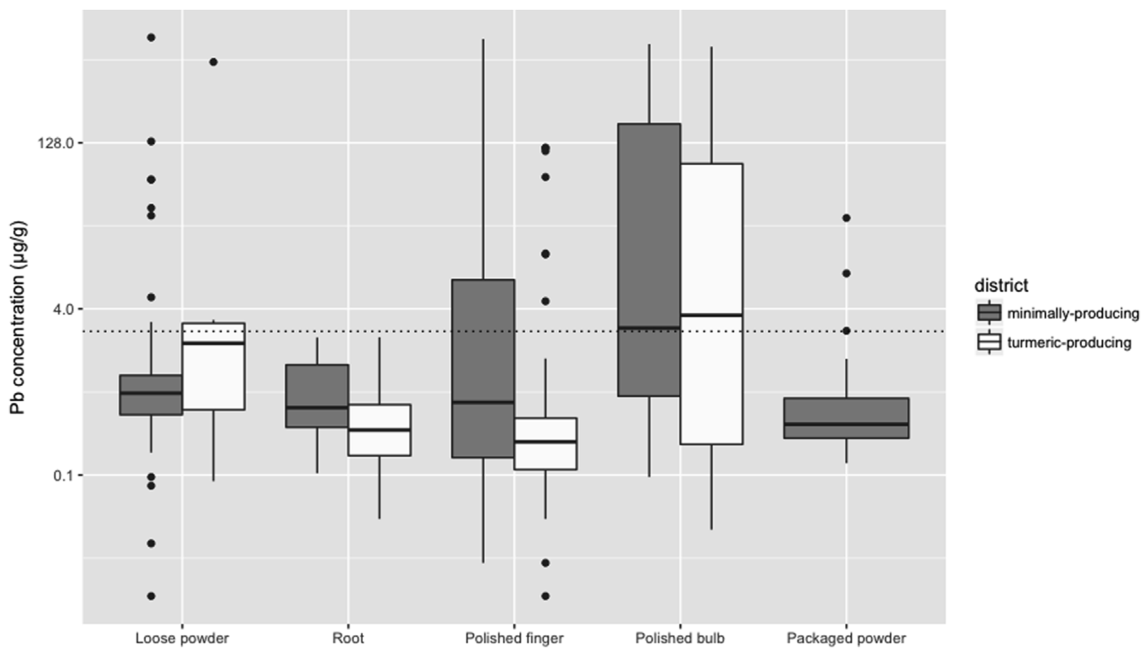

Fig. 2. Pb concentrations (log-scale) of turmeric sampled between 2016 and 2018 from nine major turmeric-producing districts, and the minimally-producing districts Dhaka and Munshiganj. The dashed line indicates the 2.5 µg/g Pb threshold for turmeric in Bangladesh (Bangladesh Standards and Testing Institution, 2001).

duplicate. These repeat measurements indicated that Pb concentrations were reproducible to within 6%.

We determined that a polishing mill exhibited physical evidence of adulteration with yellow pigments if any of the following were true based on informal observations and sampling: i) yellow pigments or yellow pigment waste bags were found on-site, ii) polishing dust (from within or below the polishing machine) and soil samples from around the mills contained Pb and Cr concentrations greater than environmental soil, or iii) polished turmeric roots were found with Pb and Cr concentrations greater than unpolished roots.

3. Results

The following results are based on interviews with 152 individuals from across the supply chain and 524 samples of turmeric, pigments, dust, and soil (Table 1, Table S3, Table S4).

3.1. Overview of turmeric supply chain: Dhaka is a hub of turmeric distribution

In Bangladesh, harvesting season is December through March, although this varies slightly by region. After harvesting, farmers boil, sun-dry, and sort roots by size and type (fingers or bulbs; Fig. S3). At mills located near farms, processors polish roots by machine or manually and add yellow pigment as needed. The purpose of polishing is to rub away dirt and the root's outer skin to expose the yellow inner part of the root. To accomplish this, machine polishing is more effective and efficient than manual polishing, which is a process by which people use their legs and feet to agitate and clean the roots in clay pots called *chari*. Once roots are polished, other processors grind them into a powder at mills located in bazaars or at company facilities where turmeric is packaged and distributed throughout Bangladesh or possibly exported. Turmeric is primarily sold as a loose powder scooped out of 40 kg burlap sacks, though wealthier consumers prefer the more expensive packaged powder (Fig. S3, Fig. S4).

Dhaka's major wholesale bazaar is the hub of turmeric distribution for Bangladesh. Middlemen transport polished turmeric roots from the different turmeric-producing districts to Dhaka where wholesalers store, sell, and re-distribute within Dhaka city as well as throughout the country to other wholesalers, especially those in districts with less turmeric production, and to companies that export internationally. The Bangladeshi companies we interviewed primarily export turmeric to the United Arab Emirates and other middle eastern countries, and also to the UK, the U.S., and Canada (Fig. S4). Although India remains the primary turmeric exporter worldwide, company representatives expressed an interest in increasing the export of Bangladeshi turmeric. Reliable estimates of turmeric import and export volumes were not reported.

3.2. Lead concentrations provide evidence of $PbCrO_4$-based yellow pigment adulteration

In total, we collected 140 turmeric samples from the 9 major turmeric-producing districts, and an additional 200 turmeric samples from the 2 minimally-producing districts, Dhaka and Munshiganj (Fig. 2, Table S4). On average, Pb concentrations were lower in the major turmeric-producing districts, with 11% of samples containing Pb in excess of the Bangladesh Standards and Testing Institution's limit of 2.5 µg/g Pb in turmeric (Bangladesh Standards and Testing Institution, 2001), compared to 26% in Dhaka and Munshiganj. Polished bulbs in all districts contained the highest Pb concentrations, followed by polished finger roots. The maximum Pb concentration of loose powder in major turmeric-producing districts was 690 µg/g compared to 1152 µg/g Pb in Dhaka and Munshiganj. Two samples of packaged powdered turmeric exceeded the national limit for Pb, containing 8.4 and 26.6 µg/g Pb. None of the 11 turmeric samples from India contained elevated Pb (average of 0.2 and a maximum of 0.7 µg/g Pb).

Among 43 total polishers, 12 out of 15 polishers from the Northwest region exhibited at least one type of physical evidence of yellow pigment adulteration, followed by 7 out of 10 in the North, 4 out of 15 in the Southeast, and 0 out of 3 in the Southwest (Fig. S5). By district, we found evidence of yellow pigment adulteration in 7 out of the 9 turmeric-producing districts. We collected 7 samples of yellow pigment, 10 yellow pigment waste bags, 39 samples of polishing dust, 35 samples of floor dust from the polishing mill, and 59 samples of soil (Table S3). Further, we collected 28 soil samples along a transect of 0–50 m in three directions from the mill of one polisher in the Northwest region known to adulterate with yellow pigment (Fig. S6).

We collected samples of yellow pigment and yellow pigment waste bags from polishing mills in every region except the Southwest, with the majority from the Northwest. The hue of the pigments ranged from bright yellow to yellow-orange. The median Pb concentration was 20,024 µg/g with a maximum of 115,500 µg/g (Fig. 3, Table S3). Five of the 7 samples were a $PbCrO_4$-based compound containing 2–10% Pb by weight, whereas one contained only 0.2 µg/g Pb. An additional 6 samples of yellow pigment were collected from color merchants in Dhaka and Mymensingh with a median Pb concentration of 27,144 µg/g. Three of the six yellow pigment samples from color merchants contained between 5 and 8% Pb by weight and one contained 6.0 µg/g Pb. In total, the average Pb:Cr ratio of the yellow pigments with elevated Pb from both polishers and color merchants was 1.26, suggesting a $PbCrO_4$-based compound with additional Pb-containing compounds. The five yellow pigment samples that contained minimal Pb did not contain elevated concentrations of other heavy metals such as Cr, zinc, or cadmium.

We collected polishing machine dust, floor dust, and soil from every region. The median Pb concentration of polishing machine dust was 25.4 µg/g and 20.5 µg/g for floor dust, with maxima of 21,166 and 66,060 µg/g Pb, respectively (Fig. 3, Table S3). Soil samples contained a median of 34.7 µg/g Pb with a maximum of 4257 µg/g Pb at a distance of 3 m from the polishing mill, though one sample taken at a distance of 50 m from a mill contained 861.6 µg/g Pb (Fig. S6, Table S3). Nearly one-third of all soil samples (32%) contained greater than the residential soil Pb limit of 80 µg/g in California (2018). Samples with higher soil Pb concentrations had molar Pb:Cr ratios between 1.2 and 1.4, similar to the yellow pigment samples (Fig. S7).

3.3. Turmeric adulteration with yellow pigment prompted by flooding and imported turmeric

Based on semi-structured interviews with producers, processors, distributors, and consumers, we determined that turmeric polishers add yellow pigment to increase profits primarily by augmenting the roots' yellow appearance, which, first, facilitates the sale of poor-quality roots and, second, reduces polishing time and the quantity of root lost during polishing (Fig. S8).

Dried turmeric roots adulterated with yellow pigment are mostly sold in Dhaka's major wholesale market, where polishers and wholesalers estimated that the practice of adding color began between 1970 and 1990. Several polishers and farmers in the Northwest described the catalyst as the big flood of 1988, which damaged the turmeric crop, resulting in improperly dried roots and an unacceptable inner-root color due to wet conditions. Because the quality of Bangladeshi turmeric was compromised, demand increased for imported Indian turmeric, which had a bright yellow exterior color. To sell local Bangladeshi roots, which then had to compete with the brighter Indian turmeric, Dhaka wholesalers began to mix yellow pigment with the roots in *chari* (clay pots). After this, Dhaka wholesalers gave the yellow pigment to polishers in turmeric-producing districts so that the polishers could themselves add color to turmeric (Table S2).

The rise in imports of Indian turmeric in the 1990s coincided with Bangladeshi companies selling and distributing packaged powdered turmeric within Bangladesh. Both factors apparently influenced the adoption of polishing machines which could produce better polished roots than manual polishing. (Table S2).

Based on interviews with Dhaka color merchants, we learned that they import industrial pigments from India and China and sell those pigments to the garment, plastics, furniture, and painting industries. Originally, the yellow pigments added to turmeric roots were intended for coloring plastic toys or bags or staining furniture; some are reportedly also used during *Holi,* a Hindu festival. Color merchants, as well as turmeric farmers, polishers, and wholesalers, used several names for the yellow pigments. Most commonly they used the terms *peuri,* (no meaning) and *sharsheful* ("mustard flower"), but also sometimes *holud* ("yellow" or "turmeric") or *pipri* or *kathali* ("jackfruit")

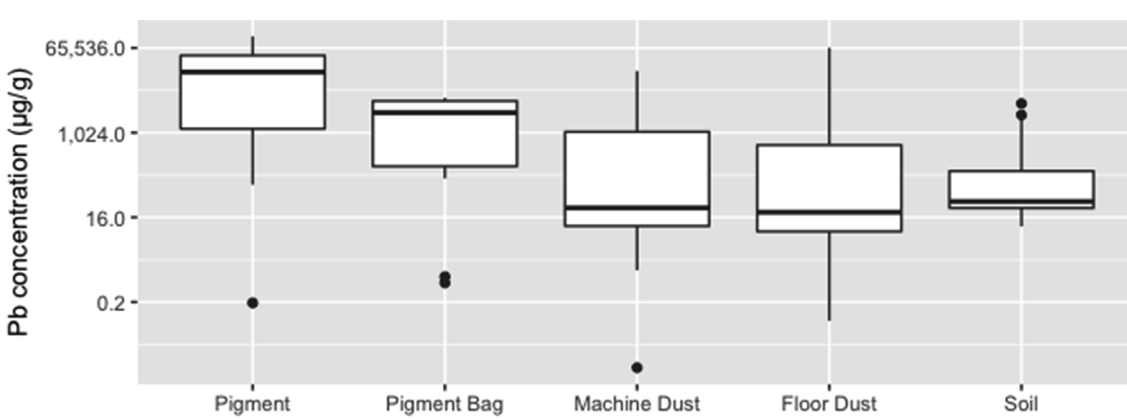

Fig. 3. Pb concentrations (log-scale) in samples obtained from polishing mills in nine major turmeric-producing districts of Bangladesh.

Table 2
Production-, consumption- and regulation-focused factors affecting the adulteration of turmeric with yellow pigment in Bangladesh.

Theme	Sub-theme	Examples
Production	Farming	
	Soil quality	"This is because of soil and seed. Hilly area's (Southeast region's) soil is red therefore the turmeric which grows in that soil has nice inner color. Some soil is very black therefore turmeric grown in that soil doesn't contain nice color." (R-1, MY) Mymensingh wholesaler
	Regional cultivar quality	"Khulna and Natore's turmeric naturally have good inner color that doesn't need any [added] color. Turmeric that does not have good quality and color needs *sharsheful* color (yellow pigment) to look good and sell at a cheaper price. As you can see, the bulbs here contain yellow color additives, that's why they're looking nice. Without color, you would never like this turmeric. That's why people add color." (R-2, K) Dhaka wholesaler
	Processing	
	Drying	"This year, people reduced the use of color since turmeric didn't get wet and it was adequately dried." (R-3, KH) Khagrachari polisher "If turmeric gets wet in the rain, no matter how you polish, good color will not come out. Then, you have to add color in order to sell in the market." (R-4, BA) Bandarbon polishers
	Polishing	"When manual polishing was common, a color called *peuri* (yellow pigment) was available. It was used during (manual) polishing in *chari* (clay pots). *Alum* is used to make turmeric dirt free and *peuri* to make it colorful. 5 g of *peuri* is used for polishing one mound (~45 kg) of turmeric along with 20 g *alum*." (R-6, PB) Pabna polisher
	Storing	"There is no problem if you eat old turmeric. However, first year's turmeric's color looks polished, then the next year the color becomes light. After that, the original color goes away and we have to mix in color." (R-2, KH) Khagrachari polisher "In season, color should not be mixed since good quality turmeric is available. Toward the end of the season, when it rains, color additives need to be added to turmeric." (R-1, KH) Khagrachari Polisher
Consumption	Consumer quality assessment	
	Upon purchase	"In case of ranking turmeric (root) quality, we first notice the size of the root and whether it is *chori* (finger) or *motha* (bulb). Between big and small, we select the big sized roots because it is in high demand and has better quality. After that, we check for the maturity of the turmeric. Then, we check if the inside color of the dried turmeric root looks like egg yolk. Finally, we check for oil content." (R-10, NA) Natore polisher "The bulbs look like egg yolk on the outside when you add *peuri* (yellow pigment). But you never find the same color on the inside and outside of the dried turmeric roots (bulbs) … Bulbs have more rough fibrous knobs on their exterior, hence people add more color to them. All of this is a dreadful practice. A person can check for inner root color by breaking the root into two pieces if it is a finger root. But it is difficult with bulbs. It is hard to break them (bulbs) by hand in the market. That's why they (bulbs) are colored most." (R-1, PB) Pabna wholesaler
	Upon cooking	"[The good quality turmeric] is powdered turmeric that requires a small amount to give curry a perfect color and doesn't taste bitter if someone uses too much in the curry." (R-3, PB) Pabna polisher
	Type of consumer	"Those who know turmeric, they will always buy colorless turmeric. On the other hand, those who only go by looks, they will buy colored turmeric." (R-2, KH) Khagrachari polisher "Colored turmeric goes to Dhaka and Chittagong. There is no demand for turmeric with color additives in the local area." (R-4, BA) Bandarbon polisher "The quantity of *peuri* (yellow pigment) depends on how colorful you want it (turmeric) to be. For the dried turmeric root of mine that you found at Shambazar (Dhaka's major wholesale market), I used 1 kg *peuri* for 500 kg of dried turmeric root." (R-9, NA) Natore polisher
Regulation	International	"We would have never known (that turmeric contained high levels of Pb) if we didn't export it. We would have never known if we just continued to sell it locally." (R-1, P) Company representative "*Kawn* (one kind of rice flour) may be mixed in some powdered turmeric. *Kawn* is 20 taka per kg. You will find it in loose turmeric powder. You will not find it packaged branded turmeric powder because none of us want companies to reject our turmeric powder. In Dubai, if they find any kind of adulteration, they destroy the shipment and throw it in the sea or they burn it." (R-1, P) Company representative
	National	"I have a grinding machine in the bazaar. There, inspectors/police visited to see my powdered turmeric. No one has visited here (where I polish dried turmeric roots)." (R-6, PB) Pabna polisher "6–7years ago trouble arose for using color. Police/inspectors started to check whether color we used or not. I don't know about punishment because I didn't see anyone get punished." (R-9, NA) Natore Polisher "Two years ago, a person from this sub-district was in the color business. He brought yellow pigments from Dhaka and sold them here. This color additive was brought only to be added to dried turmeric root. He sold it to the polishers. After the police came by, he stopped bringing it. Now the polishers have to bring it from Dhaka." (R-5, PB) Pabna wholesaler

color. One polisher who did not know the name called it the *kukhaddo* ("inedible") and *otironjito* ("exaggerated") color. Color merchants reported that none of their dyes or pigments were intended for use in food, a statement that was printed on their business cards because they had heard that some *kharap lok* ("awful people") add the pigments to food. Aside from turmeric, color merchants reported that pigments were also added to rice cakes, known as *pitha.* We identified the group of merchants selling food-grade color additives at the color bazaar but were unable to identify any food-grade yellow color powders available for sale.

3.4. Present-day production, consumption, and regulatory factors incentivize turmeric adulteration

3.4.1. Production

Production factors that influence the addition of color include growing conditions, soil type, and turmeric type (cultivar), as well as processing factors, particularly those related to drying, storage, and polishing conditions (Table 2). Interviewees consistently mentioned that the 'soil and seed' both impact the turmeric color, oil content, size, shape, taste, smell, and other quality characteristics. Polishers and wholesalers referred to color using evocative and descriptive language. For example, interviewees described the inside root color of the high-quality cultivar grown in Khulna as "egg yolk" or "gold." Because it is considered the highest-quality among Bangladeshi turmeric, polishers and wholesalers reported that Khulna's turmeric does not require added coloring. A polisher from another district attributed the naturally bright, deep color to the soil quality along with the care that farmers in Khulna take in sowing the seeds. One company representative referred to color by the percent content of curcumin, the color-producing compound naturally found in turmeric, stating that turmeric from the North region (Mymensingh and Tangail), had the least curcumin (~1%).

Polishers mentioned that turmeric roots with high moisture content must be fully dried or they will not become yellow during polishing and will "require" color additives to sell. Turmeric roots are sun-dried for 10–50 days. One polisher from the Southeast region mentioned that color was not needed in 2017 because there was enough sunlight to adequately dry the roots. Optimal drying, primarily associated with the weather, is also affected by farmer-specific practices such as turning and drying roots on dirt-free surfaces.

Through interviews, we discovered that polishing time impacts profitability and varies based on moisture content of the root as well as whether the root is polished manually or by machine. For every 10–20 min of machine polishing, 10% of the turmeric (by weight) is lost; therefore, shorter polishing time allows for a greater mass of root to be retained and sold. Turmeric roots with lower moisture content require less time to polish. Adding color shortens polishing time and results in a desirable yellow color, especially for roots with high moisture content. Even for well-dried roots, polishing long enough to produce a desirable color is time-consuming, especially when polished manually: several hundred kilograms of roots can be polished in an hour by machine, a task that would take a full week for a manual polisher. To reduce effort, 23 out of 43 of the machine-polishers and all 3 of the manual-polishers we observed use color additives. Overall, wholesalers and polishers in all districts reported that acquiring polishing machines reduced the use of color, especially the amount of color added.

3.4.2. Consumption

Consumer preferences greatly impact the addition of color, with Dhaka customers demonstrating the highest demand for artificially colored turmeric roots. Polishers in the North and Northwest stated that colored turmeric roots are not for sale in turmeric-producing areas and that polishers do not decide whether to add color; rather, polishers respond to the demands of their customers. Several polishers stated that Dhaka wholesalers or middlemen insist on adding color and frequently supply polishers with yellow pigment. Some polishers referred to these turmeric businessmen who request color during polishing as *osoth lok* ("dishonest people"), more concerned about their profits than the well-being of others. Many polishers classified the yellow pigments as unnatural chemical additives that would likely be harmful to health if consumed in large enough quantities. However, none of the polishers were aware that the yellow pigments contained Pb, a potent neurotoxin.

During interviews, consumers described how they would judge the quality of their turmeric at the time of purchase, cooking, or both. Consumer preferences depend on the type of turmeric being purchased and concern about quality attributes like color, purity, and price. Turmeric may be purchased as a whole root, either as fingers or bulbs, or it may be ground into a powder and sold loose or packaged and branded. At the time of purchase, consumers are only able to accurately assess the quality of turmeric roots. Specifically, roots in the finger form provide consumers with the most information about the quality. Consumers can visually inspect outside color, size, shape, and smell of the finger before breaking it in half to further assess oil content and color on the inside of the finger. Bulbs, however, cannot be broken, so consumers look primarily for external color. As a result, polishers and wholesalers mentioned that bulbs are more often polished with yellow pigment than fingers. Companies and consumers in turmeric-producing regions who were knowledgeable and concerned about turmeric root quality stated they would never knowingly purchase yellow-colored roots. This was not because of a specific concern about Pb but rather because of a general belief that any artificial chemical additive could harm health. One company representative noted that he could rub the root on his finger to determine whether artificial color was added. On the other hand, most restaurant owners and some retailers stated that they preferred to purchase the yellow-colored roots.

At the time of cooking, all consumers assess quality based on the ultimate test: the yellow color that "blooms" in the curry. Vibrant yellow curries and sauces made with turmeric were described as integral to Bangladeshi cuisine. Serving dull-colored foods would not only reflect poorly on the cook's abilities, but would also go against cultural norms. Given this focus on color, consumers purchasing turmeric powder were most concerned about a type of adulteration where grinders would mix turmeric and rice powder. This adulteration forced consumers to increase the quantity of turmeric added to curries to achieve the appropriate yellow hue.

Household consumers from all regions repeatedly mentioned the importance of purchasing turmeric and other goods from a reputable source since they stated how "all food" is likely to be adulterated in Bangladesh. Household consumers without a lot of disposable income commonly purchased loose powdered turmeric. These consumers described the importance of finding a trustworthy seller so as to avoid weak curry color from adulterated turmeric powder. Those with enough money preferred packaged, branded turmeric power because of the consistent quality and reputation for purity, especially in Dhaka and Munshiganj.

3.4.3. Regulation

Interviews with corporate representatives suggested that international food safety regulations and recalls of exported turmeric incentivized companies to ensure that polishers do not add yellow pigment to their turmeric root. One major Bangladeshi company with nearly one-third of the market share learned about Pb in their turmeric in 2012 from North American food regulators who issued a recall of all turmeric imported from Bangladesh. This incident prompted news reporting throughout Bangladesh as well as government checks for Pb in powdered and whole turmeric root. The corporate representative reported that the company suffered financial losses from the recalled turmeric, which prompted them to invest in an inductively coupled plasma optical emission spectrometer to test for Pb and avoid future losses. The company representative visited the Southeast region, which is the source of the company's turmeric. The representative then sampled intensively, finding high levels of Pb in their bulb turmeric roots. Representatives from other companies referred to this incident, stating zero tolerance for adulterated products. Polishers and wholesalers from around Bangladesh noted that, if they were selling directly to a company, color would not be added.

National regulations have not prioritized polishing mills and wholesalers who produce or sell yellow-colored turmeric nor color merchants who sell Pb- and Cr-containing yellow pigments. Nationally enforced restrictions against the use or import of the yellow pigments were not reported by interviewees. According to inspectors, polishers, and wholesalers in all districts, turmeric-related inspection focused on grinding mills to see whether rice flour was mixed in, an offense that could be penalized by fines up to 600,000 taka ($7000) and 3 years in jail. None of the interviewees, however, had actually enforced this or witnessed such punishment.

Inspectors reported that they had inadequate human, financial, and technical resources to implement and enforce regulations. Several stated that the number of inspectors is too few, with only one inspector tasked to monitor all of the bazaars, shops, restaurants, and grinding mills in the *upazilla* (sub-district). Other inspectors mentioned that there is no budget for collecting samples. Instead, inspectors paid for samples out of their own salary, which disincentivized sample collection and testing. Moreover, with the exception of milk, which could be tested on-site using a lactometer, samples of other foods had to be sent to Dhaka for testing, requiring two to three months for results.

4. Discussion

This study highlights the public health threat from turmeric adulterated with industrial yellow pigments that contain Pb and Cr. We report Pb levels in turmeric that exceed the Bangladesh national limit by up to 500 times and are 2–10 times higher than the maximum concentrations reported in other studies (Cowell et al., 2017; Gleason et al., 2014; Forsyth et al., 2018; Syed et al., 1987). Turmeric is consumed daily in the Bangladesh context. Prior research has linked Pb in turmeric to Pb in pregnant women's blood in rural Bangladesh (Forsyth et al., 2019). Therefore, Pb from adulterated turmeric could directly alter health and development, particularly among children. Moreover, $PbCrO_4$-based pigments added to turmeric are a source of hexavalent Cr which is highly carcinogenic and could have additional adverse effects (Saha et al., 2011).

Our study identifies turmeric adulteration as a predominantly national problem. Similar to other low- and middle-income countries, the turmeric sector in Bangladesh is dominated by small, minimally-regulated informal actors with only a few large companies incentivized to comply with international regulation (Grace, 2015). In these contexts, importing-country food safety standards influence large-scale food processors, but do not alter the practices of processors servicing the informal and domestic sectors (Lam et al., 2013; Jaffee and Jabbar, 2005). Our results support this pattern in Bangladesh, where importing-country food safety checks have incentivized polishers to minimize the adulteration of export-bound turmeric. However, the current system of periodic food safety checks may catch only a fraction of the adulterated turmeric being traded worldwide. We recommend that ports of import regularly screen turmeric for Pb and Cr using portable handheld x-ray fluorescence (XRF) analyzers. XRF testing is advantageous because it is nondestructive and provides a rapid measurement of multiple elements simultaneously.

We identify that the industrial yellow pigments added to turmeric are $PbCrO_4$-based, containing 2–10% Pb by weight. Such compounds are the least expensive and most effective yellow pigments, still traded and widely used as industrial pigments in most low-, middle-, and high-income countries (Saha et al., 2011). Within the last 5 years, a major pigment-producing company in Europe has developed alternative pigments, and they are committed to phasing out the production of $PbCrO_4$-based chrome yellow (World, 2014). Even though $PbCrO_4$-based pigments continue to be used industrially, laws in high-income countries have prohibited their use as food color additives since the early 1900s (Burrows and Adam, 2009). Nontoxic food-grade color additives have replaced the toxic coloring agents around the world. However, we did not find any yellow food-grade powders available at the largest bazaar for pigments and dyes in Dhaka on the day we visited.

Taken together, these data suggest a market failure. Consumers are not able to accurately assess the quality of their turmeric at the point-of-purchase. Consumers who cannot afford to purchase packaged turmeric powder are likely to be at highest risk of Pb exposure. We found higher concentrations of Pb in turmeric in minimally-producing districts, which may be a result of greater demand for brighter-yellow roots distributed by Dhaka wholesalers and less awareness throughout the supply chain about inherent turmeric quality. Moreover, adding yellow pigments to turmeric enhances the color of curries and aligns with consumers' goals of making yellow-colored curry, perpetuating the cycle of adulteration. By contrast, other types of adulteration, such as mixing rice flour with turmeric powder, dulls the color of curry and discourages consumers from purchasing that turmeric again.

Food safety laws are designed to address such market failures and ensure public health when producer incentives do not, and when risks are unknown to consumers (Jaffee and Jabbar, 2005). Although 15 laws have been enacted to ensure food safety in Bangladesh, the government has been unable to consistently enforce those and other regulations (Kamruzzaman, 2016; Ahmed et al., 2018; Murshed, 2013; Hoque, 2004; Luby et al., 2015). Even if national regulatory standards could be easily enforced, this study demonstrates that there is no specific mandate against the addition of yellow pigments to turmeric. Food safety inspectors in turmeric-producing districts were focused on the undesirable, yet harmless, adulteration of powdered turmeric with rice flour and appear to be unaware that polishers add toxic $PbCrO_4$-based industrial pigments to roots.

Given the difficulty in implementing and enforcing national-level regulatory standards, influencing consumer behavior may be another way to reduce the consumption, initially, and the production, eventually, of contaminated turmeric. Consistent with other studies, we provide evidence that Bangladeshi consumers consider food adulteration a constant threat (Ali, 2013; Nasreen and Ahmed, 2014). Over the past decade, more than half of all food samples that the Institute of Public Health tested were found to be adulterated in some way (Kamruzzaman, 2016; Nasreen and Ahmed, 2014). Media outlets frequently cover food fraud in Bangladesh, with issues ranging from brick dust in chili powder (The Daily Star, 2011) to rice made from plastic (The Asian Age, 2017). Starting in 2007, media channels reported that formalin, a derivative of formaldehyde, was being added to fish as a preservative (Kamruzzaman, 2016). As a result, formalin fear spread widely and Bangladeshi consumers started purchasing live fish, despite little scientific evidence of harm from formalin, which is a naturally occurring compound in foods. Nonetheless, the formalin incident became so well-known throughout Bangladesh that several respondents in this study used the term *formalin* synonymously with *food adulteration* and *chemical additives*.

In Bangladesh, publicizing our findings that turmeric is adulterated with neurotoxic yellow pigments could result in consumer-behavior shifts that might, in turn, reduce incentives for polishing with color. As shown in this study, awareness about yellow-pigment-adulterated turmeric is low among consumers and food safety inspectors alike. Not only is the adulteration invisible, but adverse effects of Pb, such as decreased IQ, do not manifest themselves immediately.

One option for increasing visibility around turmeric adulteration could be to equip food safety inspectors and NGO stakeholders with technologies to measure and then publicize and interpret Pb- and Cr-concentrations in turmeric. Several options exist to measure Pb in turmeric, such as inexpensive color-changing test strips or portable handheld XRF analyzers (Palmer et al., 2009; Feigl and Suter, 1942). During our laboratory experimentation with the test strips, however, they were unable to distinguish Pb-containing and Pb-free turmeric. Additionally, portable XRF analyzers cost > 20,000 USD, making their use in the field expensive to implement. Nonetheless, if credible information could be disseminated along the supply-and-demand chain that turmeric contained $PbCrO_4$-based yellow pigments, wholesalers might reject lots of colored turmeric root and price-sensitive household consumers who cannot afford to purchase packaged, powdered turmeric might shift to purchasing dried, unpolished turmeric roots. Household consumers in turmeric-producing districts have already reported such behaviors in order to avoid the adulteration of loose powdered turmeric with rice flour.

Although increasing consumer awareness may empower individuals to minimize personal health threats and possibly incentivize producers to make safer goods available, engaging with producers directly is another path toward sustained change so long as solutions align with business incentives (Grace, 2015). By increasing technical capacity, for example, producers can generate higher quality goods at a reduced cost or with greater efficiency. We understand from this study that being able to properly dry turmeric is a major factor influencing if and how much yellow pigment is added. The current practice of sun-drying turmeric root depends on climate conditions. Notably, flooding in 1988 catalyzed the practice of adding color to turmeric. The link between proper drying and color is a well-known phenomenon in agricultural studies (Krokida et al., 1998; Borah et al., 2017).

Given that Bangladesh is considered one of the countries most prone to the adverse effects of climate change, particularly sea-level rise and flooding (Karim and Mimura, 2008), the frequency and intensity of adding yellow pigment to turmeric may increase if wet conditions become more common in Bangladesh. In order to more efficiently and effectively dry turmeric root, some Indian processors have begun using solar or mechanical drying machines rather than spreading roots in a drying yard. Numerous drying technologies of varying complexities and costs have been evaluated for their effect on turmeric quality, especially color characteristics and curcumin content (Singh et al., 2010; Hirun et al., 2014; Behera et al., 2017; Lokhande et al., 2013). Similar to the reported reduction in yellow pigment adulteration after acquiring polishing machines in the mid-1990s, it is likely that the adoption of drying machines would further reduce the need for yellow color additives in turmeric. Of course, a barrier to such change may be the capital required for such an investment, if the benefits do not outweigh the costs.

5. Conclusions

Lead is a potent neurotoxin that irreversibly damages the brain and permanently lowers IQ (Budtz-Jørgensen et al., 2013). Given this significant burden of lead exposure, interventions to reduce or prevent lead exposures are well worth the effort. Prior studies have indicated that turmeric is linked with lead exposure and contributes to elevated blood lead levels in rural Bangladesh (Gleason et al., 2014; Forsyth et al., 2018, 2019). We provide evidence of the structure of incentives that have perpetuated turmeric adulteration with industrial $PbCrO_4$-based yellow pigments, resulting in elevated Pb- and Cr-levels in a spice that is consumed daily throughout Bangladesh and South Asia. Our results can be used to make progress on the path to Pb-free turmeric, a path that will likely require a combination of efforts to engage consumers, producers, and other stakeholders focused on food safety and public health. Since there has been extensive research into the health and developmental effects of Pb exposure for decades, we encourage future research to focus on developing, implementing, and evaluating interdisciplinary approaches to reducing exposure rather than simply generating more evidence highlighting the damage Pb is causing.

Declarations

Ethics approval and consent to participate

We obtained written informed consent from all study participants. The study protocol was reviewed and approved by the ethical review committee at icddr,b and Stanford University (protocol number 37745).

Consent for publication

Consent for publication was obtained for data presented in this manuscript.

Availability of data and material

The datasets used during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare they have no competing interests.

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Authors' contributions

JEF led the development and design of the research and writing under the advising of SPL. SN, SI, MB, DY, MSI, and MR executed field work. SF oversaw laboratory methods and analyses. NMA and PJW oversaw the design and development of the qualitative components. All authors read and approved the final manuscript.

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Appendix A. Supplementary data

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