Journal of Environmental Management 321 (2022) 115904

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

# Lead and other toxic metals in plastic play foods: Results from testing citizen science, lead detection tools in childcare settings

Kaleem Ahmid [a,b,*], Aaron Specht [c], Larissa Morikawa [b], Diana Ceballos [e], Sara Wylie [d,f]

[a] Bouvé College of Health Sciences, Northeastern University, 360 Huntington Ave, Boston MA, 02115, USA
[b] Wylie Environmental Data Justice Lab, Northeastern University, 360 Huntington Ave, Boston, MA, 02115, USA
[c] Department of Environmental Health, Purdue University, 550 Stadium Mall Drive West Lafayette, IN, 47907, USA
[d] Department of Anthropology and Sociology, USA
[e] Department of Environmental Health, Boston University School of Public Health, 715 Albany St., Boston, MA, 02118, USA
[f] Social Science and Environmental Health Research Institute, Northeastern University, 360 Huntington Ave, Boston, MA, 02115, USA

ARTICLE INFO

*Keywords:*
Citizen science
Lead-exposure
Plastic toys
Environmental health

ABSTRACT

A method development pilot study examining citizen science tools for assessing lead in childcare settings identified plastic food toys as an unexpected potential source of lead and arsenic. Collaborating researchers at three universities sought to develop a low cost, replicable approach for use in childcare centers to identify lead. Through graduate Environmental Health courses at Northeastern and Boston Universities, 197 Plastic Food Toys (PFTs) used in a childcare center were tested for lead using a portable X-Ray fluorescence (XRF) instrument and a colorimetric wipe method for detecting surface lead. The XRF identified concerning levels of lead and co-occurring arsenic in PFTs. The XRF analysis found 8.63% (17/197) of PFTs from the childcare center contained more than 100.00 ppm of lead, the U.S. Consumer Protection Safety Commission's (CPSC) upper regulatory threshold for lead in childrens' products. However, wipes did not detect removable surface lead. Lead concentrations ranged from 6.14 ppm to 11,999.00 ppm with a median of 40.00 ppm. Additionally, 7.10% of all PFTs tested had detectable levels of arsenic which ranged from 9.30 ppm to 1134.42 ppm and had a median value of 113.20 ppm. Arsenic concentrations in 6.60% of PFTs' exceeded the US voluntary standard for arsenic in children's products of 25.00 ppm (adopted from the EU standard). These findings prompted further sampling of similar newly-purchased PFTs. None of the newly-purchased PFTs tested positive for lead or arsenic (0/87). Several other elements were also identified, particularly in the used PFTs. Because these food-like toys are frequently put in children's mouths, we recommend further investigation of PFTs in circulation via citizen science combining the wipe and XRF method as they provide immediate data to participants. Additionally, CPSC should consider a systematic recall of some used PFTs to prevent exposure disparities by socio-economic status and increased surveillance for other toxic metals in new PFTs.

## 1. Introduction and background

Childcare centers are potential understudied sites of lead exposure, as both lead in playground materials and lead in toys serve as potent exposure sources (Kim et al., 2012; Sanders et al., 2013). Additionally, there are no reliable citizen science methods for childcare centers to rapidly and visually assess sources of lead. As part of Environmental Health courses in Masters of Public Health programs at Northeastern University and Boston University, we analyzed sources of lead in a childcare setting using SKC Full Disclosure® Lead Detection colorimetric wipes and a portable x-ray fluorescence spectroscopy (XRF) instrument. The initial aim of this pilot study was to explore the utility of low cost, colorimetric wipes to identify lead on surfaces in order to develop citizen science tools that childcare centers might use independently to assess lead on surfaces. As we developed study questions, the center's director noted that children frequently put plastic food toys in their mouths as they pretend to eat and prepare food. Given the literature on lead in plastic toys, a student group in the class sampled a small subset of the center's plastic food toys (PFTs) along with other toys that the literature suggests might contain lead in particular toy made from

* Corresponding author. Bouvé College of Health Sciences, Northeastern University, 360 Huntington Ave, Boston MA, 02115, USA.
*E-mail addresses:* ahmid.k@northeastern.edu (K. Ahmid), aspecht@purdue.edu (A. Specht), morikawa.l@northeastern.edu (L. Morikawa), ceballos@bu.edu (D. Ceballos), s.wylie@northeastern.edu (S. Wylie).

https://doi.org/10.1016/j.jenvman.2022.115904
Received 10 January 2022; Received in revised form 25 July 2022; Accepted 28 July 2022
Available online 25 August 2022

yellow and red PVC plastic, metallic and metallic painted toys and lower priced toys (Greenway and Gerstenberger, 2010; Hillyer et al., 2014; Miller and Harris, 2015; Sanders et al., 2013; Shen et al., 2018).

High levels of lead and arsenic in the popular PFTs at the center prompted the center's request to assess other plastic food toys. This paper reports on findings from the XRF analysis of plastic food toys and reflects on the utility of portable XRF and SKC Full Disclosure® Lead Detection colorimetric wipes in a childcare setting. The goal of this paper is to alert environmental health researchers, clinicians, and childcare centers to PFTs as a route of lead and arsenic exposure.

### 1.1. Sources of lead exposures and the need for studies in childcare settings

Lead is a well-documented neurotoxicant that delays and reduces cognitive development in children (Toxicological Profile for Lead, n.d.; Cory-Slechta, 2012; Flora et al., 2012). There is no safe level of lead exposure and it is estimated that half of the United States (US) population is exposed to harmful levels of lead in childhood (McFarland et al., 2022). Sources of lead exposure in the US are numerous and nearly ubiquitous from the use of lead in gasoline and paint for the majority of the 20th century (Dignam et al., 2019).

Traditionally, the sources of lead exposure have been identified as soil, water, air, paint, and dust (O'Flaherty, 1998; Swaringen et al., 2022). Lead in air has dissipated proportionally with the decrease in lead in gasoline (Dignam et al., 2019). Paint in older homes can still be problematic but can be avoided by local regulations for protection of children. As lead in air and paint become more regulated, other sources of novel origin become more serious threats to environmental health. Oftentimes, these sources of exposure can be community dependent. A previous environmental health study of lead poisoned children in China identified alternative medicines as a major source of exposure (Specht et al., 2016). Communities with occupational exposures have significant childhood lead exposures from take-home lead (Rinsky et al., 2018). Finally, a study in Massachusetts indicated that firearms may serve as an additional source of lead exposure (Hoover et al., 2021). As the traditional environmental toxicants, like lead, become more scarce, community specific sources become a significant contributor to the underlying lead exposure burden. One previously overlooked source of exposure, namely childcare centers, could serve as a unique source of community exposure to children through toys.

### 1.2. Lead and arsenic in toys and the need for citizen science

Lead contamination in toys is a well-documented problem, and some work has been done identifying characteristics of toys that have higher likelihoods of containing lead. For instance, in polyvinyl chloride (PVC) plastic toys, yellow and red toys are more likely to contain lead added to improve the brightness and fastness of dyes (Greenway and Gerstenberger, 2010; Hillyer et al., 2014; Kang and Zhu, 2015; Miller and Harris, 2015; Sanders et al., 2013; Shen et al., 2018). Metallic and metallic-painted toys are also more likely to contain lead to increase their weight, particularly in lower priced toys (Hillyer et al., 2014). Lead is also added to increase the weight and authentic feel of plastic jewelry in particular (Hillyer et al., 2014; Mateus-García and Ramos-Bonilla, 2014). The literature on lead and arsenic in non-metallic children's toys is not extensive, though there is some literature on the presence of lead in plastic metallic costume jewelry (Guney and Zagury, 2012; Yost and Weidenhamer, 2008). There are a few studies on lead in toys in childcare centers (Greenway and Gerstenberger, 2010; Kumar and Pastore, 2007; Sanders et al., 2013; Turner, 2018). However, we are not aware of available literature on the presence of lead or arsenic in PFTs specifically. Evaluating this exposure route is particularly important as PFTs are frequently mouthed by children as they mimic preparing and eating food (Juberg et al., 2001; Tulve et al., 2002).

Arsenic, a carcinogen and potent toxicant, has historically also been identified in certain children's toys, but has become less prevalent with increased regulation of toy manufacturing. Arsenic has been added to PVC toys to add sheen and luster to translucent elements and is still commonly detected using XRF methods in vintage toys (Miller and Harris, 2015). More broadly, exposure science is beginning to question whether plastics should be used to manufacture toys at all: a recent study found contaminant exposure from 126 chemicals in plastic toys through dermal, gastrointestinal, and respiratory routes poses a "non-negligible health risk to children" (Aurisano et al., 2021).

Recent attention to the problem of lead in toys has led to improved US sampling and regulations. The 2008 Consumer Product Safety Improvement Act (CPSIA), which incorporated Henry Waxman's "Lead-Free Toy Bill" (H.R. 2840), sought to drastically reduce lead in children's products by setting a threshold of 90 ppm of lead in paint and painted items, effective from 2009, as well as a reduction in acceptable lead concentrations in childrens' products of 100pm, as of 2014 (Lead Contamination Control Act Amendments of 1991 (1991 - H.R. 2840), n.d.; Rush, 2008). Although toys with lead paint are banned in the US, toys containing lead can still be found in the US, especially if they are older toys produced before the ban or have been imported from countries that do not have the same lead regulations. Additionally, CPSIA amended the Consumer Product Safety Act of 1972 and made the American Society of Testing and Materials Toy Safety Standard (ASTM F963) mandatory (ASTM F 963-17 Requirements, n.d.). This requires that all US children's products be tested by accredited third-party laboratories. Nonetheless, not all US state governments have adopted legislation that bans lead in children's products. Despite CPSIA, more than twenty million toys have been recalled globally in the last decade due to chemical safety standard breaches (Guney and Zagury, 2013). The widespread problem of toxic contaminants in toys make it practically impossible to sample all toys, and there is no testing of toys that are already in circulation.

### 1.3. Citizen science in childcare settings

Citizen science methods may help fill that testing gap, particularly in childcare settings (Walls et al., 2022). Citizen or community science is a growing field of work attempting to bridge large gaps in environmental monitoring and assessment by engaging non-professional scientists in research (Kimura and Kinchy, 2016; Strasser et al., 2019). The field is debating use of the term citizen or community science to describe the degree and kind of public engagement in research (Shirk, 2022). We use both terms in this article as we are attempting to develop tools that can be used in a community setting (childcare centers) by non-professional researchers (characteristics of community science) but we also find the methods require support from professional scientists and university infrastructures (characteristic of citizen science). Typically, citizen science projects involve image analysis, water sample collection, or air sampling, not toys (Bonney et al., 2014). To date, there are no published reports of citizen science projects that analyze toy contamination. However, several citizen science projects have developed kits for testing lead exposures in other contexts: the Filippelli group in Indianapolis uses an XRF-based citizen science methodology to test lead in soil (Tighe et al., 2020). The LeadCheck Swab produced by Hybrivet has been widely available for domestic semi-qualitative lead dust testing for almost 20 years, but studies have questioned the low detection and lack of accuracy and reliability of this method under non-laboratory conditions (Korfmacher and Dixon, 2007). In North Carolina, citizen science methodologies tested more than 1000 drinking water samples from childcare centers for lead (Redmon et al., 2020). To date, only one other published citizen science project has been conducted in a childcare setting but not on toys (Redmon et al., 2020).

A limitation of some citizen science projects is their reliance on "citizen-science sampling + laboratory testing." When non-professionals only participate in sample gathering, they can be excluded from the full process of research which includes defining research questions, study design, data analysis, and data interpretation. Building on Community-

based Participatory Research and Participatory Action Research where academic and non-academics collaborate as co-producers of research, researchers advocate for shifting from citizen to community science where none professionals do more than just gather samples (Hendricks et al., 2022; Minkler and Wallerstein, 2011). The potential for collaborative community science is improved if expensive laboratory analysis is not required as results can be immediately available to all participants. Therefore, this study tests two methods that provide immediate data to participants.

In Massachusetts, childcare centers are required to undergo lead paint inspections, however there is no requirement for environmental arsenic testing. Childcare centers' furnishing, materials and equipment are also required to be free of lead paint and "other hazards that may be dangerous to children" (606 CMR 7.00, n.d.). However, toys and furnishing are not tested as part of lead paint inspections and there are few affordable, easy-to-use, and accurate kits available for childcare centers to analyze potential sources of lead or other hazards in furnishings, materials, or equipment. To close that gap, the SKC Full Disclosure® Lead Detection wipes used in industrial workplaces could be used in identifying surface lead on walls, toys, and playground materials in settings such as childcare centers (NIOSH Manual of Analytical Methods (NMAM), 2021; Ashley et al., 2011; Beaucham et al., 2017). This method has been widely used by the National Institute for Occupational Safety and Health (NIOSH) for workplace assessments, is sensitive to low levels of lead, is affordable, and provides easy to interpret colorimetric results (see Fig. 2). We combine the wipes with portable XRF analysis to explore the utility of both tools for identifying lead in a childcare setting.

## 2. Study design and methods

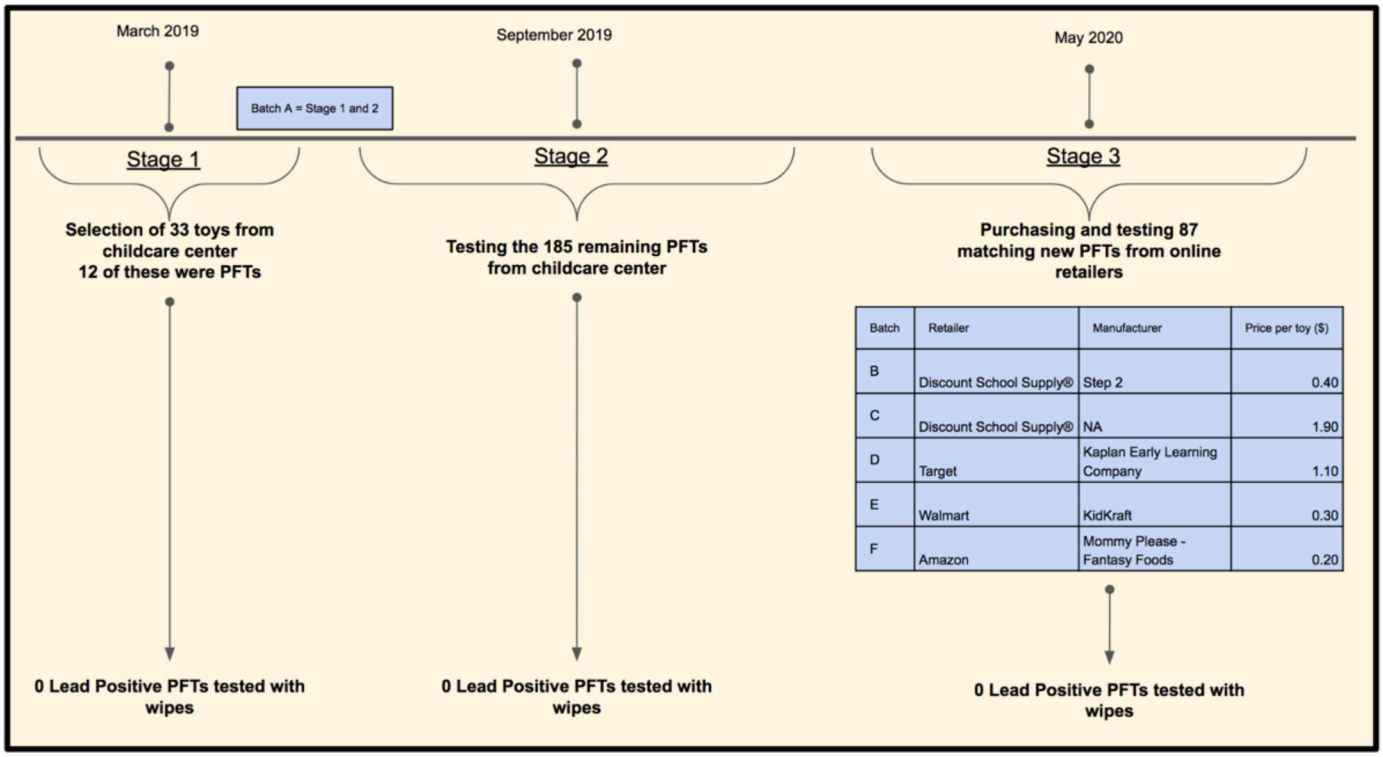
Paint, tiles, metallic features, play surfaces, and objects (including toys) inside and outside a childcare center in Boston were tested for lead using portable XRF and SKC Full Disclosure® colorimetric wipes. Researchers examined 33 toys from the childcare center, 24 were plastic including 12 that were plastic toys imitating foods (Plastic Food Toys, or PFTs). As 6 of the PFTs contained lead, arsenic, and other toxicants, we further investigated this kind of toy.

This study consisted of three chronological stages of PFT sampling (with the initial exposure study counting as Stage 1), between March 2020 and September 2020 (Fig. 1). A non-randomized multistage sampling method was used. In Stages 1 and 2, a large, stratified sample of childcare center toys was tested using XRF. Stratification was determined using hypotheses found through examination of the literature with input from the childcare center director on toy use, specifically we selected PVC toys with a balance of painted vs non-painted, a range of colors with representation of red and yellow colors, and a range of masses.

High co-occurring lead and arsenic XRF concentration findings in the Stage 1 (n = 12 PFTs) prompted the testing of all PFTs in the childcare center in Stage 2, during June 2020. In this paper, "positive results" refers to any XRF reading above the limit of detection (LOD). In Stage 2 an additional 185 PFTs were taken from the childcare center, digitally cataloged (Table 1), and sampled using XRF. Based on further positive results in Stage 2, we pursued a third round of sampling in Stage 3 with newly purchased PFTs for comparison (Table 1).

Unfortunately, as the child care center's PFTs were purchased over the span of 20 years from different retailers and manufacturers and the PFTs have no branding, it was impossible to determine the manufacturer or retailers for PFTs in Stages 1 and 2. As origins and manufacturers of the used toys were unknown, in Stage 3 we analyzed whether newly purchased similar PFTs also contained lead and arsenic. The used childcare center toys from Stage 1 and 2 are referred to as "Batch A".

Stage 3 of testing was conducted on 87 newly purchased PFTs. The 87 toys were non-randomly selected from 5 sets of PFTs (Batches B–F from herein). The non-random selection was based on the characteristics of PFTs which tested positive in Stages 1 and 2. Stage 3 toys all shared one or more characteristics of toys which tested positive in Stages 1 and 2, such as color and food type. The toys in Stage 3 were purchased from four major retailers (Walmart, Target, Amazon, and Discount School Supplies). We chose five popular manufacturers (Step2, Kaplan Early Learning Company, KidKraft, Mommy Please, and Discount School




| Batch | Retailer | Manufacturer | Price per toy ($) |
|---|---|---|---|
| B | Discount School Supply® | Step 2 | 0.40 |
| C | Discount School Supply® | NA | 1.90 |
| D | Target | Kaplan Early Learning Company | 1.10 |
| E | Walmart | KidKraft | 0.30 |
| F | Amazon | Mommy Please - Fantasy Foods | 0.20 |

**Fig. 1.** Study design and timeline showing sampling approach, naming and sources and costs of PFTs.

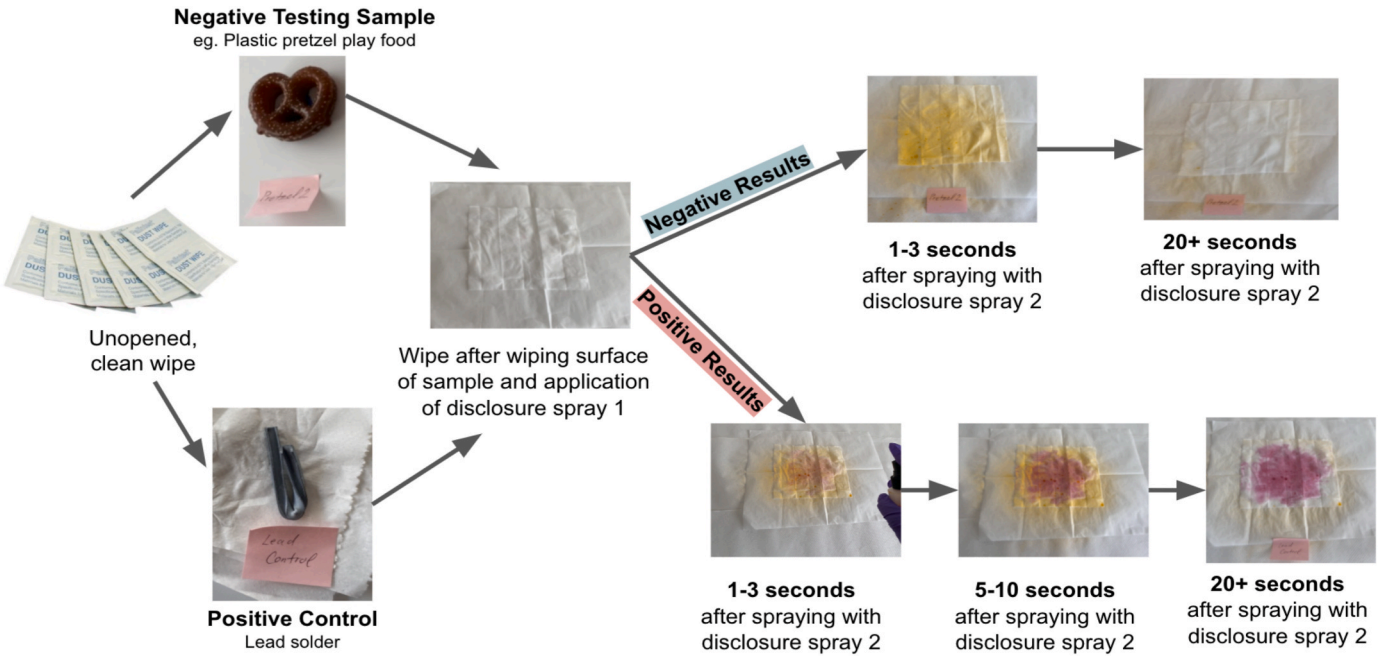



**Fig. 2.** Images of SKC Full Disclosure® Lead Detection wipes showing a negative sample test (a plastic pretzel) compared to a positive control (lead solder). The positive control is red confirming the presence of lead and the negative sample is yellow suggesting no lead. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

**Table 1**
Descriptive categorization of all PFTs tested in the Study.

| Stage | Batch | Number of toys tested | Painted | Mean Weigh t (g) | Color Br/G/O/R/Y* | New/ Used | Source |
|---|---|---|---|---|---|---|---|
| 1 | A | 12 | 6/12 (50.00%) | NA | 3/3/0/1/4 | 0/12 | childcare center |
| 2 | A | 185 | 54 /185 (29.19%) | 20.31 | 33/19/19/28/28 | 0/185 | childcare center |
| 3 | B-F | 87 | 20/87 (22.99%) | 15.65 | 24/14/18/14/16 | 87/0 | online Retailers |

Supplies). The 5 sets were manufactured by 4 different manufacturers, and contained 504 toys in total, with price points ranging from $23.99 to $72.99 per set, or $0.19 to $1.92 per PFT. The 87 selected toys were cataloged and sampled using XRF, following the identical procedure followed in Stage 2. The XRF results for all three stages were compared across stages, colors, paintedness, and mass categories (Table 1).

Table 1: provides details on the PFTs tested in this study including whether they are new or used, as well as their color, weight and source. * (Br) Brown, (G) green, (O) orange, (R) red, (Y) yellow.

### 2.1. XRF methods

X-ray fluorescence spectroscopy (XRF) was conducted using a portable Thermo Niton XL3T XRF (Thermo Fisher Billerica, MA). XRF can determine elemental composition non-destructively using radiation from an x-ray tube. The x-rays from the device interact with the sample on an atom-by-atom basis. XRF relies on the photoelectric interaction, ejecting an inner-shell electron from the atom and exciting the atom in the process. The de-excitation releases an energy characteristic of the element, and collection of these characteristic x-rays allows for broad-scale elemental quantification. The precision and reproducibility of XRF analysis is very high.

Measurements were made with the toys sitting directly on the top of the XRF with the XRF secured in a vertical orientation and operated from a nearby computer. We used a 30-s measurement on each PFT, which was optimized for primarily heavy metal quantification, but would determine up to 30 elements if they were present within the detectable range. The detection limit for most measurable elements in the PFTs was in the part per million (ppm) range.

#### 2.1.1. XRF calibration

A blank control (silicon powder) was used to ensure the XRF was calibrated before use in the field and the XRF device is calibrated annually to assure result integrity. The XRF was calibrated using a set of National Institute of Standards and Technology (NIST) standards (NIST 2709a and NIST 2579) and plastics with known concentrations of metals. The calibration was set to attempt to correct for thickness differences between samples to allow for the variations in sampling parameters experienced during toy measurements (paint, plastic, wood, etc). The calibration normalization to the Compton scattering peak of the silver (Ag) anode characteristic x-ray production should account for most variations in thickness between a few millimeters and infinitely thick as seen by the XRF, which would correspond with 1–2 cm of thickness in most plastics. We used a 50 kV max energy with our Ag anode which optimized the energy for measurements in elements with emissions in the 8–15 keV range.

Our fitting deconvolution algorithm utilized alpha and beta peaks for most elements with K, L, and M shell measures in the appropriate energy

ranges. The detection limits depend on parameters from each measurement. The XRF measures about 1 $cm^2$ area of the sample, but with the calibration and normalization procedure, units are given in parts per million and comparable to microgram per gram. The detection limit does depend on the thickness of the samples themselves, as more samples will produce more elemental signals. As arsenic and lead can interfere with each other in XRF measurement, we utilized a measurement of the lead beta peak at 12.6 keV to ensure correct fitting of the lead alpha at 10.55 keV while in the presence of arsenic. The arsenic alpha peak is at 10.54 keV, which for many fitting algorithms can present a problem when disentangling from lead. We used epoxy standard phantoms to test our fitting of lead in the presence of arsenic and without arsenic to demonstrate its abilities in this regard.

### 2.2. Colorimetric wipe method

SKC Full Disclosure® Lead Detection kits (model number 550–002, SKC Inc.) were used as a semi-quantitative colorimetric test for lead on the surface of sampled toys. Colorimetric surface wipe sampling is a technique widely used in the occupational environment to determine sources of lead in workplaces, but to our knowledge application of this method in other environments outside the workplace is limited (Ashley et al., 2011; Beaucham et al., 2017). A pre-cleaned wipe is used to sample 10 cmX10cm surfaces for metal contamination. The wipes are then sprayed with potassium rhodizonate solution, and then 5% acetic acid to develop an immediate colorimetric reading (reddish orange for lead over 18 μg, yellow for no lead or <18 μg). Color intensity is proportional to the amount of lead in the wipe, and color calibrations (from intensity of 0–3) have been done in a controlled laboratory for skin wipes (Ashley et al., 2011) and during field sampling in work environments (Beaucham et al., 2017).

Preparation of materials and sampling of the surfaces was conducted as per instructions included in the testing kit with the modification of taking photos of the labeled wipes for record keeping (Full Disclosure Kit, n.d.). We did not record an area since the samples were irregularly shaped, however, wipes were used to sample all outer surfaces of the sample for at least 10 s. Positive and negative controls were also sampled and documented photographically. The wipe test has a lower limit of detection of 18 μg of lead per $cm^3$ (Full Disclosure Kit, n.d.). A positive sample for lead means that the sample was above 18 μg and appears reddish orange when sprayed with the disclosure sprays, while a negative result remains yellow (Fig. 2). Wipe-testing was conducted by one researcher for consistency, avoiding contamination of samples through the use of a designated pair of "clean hands" and "dirty hands" per test and changing disposable gloves between samples. Samples were not sent to a lab for further analysis due to funding constraints. All potentially hazardous waste was appropriately disposed of through Northeastern University's Environmental Health and Safety Department.

### 2.3. Data analysis methods

Data collected from XRF sampling was transferred to a computer as a comma separated values (csv) input in Microsoft Excel. Data was cleaned by deleting readings for elements which had no occurrence in any toys tested and their corresponding error ranges. The CSV sheet was checked manually for consistency of correspondence between "reading number" and the "sample number" physically registered on each sample. The mean, standard deviation, mode, range, and proportion of samples testing above the Level of Detection (LOD) for each element were calculated and recorded (in Supplemental tables S1 and S2 - except for lead (Pb), where descriptive statistics were estimated using algorithmically synthesized point estimates). One-sided Z Score tests were used to determine if there was a significant difference in the proportion of ">threshold" between new and old toys (Table 2).The Z score test

**Table 2**
Rate of XRF PFTs concentrations measured above CPSIA upper threshold for lead or the US Voluntary Standard for arsenic. "Used" refers to samples from the childcare center, "New" refers to newly purchased samples.
*** indicates significance at the alpha=0.05 level.

| | Lead | | | Arsenic | | |
|---|---|---|---|---|---|---|
| Category | Rate of PFTs above CPSIA threshold for lead in new and used toys per color, paint, and mass category (number/total (%)) | | Fisher Exact test (p value) | Rate of PFTs above US voluntary threshold for arsenic in new and used toys per color, paint, and mass category (number/total (%)) | | Fisher Exact test (p value) |
| | Used (n=197) | New (n=87) | | Used (n=197) | New (n=87) | |
| Orange (n=37) | 4/19 (21.05%) | 0/18 (0.00%) | 0.020*** | 2/19 (10.53%) | 0/18 (0.00%) | 0.078 |
| Red (n=44) | 3/29 (10.34%) | 0/15 (0.00%) | 0.099 | 2/29 (6.90%) | 0/15 (0.00%) | 0.149 |
| Brown (n=60) | 7/36 (19.44%) | 0/24 (0.00%) | 0.011*** | 6/36 (16.67%) | 0/24 (0.00%) | 0.011*** |
| Green (n=36) | 2/22 (9.09%) | 0/14 (0.00%) | 0.123 | 1/22 (4.55%) | 0/14 (0.00%) | 0.046*** |
| Yellow (n=48) | 2/32 (6.25%) | 0/16 (0.00%) | 0.154 | 2/32 (6.25%) | 0/16 (0.00%) | 0.104 |
| Silver (n=7) | 0/7 (0.00%) | 0/0 (0.00%) | NA | 0/ (0.00%) | 0/0 (0.00%) | NA |
| White (n=16) | 0/16 (0.00%) | 0/0 (0.00%) | NA | 0/ (0.00%) | 0/0 (0.00%) | NA |
| Black, blue, purple (and other) (n=36) | 0/36 (0.00%) | 0/0 (0.00%) | NA | 0/32 (0.00%) | 0/0 (0.00%) | NA |
| Painted (n=80) | 11/60 (18.33%) | 0/20 (0.00%) | 0.020*** | 9/60 (15.00%) | 0/20 (0.00%) | 0.026*** |
| Not-painted (n=204) | 7/137 (5.11%) | 0/67 (0.00%) | 0.030*** | 4/137 (5.11%) | 0/67 (0.00%) | 0.047*** |
| >20g (n=95) | 10/73 (13.70%) | 0/22 (0.00%) | 0.033*** | 7/73 (9.59%) | 0/22 (0.00%) | 0.066 |
| <20g (n=189) | 8/124 (6.45%) | 0/65 (0.00%) | 0.018*** | 6/124 (4.84%) | 0/65 (0.00%) | 0.003*** |
| Total (n=284) | 17/197 (9.14%) | 0/87 (0.00%) | 0.002*** | 13/197 (6.60%) | 0/87 (0.00%) | 0.002*** |

assumes the proportion of concentrations in each sample follows a normal distribution, however we do not know if lead is normally distributed in all PFTs. However the XRF measurements do roughly fit a normal distribution centered ~700.00 ppm, well over the CSPIA threshold of 100.00 ppm. Therefore, running a one-sided z-score test seems valid, and results are useful particularly when p-values are below $p = 0.05$. The Fisher Exact test was used to determine whether there was a true difference in proportion of readings ">threshold" between childcare toys and the new toys and "other elements: XRF". In modeling analyses, we used binomial approaches with positive and negative XRF results, and in an additional model we were able to represent < LOD readings as a quantified result using error propagation along with the point estimate concentration typical of XRF readings. Basic descriptive statistics were generated for the total sample, as well as each subset of the sample, stratified by color, material, batch, how damaged they were (usedness), whether they were painted (paintedness), and mass (Table 1). Cumulative frequencies were calculated using the same strata (Table 2). Color intensity from the wipes was summarized to be compared with the XRF data. Color intensity was labeled zero (0 – yellow – no lead on surfaces) up to three (3 – red – high lead on surfaces).

Both linear regression and logistic regression modeling were used to investigate the relationship between weight, paintedness, mass, and color with lead, arsenic, and uranium concentrations. Three models were assessed, one replacing "<LOD" lead readings with 0.00, one categorical model using "<LOD" vs ">LOD" as a dummy variable, and one using point estimates for "<LOD" lead readings. The point estimate model was most preferable, due to the very high proportion of "<LOD" readings in the sample (11% of readings were >LOD).

## 3. Results

In total, 35 PFTs tested above the XRF LOD for lead, 14 of which also tested above the LOD for arsenic. We describe the XRF findings exceeding the CPSIA lead threshold (100 ppm) and the US voluntary arsenic threshold (25 ppm) for new and used PFTs by color, paintedness, and weight (Table 2). No new PFTs tested positive for lead or arsenic. Of the used PFTs, orange, red, brown, green, and yellow PFTs tested positive for lead and arsenic. Additionally, 1 silver and 3 white PFTs tested positive for lead only. No black, blue, or purple toys tested positive for lead or arsenic. Brown, orange, and red PFTs in our Stage 1 and 2 samples were most likely to test positive for lead. Brown toys were most likely to test positive for arsenic. Painted toys were mostly likely to test positive for lead and arsenic, and heavier toys were more likely to test positive for lead but not for arsenic.

Models determined that paintedness (binary) and mass (continuous) were significantly ($p < 0.05$) associated with both lead and arsenic concentration measured by XRF (details in Appendix 1). No other variables were found to be explanatory.

Table 2: Percentage of PFTs with lead and arsenic concentration over CPSIA upper threshold for lead (100 ppm) and US Voluntary Standard for Arsenic (25 ppm) respectively.

Table 2: Rate of XRF PFTs concentrations measured above CPSIA upper threshold for lead or the US Voluntary Standard for arsenic. "Used" refers to samples from the childcare center, "New" refers to newly purchased samples.

*** indicates significance at the alpha = 0.05 level.

### 3.1. Lead: XRF and colorimetric wipes

In Stages 1 and 2, 197 PFTs were tested using the portable XRF instrument. The US maximum threshold for lead in paint is 90 ppm, and the CPSIA's threshold limit for lead in childrens' products is 100.00 ppm as of 2014. In Stage 1, 6/12 toys tested positive for lead in Stage1 (range: 38.02 ppm - 11,999pm). 5/6 of those readings were above 100.00 ppm. In Stage 2, 29/185 PFTs tested positive for lead (range: 6.14 ppm - 3203.43 ppm); 12/29 positives were above 100 ppm (Fig. 3). Colorimetric wipe testing was conducted on all 35 samples which tested positive using XRF from Stages 1 and 2. All colorimetric wipe tests showed no detectable levels of lead. While 17.77% of used toy samples had readings > LOD for lead, no new toys had levels of lead above the LOD.

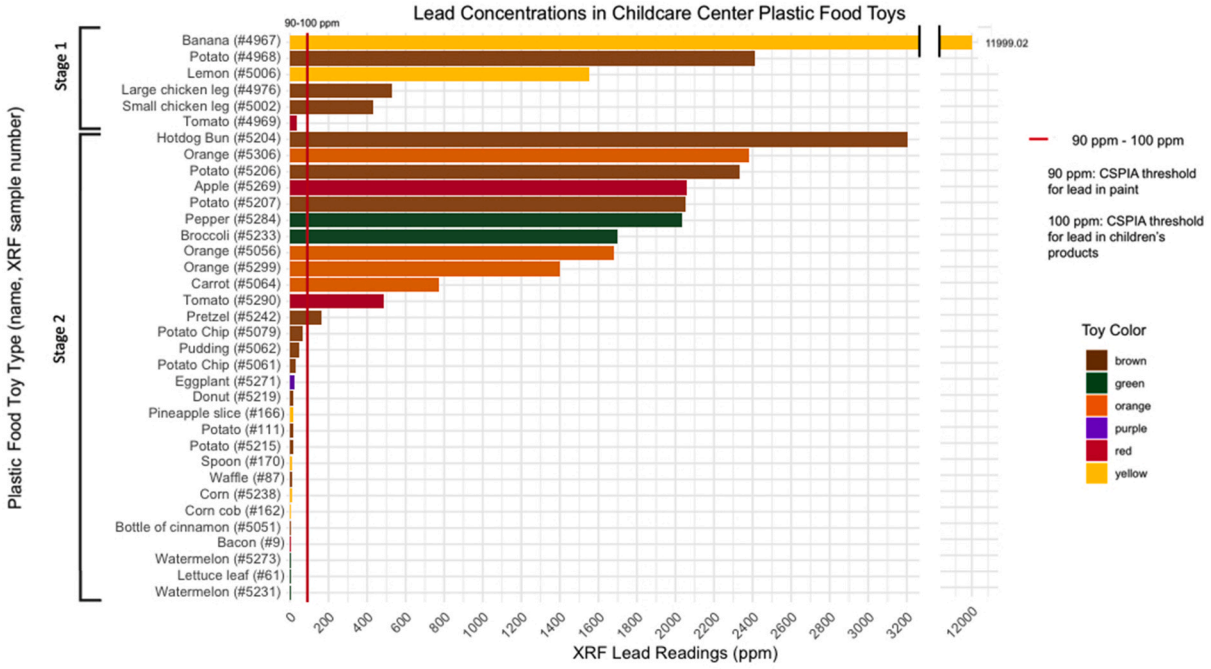



**Fig. 3.** Lead XRF concentration results for PFT samples above limits of detection (n = 35) across Stages 1 and 2 (Batch A). The red threshold line indicates the range from the CPSIA maximum concentration limit for lead in paint of 90 ppm–100 ppm, the CPSIA limit for lead in toys. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

### 3.2. Arsenic and its occurrence with lead: XRF

In Stages 1 and 2, 14 PFTs tested positive for arsenic (9.30 ppm–1134.42 ppm, median: 113.21 ppm). All of these PFTs also tested positive for lead (See "XRF methods" for how we accounted for possible lead arsenic interference). 13 of the 14 PFTs positive for arsenic exceeded 25.00 ppm, the US voluntary threshold for arsenic levels in toys (Fig. 4). Orange, red, and brown toys were most likely to contain arsenic, while no silver, white, black, blue, and purple PFTs contained arsenic above LOD.

Of the 17 PFTs which tested above 100.00 ppm for lead, 14 also tested above the voluntary safety limit of 25.00 ppm for arsenic (Fig. 4). The concentration of lead and the concentration of arsenic in these PFTs was weakly correlated (Pearson Coefficient = 0.31, $R^2$ = 0.09). Expanding the range of samples included in the Pearson correlation calculation to include all PFTs that tested positive for lead (n = 35), lead and arsenic concentrations were moderately positively correlated (Pearson Coefficient = 0.52, $R^2$ = 0.27), suggesting that there is a tendency for high lead concentration to co-occur with a high arsenic concentration.

### 3.3. Other contaminants of concern: XRF

Although concentrations of 30 elements were measured by XRF (Supplement 1 and 2), those that are typically of concern in children (beyond lead and arsenic) products are cadmium, selenium, chromium, and mercury. In general, the used PFTs had more contaminants of concern than the new PFTs. Cadmium, selenium, chromium, and mercury were only identified in a small number of the used PFTs and not in the new PFTs.

Selenium was identified in none of the used PFT and in none of the new PFTs, and cadmium in 1.28% of used toys and none of the new PFTs. Chromium was identified in slightly more of the used PFTs (3.51%) but in none of the new PFTs. No used or new toys were positive for mercury. Perhaps because of the small sample size of new toys, however, there was no statistical difference (using the Fischer exact test) at the 5.00% level in rates of cadmium, selenium, chromium, and mercury detection between used and new PFTs.

Regarding outliers, three toys tested between 300.00ppm and 400.00 ppm of cadmium - an orange, a pear, and an apple. All three toys were different colors. Within the overall sample of PFTs there was a visually identical twin of both the orange and the apple, both of which tested below the LOD for cadmium. Five toys tested between 700.00ppm and 1800.00 ppm for chromium - a pear, a potato, a chicken leg, a red apple, and an orange. The five toys which showed high concentrations of chromium all belonged on the red-brown range color spectrum.

Other less toxic elements were also found in a great portion of used toys including copper, zinc, and iron. Of the used toys, 70.29% had copper levels > LOD, with a mean of 217.70 ppm. There was only one outlier, a red watermelon with green paint, that had higher levels of copper (16,294 ppm). In the used toys 69.33% tested > LOD for zinc, with a mean concentration of 395.20 ppm. The only outlier with regards to zinc was a non-painted orange (which also had high levels for lead and arsenic) which had 6074.00 ppm of zinc. In the used toys 57.83% tested > LOD for iron, with the mean concentration of 386.00 ppm. The one outlier with regards to iron was a yellow unpainted pear, which had 14,580.00 ppm of iron.

Notably, the XRF analysis of new and old toys identified 31 samples with detectable levels of Uranium (range LOD - 8.83 ppm). Stages 1–2 identified uranium in 10 PFTs (5.08% of all PFTs tested) and 14 toy plates and utensils for use with PFTs (Supplement 3). Stage 3 identified seven new PFTs with Uranium concentrations above LOD. All samples tested within the sampling error range of uranium in soils (3.00 ppm); there are no comparable standards for uranium in toys or foods thus soil

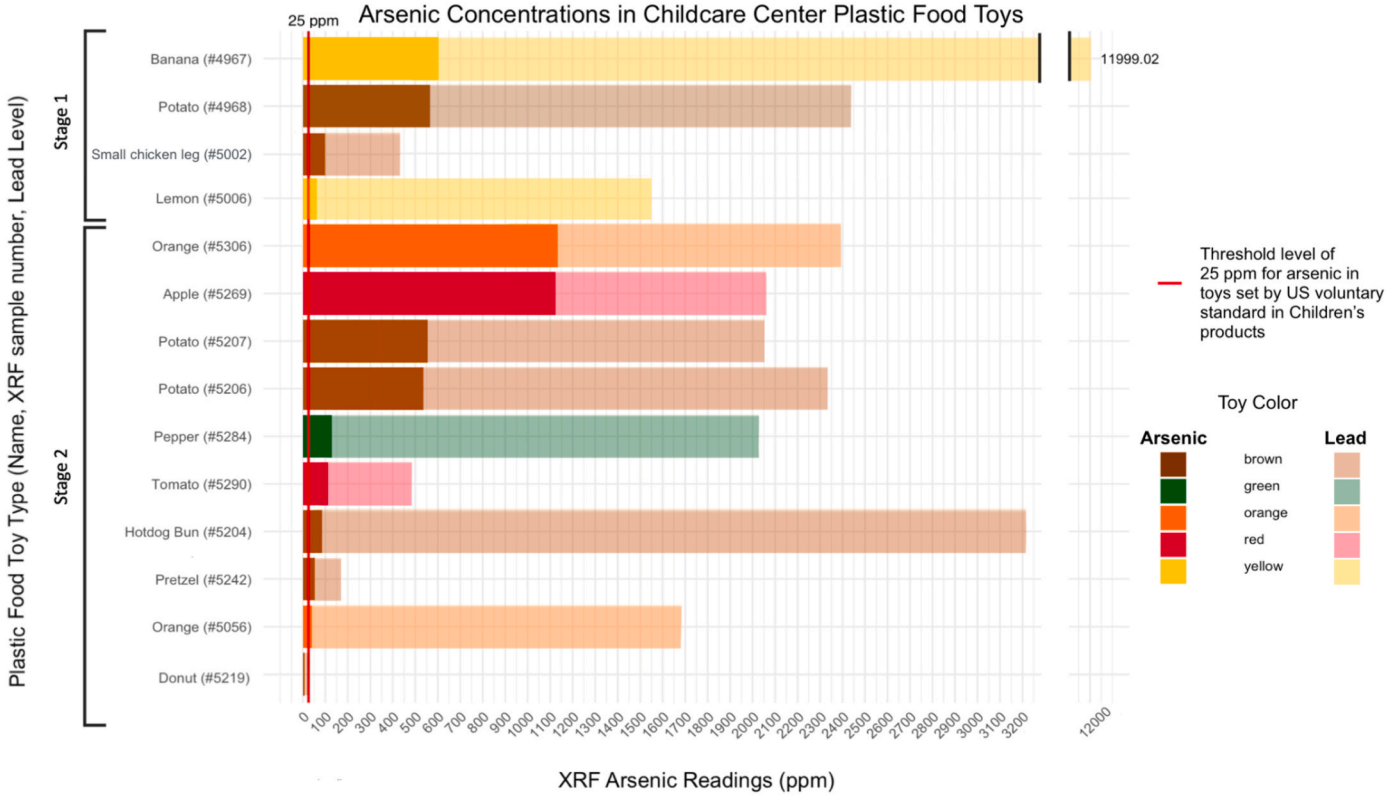



**Fig. 4.** Arsenic XRF concentrations of PFT samples (n = 14) above limit of detection, and their corresponding lead XRF concentrations, across Stages 1 and 2 (Batch A). The red threshold line (x = 25 ppm) indicates the voluntary maximum concentration limit for arsenic in children's products in the USA. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

is the closest solid media.

## 4. Discussion

### 4.1. SKC Full Disclosure® Lead Detection wipes

The wipes were easy to use. All student groups and the childcare center director correctly used the wipes with minimal training as indicated by the correct results with positive and negative controls. It is encouraging that the colorimetric wipe tests did not detect lead on the toys' surfaces even though this method has a low limit of detection of 18 μg of lead per $cm^3$. This suggests that lead was not freely available on the toys' surfaces, even though the toys had been used for many years. However, even though the toys were used, they were all in good condition i.e. they were not flaking paint or visibly worn. Had the toys been more damaged, lead may have been more readily available. Finally, the wipes' results may not adequately assess oral exposures.

The lack of positive wipe results limits our ability to compare the wipes to XRF results. Further testing of the wipes with known positives is required to assess the correlation between XRF and wipe results.

### 4.2. Plastic food toys' lead XRF findings

While no new toys had detectable levels of lead, 17.77% of used toys had detectable concentrations of lead. Of the used toys, 8.63% contained lead above the 100 ppm CPSIA threshold for children's products. Used painted toys were 3.6 times more likely to contain more than 90.00 ppm of lead than used non-painted toys (18.33% compared to 5.11%) and used toys of more than 20.00 g were 2.1 times more likely to contain more than 100.00 ppm of lead than those lighter than 20 g (13.70% compared to 6.45%). This suggested that paint may be a source of lead in the PFTs rather than plastic. Although more than 9.50% of the used red, brown, orange, white, yellow, silver, and green toys samples tested positive for lead, there is more than a two-fold difference between the color with the lowest rate of lead positivity (yellow, 4.17%) and the color with highest rate of lead positivity (brown, 11.67%). Because we do not know the origin, and therefore the price, of the used toys from the childcare center, we are not able to test for any correlations between the price of PFTs and the presence or concentration of metals in them.

### 4.3. Plastic food toys' arsenic XRF findings

XRF data shows 7.12% of used toys contained arsenic. However, none of the new toys contained arsenic. Arsenic levels did not vary significantly by mass in the used toys (9.56% for toys greater than 20 g compared to 4.84% for toys less than 20 g). However, used painted toys were 3.7 times more likely to contain arsenic than used non-painted toys, and orange and brown toys were almost more than twice as likely to test positive for arsenic than other colors (10.53% and 16.67% respectively). While there are semi-qualitative colorimetric wipe tests for detecting arsenic available for purchase and use by the public, the measurement of arsenic on the surface of PFTs was beyond the scope of this study and warrants further investigation in the future (S. Middleton et al., 2018).

In sum, consumers and childcare centers concerned about lead or arsenic exposure through PFTs should consider replacing older PFTs, particularly painted and red, brown, orange, green and yellow PFTs, with new toys. Risk can be mitigated by purchasing from reputable online retailers, and by manufacturers with a good track record of CPSIA compliance.

### 4.4. Lead and arsenic XRF co-occurrence

XRF measurements of lead and arsenic have known problems with interference due to overlap of their primary detection peak (lead L-alpha peak 10.55 keV and Arsenic L-alpha 10.54 keV) (X-Ray Data Booklet, n. d.). This interference increases as the concentration of lead increases, particularly for measurements over 5000.00 ppm of lead. Only 1 sample contained lead over that 5000.00 ppm threshold, a plastic banana (11, 999.00 ppm), so we regard the arsenic concentrations for all other samples to be reliable. Additionally, as discussed in the methods section, current XRF fitting modalities disentangle these peaks more effectively, as lead contains a secondary peak isolated from interferences (lead L-beta 12.6 keV).

### 4.5. Plastic food toys' uranium XRF findings

Uranium is spotlighted here because it is the only neurotoxic element which was present in both the used and new toys sampled, though uranium was present in a smaller proportion of samples. Only 25/197 used toys contained detectable levels of uranium, while 7/87 new toys contained detectable levels of uranium. We are unsure of the sources of uranium in these PFTs. Further attention to uranium in toys may be warranted, particularly since the positive-testing PFTs came from the two sets which represented the lower end of the price spectrum sampled: 3 samples came from the 101-piece Step2 Toddler Pretend Play food set from Discount School Supply (Batch B $0.19 per PFT), 4 samples came from the 115-piece KidKraft Deluxe Tasty Treats Pretend Play-Food set from Walmart (Batch E $0.37 per PFT). Comparatively, the more expensive brands cost up to $1.92 per PFT. Further study is also needed to assess whether uranium is present in other PFTs, and what the bioavailability of such uranium is.

Radioactive materials are not uncommon in certain consumer products, and are present in very small quantities in food, which is considered safe (US EPA, 2019b, 2019a). However, the danger posed by consumable uranium is not its radioactivity, but its renal toxicity and neurotoxicity (Dinocourt et al., 2015). The sale of child products containing hazardous substances, including uranium, was banned in the U. S. through the 1966 Child Protection Act by the U.S. Secretary of Health, Education, and Welfare and strengthened by the 1969 Child Protection and Toy Safety Act and the Toxic Substances Control Act of 1976 (TOPN, n.d.).

### 4.6. Limitations

The 87 newly purchased PFTs from 5 different retailers represent a tiny fraction of PFTs available to consumers. A larger sample from a larger variety of manufacturers and price-points is needed to assess the absence of lead and arsenic more reliably in new PFTs. The categorization of toys by color was made without a calibrated or standardized scale; this means categorization of similar toys in other studies may not be readily replicable.

The wipes and XRF cannot directly assess exposure from mouthing, ingestion or respiration of dust and cannot assess bioavailability. Further validation of the wipe method with a focus on the bioavailability of lead within materials, as conducted in Kang et al.'s study of plastic toys bought on the Beijing market (Kang and Zhu, 2015), is needed to assess bioavailability of lead, arsenic and uranium from PFTs. However, since all toys will eventually break down, focusing on only protecting immediate consumers is insufficient.

Although painted toys were more likely to test lead positive than unpainted toys, the methods in this study are insufficient to conclude whether lead is present in the plastic or the paint of painted toys without employing destructive sampling methods – this is problematic given the two different allowed upper limits for paint and children's toys.

Cadmium is a neurotoxicant that is studied in conjunction with lead and arsenic in consumer goods (Kumar and Pastore, 2007). Although we included the results of our findings for transparency, the XRF optimization utilized in this study has poor performance with respect to detecting cadmium. Only 3 samples showed cadmium levels above detectable levels, however there are likely to be more than 3 in our sample. Consequently, further study of cadmium in PFTs by different

methods is warranted. Further study should also explore any undiscovered explanatory factors or determinants leading to excess heavy metals, beyond those determined in this study.

### 4.7. Opportunities for citizen science

"Who knew there was lead in plastic toys?! Thanks to this study we were able to identify and immediately remove contaminated toys and replace them with wooden play foods. As these kinds of toys are still being used elsewhere and these toys are frequently put in kids' mouths, it's important to get the word out to other childcare centers." ~Childcare center director.

While environmental health researchers may know lead can occur in plastic toys, it is not common knowledge even among those who work professionally with children and are alert to dangers of lead exposures. Studies like this one that directly engage with concerned communities and investigate their research questions, such as the director's inquiry about the plastic food toys, can help bridge the gap between academic knowledge and concerned communities. In this context it is particularly important to use methods that rapidly provide participants with actionable data. If this had been a lab-based study it might have taken months before results were reported back to the childcare center and toys were removed. Thanks to the rapid XRF results we were able to quickly identify and remove the PFTs and replace them with wooden toys. Additionally, the immediate lead wipe results showing that lead was not readily removable from the toys surfaces helped ameliorate the staff's pressing concerns about the severity of possible exposures due to mouthing of the toys. The combination of the two methods provided compelling and complementary forms of evidence that identified a risk and helped contextualize its severity (Vera et al., 2020; Offenhuber, 2019).

However, we find the wipes are insufficient as a community science tool (where research is conducted independently by non-professionals) for analyzing toys, as contaminants were only positively identified via portable XRF. Additionally, the use of the wipes is limited by the need for appropriate waste disposal. As the wipes require nitric acid and rhodizonic acid, mild skin irritants, we disposed of the waste through the university environmental health and safety division. Thus, the method is appropriate for use where access to safe waste disposal is possible, such as universities. This suggests a need for more consumer-oriented tools for community science.

The difference between the XRF and wipe findings highlights the importance of small-scale validation studies, like this one, to assess citizen science methods' strengths and limitations and assure data quality in community science work (Walls et al., 2022). Indeed, that this tool testing project inadvertently identified a novel and reportable source of environmental toxicants based on the childcare center's director's request to look at PFTs, suggests that small-scale, low-cost studies guided by community members' questions can become important avenues to developing further academic and policy work.

We suggest universities support curriculum-based, student-led Community Based Participatory Research projects like this, to offer services to regional childcare centers for XRF analysis of PFTs. Valuable scientific and public knowledge could be generated if this type of citizen science were commonly carried out by students in environmental health courses (Kenny et al., 2019).

### 4.8. Recall and disposal of plastic food toys

Regardless of lead and arsenic's immediate bioavailability, these products will eventually degrade and release lead, arsenic, uranium, and other toxic metals and plastic into the environment. As CPSIA requires, "Any children's product on the market that does not comply with the new lead standards will be considered a banned hazardous substance" (CFA, 2013) to further investigate and test PFTs in circulation, we suggest a broad recall of used PFTs and systematic testing of recalled products (Rush, 2008; Freedman et al., 2012). A systematic approach to this environmental health issue is important because if left to consumer choice, higher income consumers and childcare centers are more likely to learn about these concerns and to replace PFTs with safer higher-priced alternatives. Low-income consumers and childcare centers are less likely to learn of risk from PFTs and have less resources to buy higher-priced alternatives. Under-served minority and low-income communities are already disproportionately burdened by lead exposure and lead related health disparities (LeBrón et al., 2019). It would be irresponsible from an environmental public health perspective to further exacerbate these disparities through toxic toy exposure. Additionally, an uncoordinated removal of PFTs may result in those toys being donated to charity organizations, leading to hazardous PFTs circulating in the second-hand market, which could also disproportionately expose children of low socio-economic status. Additionally, hazardous PFTs would likely be sent to landfills which are not authorized to manage hazardous materials.

Another interesting question raised in this study and others is how to properly dispose of hazardous toys. Currently, the US EPA recommends that toys testing positive for lead be returned to the manufacturer. This is not possible in the context of this study as the manufacturers are unknown. Households are exempt from current hazardous waste laws; but consumers are responsible for determining if this complies with state and local laws (EPA HHW, 2022). That consumers bear the burdens of incorrectly disposing of contaminated goods disincentivizes consumers from identifying contaminants in toys and other goods. Consumers are not to blame for toxic contaminants in PFTs and they should not bear the burden of managing this exposure route. Instead, we recommend contaminated toy disposal be integrated into cities' and states' established lead e-waste collection and disposal systems. Alternatively, to properly adjudicate responsibility, manufacturers of PFTs could receive recalled toys based on their historical market share, as per the Market Share liability doctrine first established in *Sindell vs Abbot Laboratories* (Murray, 1981).

Our study highlights the need to further strengthen the oversight and accountability of manufacturers by requiring branding on all toys. Additionally, to incentivize rather than disincentivize citizen science around consumer products, public sample collection systems could be established, such as public collection sites for potentially contaminated toys, so they do not end up in municipal landfills. Additionally, public data repositories could be established where citizen scientists can share their results with regulatory agencies such as the Consumer Product Safety Division.

## 5. Conclusions

While findings from this study present reasons to be cautiously optimistic about the unlikelihood of lead exposure from new PFTs, their uranium content is worth further investigation. Regulatory agencies should also consider the general toxicity of plastic-based toys, as Rochman et al.'s scoping review and current research suggests that plastic itself should be considered hazardous given the human and ecological health risks posed by plastic during decomposition (Rochman et al., 2013). Additionally, many used PFTs could contain levels of lead and arsenic that exceed current regulatory thresholds; our study identified 35 (17.77%) older PFTs that had detectable levels of lead and 14 with arsenic. Given that there is no safe level of lead, policymakers should further reduce the acceptable level of lead in all consumer products, but especially children's toys. We also recommend establishing policy pertaining to limits on arsenic and uranium in children's products (Schmidt, 2008). We recommend that individuals and those running childcare centers replace used PFTs or of unknown manufacture date, with new PFTs made by reputable manufacturers unless they can get them tested.

Although this study shows potential sources of heavy metals in childcare facilities, the findings should also alert consumers and

researchers and clinicians in the environmental health and consumer-products fields. Future work needs to be done to investigate the mouthing behaviors of children with regards to PFTs specifically. The methods and mindset characterizing this study are important to expanding citizen science into investigation of product safety. The limitations of the low-cost citizen science methods illustrate the need to improve citizen science tools so consumers and classrooms might readily assist in analyzing product safety. With the support of universities and regulatory agencies, given their position to act as data repositories, citizen science could augment the public's ability to analyze and assess the safety of commercial products. It is important for universities and research institutions to further support the citizen science research of consumer products and environmental pollution through coursework, analytics, and proper waste removal services.

## Credit roles

**Kaleem Ahmid**: Conceptualization, Investigation, Data Curation, Writing – Original Draft, Writing – Review and Editing **Aaron Specht:** Investigation, Formal Analysis **Larisa Morikawa:** Investigation, Visualization **Diana Ceballos:** Conceptualization, Writing – Review and editing **Sara Wylie:** Methodology, Conceptualization, Writing – Review and editing, Supervision, Project administration.

## 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.

## Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.Any brand names and business names are included for scientific and informational purposes only, and do not suggest endorsement of any kind.Thanks to the assistance and support of the staff at the childcare facility in this study. Thanks also to Atsushi Matsumoto, Audrey McCarthy, Ziqi Tang, and students from the Fall 2019 EH804 Field Methods in Exposure Science graduate course in Boston University School of Public Health that assisted with some of the preliminary work that based this study. Thanks to the members of the *Wylie Environmental Data Justice Lab* and the *Social Science Environmental Health Research Institution* for reviewing the paper. Thanks to the students in Northeastern Environmental Health (Spring 2020) who participated in the data collection for this study.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115904.

## References

Ashley, K., Wise, T., Esswein, E., 2011. Evaluation of a handwipe disclosing method for lead. Journal of ASTM international. https://doi.org/10.1520/JAI103390, 8-7.

ASTM F 963–17 Requirements, 2018 (n.d.). U.S. Consumer Product Safety Commission. Retrieved 16 June 2022. https://www.cpsc.gov/Business-Manufacturing/Business-Education/Toy-Safety/ASTM-F-963-Chart.

Aurisano, N., Huang, L., Milà i Canals, L., Jolliet, O., Fantke, P., 2021. Chemicals of concern in plastic toys. Environ. Int. 146 (106194) https://doi.org/10.1016/j.envint.2020.106194.

Beaucham, C., Ceballos, D., King, B., 2017. Lessons learned from surface wipe sampling for lead in three workplaces. J. Occup. Environ. Hyg. 14 (8), 609–617. https://doi.org/10.1080/15459624.2017.1309047.

Bonney, R., Shirk, J.L., Phillips, T.B., Wiggins, A., Ballard, H.L., Miller-Rushing, A.J., Parrish, J.K., 2014. Next steps for citizen science. Science 343 (6178), 1436–1437. https://doi.org/10.1126/science.1251554.

CFA Consumer Federation of America, 2013. CPSIA and Lead Fact Sheet. Retrieved 29 June 22. https://consumerfed.org/pdfs/CPSIA-and-Lead-Fact-Sheet-8-5-13.pdf.

606 CMR 7.00: Standards for the licensure or approval of family child care; small group and school age and large group and school age child care programs | Mass.gov. (n.d.). https://www.mass.gov/regulations/606-CMR-700-standards-for-the-licensure-or-approval-of-family-child-care-small-group-and-school-age-and-large-group-and-school-age-child-care-programs (Retrieved 16 June 2022).

Cory-Slechta, D.A., 2012. Low level lead exposure harms children: a renewed call for primary prevention. 65. Report of the Advisory Committee on Childhood Lead Poisoning Prevention of the Center for Disease Control. Retrieved 29 June 2022. https://www.cdc.gov/nceh/lead/acclpp/final_document_030712.pdf.

Dignam, T., Kaufmann, R.B., LeStourgeon, L., Brown, M.J., 2019. Control of lead sources in the United States, 1970-2017: public health progress and current challenges to eliminating lead exposure. J. Publ. Health Manag. Pract. https://doi.org/10.1097/PHH.0000000000000889. JPHMP, 25(Suppl 1 LEAD POISONING PREVENTION), S13–S22.

Dinocourt, C., Legrand, M., Dublineau, I., Lestaevel, P., 2015. The neurotoxicology of uranium. Toxicology 337, 58–71. https://doi.org/10.1016/j.tox.2015.08.004.

EPA HHW, 2022. United States Environmental Protection Agency. "Household Hazardous Waste". Last updated 5.14.22. (Retrieved 29 June 22). https://www.epa.gov/hw/household-hazardous-waste-hhw.

Flora, G., Gupta, D., Tiwari, A., 2012. Toxicity of lead: a review with recent updates. Interdiscipl. Toxicol. 5 (2), 47–58. https://doi.org/10.2478/v10102-012-0009-2.

Freedman, S., Kearney, M., Lederman, M., 2012. Product recalls, imperfect information, and spillover effects: lessons from the consumer response to the 2007 toy recalls. Rev. Econ. Stat. 94 (2), 499–516. https://doi.org/10.1162/REST_a_00162.

Full Disclosure Kit. (n.d.). https://www.skcltd.com/products2/surface-skin-sampling/full-disclosure-kit.html (Retrieved 22 June 2022).

Greenway, J.A., Gerstenberger, S., 2010. An evaluation of lead contamination in plastic toys collected from day care centers in the las vegas valley, Nevada. USA. Bulletin of Environmental Contamination and Toxicology 85 (4), 363–366. https://doi.org/10.1007/s00128-010-0100-3.

Guney, M., Zagury, G.J., 2012. Heavy metals in toys and low-cost jewelry: critical review of U.S. And Canadian legislations and recommendations for testing. Environ. Sci. Technol. 46 (8), 4265–4274. https://doi.org/10.1021/es203470x.

Guney, M., Zagury, G.J., 2013. Contamination by ten harmful elements in toys and children's jewelry bought on the north American market. Environ. Sci. Technol. 47 (11), 5921–5930. https://doi.org/10.1021/es304969n.

Hendricks, M.D., Meyer, M.A., Wilson, S.M., 2022. Moving up the ladder in rising waters: community science in infrastructure and hazard mitigation planning as a pathway to community control and flood disaster resilience. Citiz. Sci. Theory Pract. 7 (1), 18. https://doi.org/10.5334/cstp.462.

Hillyer, M.M., Finch, L.E., Cerel, A.S., Dattelbaum, J.D., Leopold, M.C., 2014. Multi-technique quantitative analysis and socioeconomic considerations of lead, cadmium, and arsenic in children's toys and toy jewelry. Chemosphere 108, 205–213. https://doi.org/10.1016/j.chemosphere.2014.01.041.

Hoover, C., Hoover, G.G., Specht, A.J., 2021. Firearm licenses associated with elevated pediatric blood lead levels in Massachusetts. Environ. Res. 202 (111642) https://doi.org/10.1016/j.envres.2021.111642.

Juberg, D.R., Alfano, K., Coughlin, R.J., Thompson, K.M., 2001. An observational study of object mouthing behavior by young children. Pediatrics 107 (1), 135–142. https://doi.org/10.1542/peds.107.1.135.

Kang, S., Zhu, J., 2015. Total lead content and its bioaccessibility in base materials of low-cost plastic toys bought on the Beijing market. J. Mater. Cycles Waste Manag. 17 (1), 63–71. https://doi.org/10.1007/s10163-013-0223-9.

Kenny, C., Liboiron, M., Wylie, S.A., 2019. Seeing power with a flashlight: DIY thermal sensing technology in the classroom. Soc. Stud. Sci. 49 (1), 3–28. https://doi.org/10.1177/0306312718823282.

Kim, S., Yang, J.-Y., Kim, H.-H., Yeo, I.-Y., Shin, D.-C., Lim, Y.-W., 2012. Health risk assessment of lead ingestion exposure by particle sizes in crumb rubber on artificial turf considering bioavailability. Environmental Health and Toxicology 27, e2012005. https://doi.org/10.5620/eht.2012.27.e2012005.

Kimura, A.H., Kinchy, A., 2016. Citizen science: probing the virtues and contexts of participatory research. Engaging Science, Technology, and Society 2, 331–361. https://doi.org/10.17351/ests2016.99.

Korfmacher, K.S., Dixon, S., 2007. Reliability of spot test kits for detecting lead in household dust. Environ. Res. 104 (2), 241–249. https://doi.org/10.1016/j.envres.2007.02.001.

Kumar, A., Pastore, P., 2007. Lead and cadmium in soft plastic toys. Curr. Sci. 93 (6), 818–822.

Lead Contamination Control Act Amendments of 1991 (1991—H.R. 2840), 2017. n.d. GovTrack.Us. Retrieved June 16, 2022, from. https://www.govtrack.us/congress/bills/102/hr2840.

LeBrón, A.M.W., Torres, I.R., Valencia, E., Dominguez, M.L., Garcia-Sanchez, D.G., Logue, M.D., Wu, J., 2019. The state of public health lead policies: implications for urban health inequities and recommendations for health equity. Int. J. Environ. Res. Publ. Health 16 (6), 1064. https://doi.org/10.3390/ijerph16061064.

Mateus-García, A., Ramos-Bonilla, J.P., 2014. Presence of lead in paint of toys sold in stores of the formal market of Bogotá, Colombia. Environ. Res. 128, 92–97. https://doi.org/10.1016/j.envres.2013.11.005.

McFarland, M.J., Hauer, M.E., Reuben, A., 2022. Half of US population exposed to adverse lead levels in early childhood. Proc. Natl. Acad. Sci. USA 119 (11). https://doi.org/10.1073/pnas.2118631119 e2118631119.

Middleton, S., , D. R., Watts, J., Hamilton, M., Coe, E.D., Fletcher, J., Crabbe, T., Close, H., Leonardi, R.S., G., A. Polya, D., 2018. Surface wipe and bulk sampling of household dust: arsenic exposure in Cornwall, UK. Environ. Sci. J. Integr. Environ. Res.: Process. Impacts 20 (3), 505–512. https://doi.org/10.1039/C7EM00463J.

Miller, G.Z., Harris, Z.E., 2015. Hazardous metals in vintage plastic toys measured by a handheld X-ray fluorescence spectrometer. J. Environ. Health 77 (6), 8–13.

Minkler, M., Wallerstein, N., 2011. Community-Based Participatory Research for Health: from Process to Outcomes. John Wiley & Sons.

Murray, R.P., 1981. Sindell v. Abbott laboratories: a market share approach to des causation. Calif. Law Rev. 69, 1179.

NIOSH Manual of Analytical Methods (NMAM) Fourth Edition. Third Supplement, 2021. https://doi.org/10.26616/NIOSHPUB2003154.

Offenhuber, Dietmar, 2019. Data by proxy—material traces as autographic visualizations. IEEE Trans. Visual. Comput. Graph. 26.1, 98–108.

O'Flaherty, E.J., 1998. A physiologically based kinetic model for lead in children and adults. Environ. Health Perspect. 106 (Suppl. 6), 1495–1503.

Redmon, J.H., Levine, K.E., Aceituno, A.M., Litzenberger, K., Gibson, J.M., 2020. Lead in drinking water at North Carolina childcare centers: piloting a citizen science-based testing strategy. Environ. Res. 183 (109126) https://doi.org/10.1016/j.envres.2020.109126.

Rinsky, J.L., Higgins, S., Angelon-Gaetz, K., Hogan, D., Lauffer, P., Davies, M., Fleischauer, A., Musolin, K., Gibbins, J., MacFarquhar, J., Moore, Z., 2018. Occupational and take-home lead exposure among lead oxide manufacturing employees, 6. In: North Carolina, 2016, vol. 133. Public Health Reports, Washington, D.C.: 1974, pp. 700–706. https://doi.org/10.1177/0033354918795442.

Rochman, C.M., Browne, M.A., Halpern, B.S., Hentschel, B.T., Hoh, E., Karapanagioti, H. K., Rios-Mendoza, L.M., Takada, H., Teh, S., Thompson, R.C., 2013. Classify plastic waste as hazardous. Nature 494 (7436), 169–171. https://doi.org/10.1038/494169a.

Rush, B.L., 2008, August 14. H.R.4040-110th congress (2007-2008). Consumer Product Safety Improvement Act of 2008 (2007/2008) [Legislation]. http://www.congress.gov/.

Sanders, M., Stolz, J., Chacon-Baker, A., 2013. Testing for lead in toys at day care centers. Work 44 (Suppl. 1), 29–38. https://doi.org/10.3233/WOR-121492.

Schmidt, C.W., 2008. Face to face with toy safety: understanding an unexpected threat. Environ. Health Perspect. 116 (2), A70–A76. https://doi.org/10.1289/ehp.116-a70.

Shen, Z., Hou, D., Zhang, P., Wang, Y., Zhang, Y., Shi, P., O'Connor, D., 2018. Lead-based paint in children's toys sold on China's major online shopping platforms. Environ. Pollut. 241, 311–318. https://doi.org/10.1016/j.envpol.2018.05.078.

Shirk, J., 2022. "Coming to terms—citizen science AssociationCitizen science". (May 5). Citizen science association. Blog. https://citizenscience.org/2022/05/05/coming-to-terms/.

Specht, A.J., Lin, Y., Weisskopf, M., Yan, C., Hu, H., Xu, J., Nie, L.H., 2016. XRF-measured bone lead (Pb) as a biomarker for Pb exposure and toxicity among children diagnosed with Pb poisoning. Biomarkers: Biochemical Indicators of Exposure, Response, and Susceptibility to Chemicals 21 (4), 347–352. https://doi.org/10.3109/1354750X.2016.1139183.

Strasser, B., Baudry, J., Mahr, D., Sanchez, G., Tancoigne, É., 2019. "Citizen science"? Rethinking science and public participation. Science & technology studies. https://doi.org/10.23987/sts.60425.

Swaringen, B.F., Gawlik, E., Kamenov, G.D., McTigue, N.E., Cornwell, D.A., Bonzongo, J.-C.J., 2022. Children's exposure to environmental lead: a review of potential sources, blood levels, and methods used to reduce exposure. Environ. Res. 204 (112025) https://doi.org/10.1016/j.envres.2021.112025.

Tighe, M., Knaub, C., Sisk, M., Ngai, M., Lieberman, M., Peaslee, G., Beidinger, H., 2020. Validation of a screening kit to identify environmental lead hazards. Environ. Res. 181 (108892) https://doi.org/10.1016/j.envres.2019.108892.

TOPN: Child Protection and Toy Safety Act of 1969. (n.d.). LII/Legal Information Institute. https://www.law.cornell.edu/topn/child_protection_and_toy_safety_act_of_1969 (Retrieved 16 June 2022).

(n.d.) Toxicological profile for lead, 2019 (Retrieved 16 June 2022). https://stacks.cdc.gov/view/cdc/37676.

Tulve, N.S., Suggs, J.C., Mccurdy, T., Cohen Hubal, E.A., Moya, J., 2002. Frequency of mouthing behavior in young children. J. Expo. Sci. Environ. Epidemiol. 12 (4), 259–264. https://doi.org/10.1038/sj.jea.7500225.

Turner, A., 2018. Concentrations and migratabilities of hazardous elements in second-hand children's plastic toys. Environ. Sci. Technol. 52 (5), 3110–3116. https://doi.org/10.1021/acs.est.7b04685.

US EPA, O, 2019. Is there radioactivity in food? [Overviews and Factsheets] a, February 11Retrieved 16 June 2022. https://www.epa.gov/radiation/there-radioactivity-food.

US EPA, O, 2019. What kinds of consumer products contain radioactive materials? [Overviews and Factsheets]. Retrieved 16 June 2022b, February 11. https://www.epa.gov/radiation/what-kinds-consumer-products-contain-radioactive-materials.

Vera, L., Malivel, G., Michanowicz, D., Kang, C.M., Wylie, S., 2020. Photopaper as a tool for community-level monitoring of industrially produced hydrogen sulfide and corrosion. Atmos. Environ. X 5 (100049). https://doi.org/10.1016/j.aeaoa.2019.100049.

Walls, D., Kinchy, A., Margalit, T., Ramírez-Andreotta, M.D., Engel-Di Mauro, S., 2022. Confronting legacy lead in soils in the United States: community-engaged researchers doing undone science. Environ. Sci. Pol. 128, 165–174. https://doi.org/10.1016/j.envsci.2021.10.035.

X-Ray Data Booklet (n.d.) (Retrieved 22 June 2022). https://xdb.lbl.gov/.

Yost, J.L., Weidenhamer, J.D., 2008. Lead contamination of inexpensive plastic jewelry. Sci. Total Environ. 393 (2), 348–350. https://doi.org/10.1016/j.scitotenv.2008.01.009.