Quantifying lead (Pb) leaching from galvanized handpump spouts, leaded brass taps, and stainless-steel alternatives using the NSF 61 test protocol: Implications for safe rural water supply

Short title (70 characters): Pb release of galvanized, brass, and stainless-steel water components

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Abstract

Lead (Pb) is a neurotoxin with no known safe level of exposure. Widespread lead contamination has been found in rural groundwater-supplied drinking water systems in low- and middle-income countries, potentially from corrosion of lead-containing materials such as galvanized steel and brass. National Sanitation Foundation (NSF) 61 is an international standard for certifying the safety of water system components in contact with drinking water based on their capacity to leach chemical contaminants, especially lead, into drinking water. Another standard, NSF 372, certifies the material composition of drinking water system components as 'lead-free' if lead content is ≤0.25% by weight for wetted surfaces. This work investigates the lead leaching potential of components frequently used in these systems and explores potential alternatives to determine which components can be safely used in drinking water systems. Galvanized handpump spouts and leaded brass taps of types widely used in rural water systems in Ghana and stainless-steel alternatives, were tested against NSF 61 and NSF 372 standards. Lead-free PVC pipe segments were used as controls. Test results indicated that all stainless-steel components and PVC controls met NSF 61 and NSF 372 standards while galvanized spouts and brass taps did not meet either. The average lead levels leached over the experiment period from the brass taps, galvanized spout, stainless-steel taps, PVC pipes, and stainless-steel spouts were 192 (SD=89), 34 (SD=3), 0.3 (SD=0.1), 0.2 (SD=0.3), and 0.1 (SD=0.1) µg/L, respectively. Overall, the use of lead-containing galvanized handpump spouts and brass taps should be avoided in water systems due to their lead leaching potential; alternative products made from lead-free materials such as stainless steel should be substituted.

Introduction

Lead (Pb) is a global environmental pollutant and neurotoxicant that causes irreversible harm to exposed persons, particularly to children and developing fetuses [1]. Lead is sometimes intentionally added in the production of various alloys and materials to enhance their properties. Lead-containing alloys including leaded brass materials and leaded zinc coatings on galvanized materials are commonly found in water supply systems and can leach lead into drinking water at levels of human health concern [2-4]. The World Health Organization (WHO) has published a guideline value for water lead levels (WLL) of 10 µg/L [5] which was exceeded in 9% of drinking water samples in a recent study carried out in three West African countries [6].

Lead release into drinking water can occur through complex electrochemical, geochemical, and hydraulic mechanisms [7]. The rate at which lead is released from materials is highly dependent on the chemistry of water with which they are in contact [7]. Water quality parameters that influence corrosion rates include pH, alkalinity, hardness, conductivity, free chlorine, temperature, chloride-to-sulfate mass ratio, and presence of corrosion inhibitors [8]. Corrosion inhibitors such as orthophosphates and silicates can prevent corrosion of leaded water system materials and components and thereby reduce WLLs, but require continuous and appropriate dosing of corrosion inhibiting chemicals, depending on influent water chemistry, to achieve and maintain the formation of stable lead scales on pipe surfaces [9]. Lead release is also a function of contact time and wetted surface area [10]. Lead concentrations in "first draw" water samples increase with increasing stagnation time, with the largest rates of leaching observed during the first 24 hours, though lead leaching continues throughout the duration of contact with water [11]. Stainless steel (SS) has been used as an alternative material in water system distribution and has been systematically validated as a suitable lead-free alternative material with high corrosion resistance following the ban of leaded brass in the US [8]. Polymers such as polyvinyl chloride (PVC) are another class of alternative materials, and can be more economical than stainless steel, but metal additives (including lead) may be added as heat stabilizers to make both new and recycled PVC more durable and less prone to thermal degradation [12]. Such leaded PVC is presumably an unsuitable alternative for reducing lead occurrence in drinking water, and knowing the composition of PVC is therefore important if they are to be considered for use in drinking water systems. Most high-income countries and a few low- and middle-income countries (LMICs) have established standards to regulate toxic metals contained in or leached by water system components in contact with drinking water, but many LMICs may not have enforceable standards in place [13]. Typically, enforceable standards specify either a maximum lead content that can be present in components (e.g., 0.25% wt/wt in the case of NSF/ANSI/CAN 372 and the International Plumbing Code) [14] or specify a maximum lead level that can leach from components under a defined testing protocol (e.g. NSF/ANSI/CAN 61) [10]. The absence of publicly available data on lead content in and lead leaching from lead-bearing parts such as brass and galvanized steel (GS) represents a critical evidence gap, as hundreds of millions of LMIC residents potentially consume water from systems containing such parts [15].

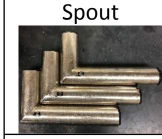
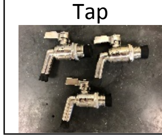
The aim of this research study is to determine whether rural water supply system components routinely installed in Ghana and other LMICs contain lead, whether the lead leaches into water at concentrations of health concern, and whether SS components could serve as suitable lead-free alternatives. This was achieved by assessing if the GS and brass components (as well as their SS alternatives) a) contained lead in excess of 0.25% w/w (per NSF 372) and b) leached WLLs above the NSF 61 standard threshold.

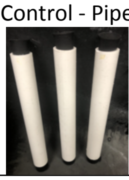
Methods

Plumbing components

Triplicate examples of two types of understudied components (India Mark II handpump spouts and ¾" taps) made from two types of high-risk materials (GS and brass, respectively) were obtained from two Ghanaian importers based in Accra and Tamale, Ghana. In addition, triplicate examples of lead-free ¾"-diameter PVC pipe was obtained from an American hardware store in Chapel Hill, North Carolina for use as a control, since this PVC pipe is certified to meet both NSF 372 and NSF 61 standards. The tested components and their respective characteristics of material, dimensions, weight, volume, and source are listed in Table 1.

Table 1. Water System Component Characteristics.

Component Tested	Type of Water System (Location in System)	Material	Dimension	Average Weight (g)	Average Internal Volume (mL)	Importer or distributor
Spout 	India Mark II Handpump (Endpoint)	Galvanized Steel	24.5 cm and 13 cm long of 5.5 cm diameter	1,519.9	650	JOISSAM Ghana Ltd, Accra, Ghana
Tap 	Mechanized Borehole (Endpoint)	Brass	5 cm and 7 cm long of 2 cm diameter	69.6	35	HABF Plumbing Shop (Canada Market), Tamale, Ghana
Spout 	Handpump (Endpoint)	Stainless Steel	24 cm and 13 cm long of 4.5 cm diameter	1,031.4	420	HTC Ghana Ltd, Accra, Ghana
Tap 	Borehole (Endpoint)	Stainless Steel	5 cm and 5 cm long of 2 and 1.5 cm diameter	268.0	15	LabMart Ghana, Tamale, Ghana

Control - Pipe 	Water distribution conveyance (Inline)	Schedule 40 PVC	25 cm long of 2 cm diameter	391.0	75	Lowe's hardware store, Chapel Hill, NC USA

Material composition

The elemental composition of each component, three samples of each, was determined by X-ray fluorescence (XRF) following the NSF 372 standard. A handheld TRACER 5i pXRF Spectrometer (Bruker, Billerica, MA) was used on the component surface, in triplicate at the same location, with the GeoExploration calibration with a multiphase method to determine the presence and concentration of individual elements.

Lead leaching

The NSF 61 Section 9 test procedure was carried out using three replicate examples of each component to quantify lead leaching and assess conformance with the NSF 61 standard [10]. Per NSF 61 test protocols, synthetic test water was created daily as follows: pH 8±0.5, alkalinity 500±0.5 mg/L as $CaCO_3$, free chlorine 2±0.2 mg/L, and dissolved inorganic carbon 122±5 mg/L [10, 16]. Total chlorine was verified using a Hach DR300 pocket colorimeter (Hach, Loveland, CO). 98% sodium hydroxide pellets (Thermo Fisher, Waltham, MA) were used to maintain pH within the specified range (8±0.5). The pH was verified using a handheld Hanna HI98129 low range Combo pH/conductivity meter (Hanna, Woonsocket, RI).

Components were incubated at room temperature with synthetic test water in triplicate per the NSF 61 testing protocol. Briefly, test components were filled with synthetic test water from a 20-L Nalgene polypropylene carboy (Nalgene, Rochester, NY). All carboys and Nalgene sampling bottles were acid-washed thoroughly with hydrochloric acid prior to use. No headspace was present when capping each orifice with a solid natural rubber stopper (Grainger, Lake Forest, IL). The test water was replaced at two-hour intervals from 8 AM until 4 PM from Monday to Friday, for three weeks (Days 1-5, 8-12, and 15-19). This was to simulate water usage with stagnant water sitting overnight, over the weekend, and bihourly usage during each weekday. The entire first draw sample – a 650, 35, 420, 15, and 75 mL aliquot for the galvanized spout, brass tap, stainless-steel spout, stainless-steel tap, and PVC pipe, respectively, was collected at the 8 AM dump-and-fill point and poured into 1-L Nalgene HDPE sample bottles (Nalgene, Rochester, NY) on Wednesday, Thursday, and Friday of the three week sample period (Days 3, 4, 5, 10, 11, 12, 17, 18, and 19). The NSF 61 Section 9 test protocol specifies only collecting the first draw samples from the morning dump-and-fill round to capture overnight water stagnation from the prior day's 16-hour dwell.

The collected samples were acidified using trace metal grade 67-70% nitric acid (Thermo Fisher, Waltham, MA) for 2% v/v acidification. After acidification, the samples were capped, thoroughly mixed, and stored at room temperature for at least 24 hours. Duplicate 10-mL aliquots were then removed from each well-mixed, acidified sample and decanted into 15-mL trace metal-free polypropylene centrifuge tubes (Labcon, Petaluma, CA) and analyzed for lead and other selected elements using an Agilent 8900 Triple Quadrupole ICP-MS (Agilent, Santa Clara, CA) per Standard Method 3125-B [17]. The limit of detection (LOD) for lead using the ICP-MS was 0.1 µg/L; calibration curves were created for each set of analyzed samples and regression equations were fitted to the curves and then used to calculate concentrations for experimental samples. Standard reference materials and blank check samples were also analyzed after every 10 experimental samples for quality control.

Results were analyzed and the test statistic Q was calculated per the NSF 61 protocol (Table 2, calculation in S1 Appendix). Briefly, the natural log was taken (Equation 1) and the collected samples were averaged for each component (Equation 2). For each triplicate set of product examples, the mean

(Equation 3) and standard deviation (Equation 4) were calculated and along with k_1 (k_1=2.60281 for a sample size of 3), the Q test statistic was then calculated (Equation 5).

Table 2. Q Test Statistic Equations..

Equation 1	$ln\,(D_i) = Y_i$
Equation 2	$Y_i = \frac{(Y_{i3} + Y_{i4} + Y_{i5} + Y_{i10} + Y_{i11} + Y_{i12} + Y_{i17} + Y_{i18} + Y_{i19})}{9}$
Equation 3	$Log - dosage\ mean = \bar{Y} = \frac{\sum_{i=1}^{n} Y_i}{n}$
Equation 4	$Log - dosage\ standard\ deviation = S = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}{(n-1)}}$
Equation 5	$Test\ statistic\ Q = e^{\bar{Y}} \cdot e^{k_1 \cdot S}$
Equations are from the NSF 61 Manual [10].	

Background lead levels

Blanks spiked with sodium bicarbonate had a background WLL of approximately 0.5 µg/L in test water. A sample of deionized water used to create the synthetic test water, was analyzed using ICP-MS resulted in Pb concentrations <LOD, suggesting that the background lead could have been from the addition of the sodium bicarbonate. To account for this, a blank sample was taken every day from the finished synthetic test water in duplicate, and the resulting background lead concentration (varying from 0.2-0.7 µg/L) was subtracted from the resulting lead from each component. The water quality parameters for each daily batch are found in Table A in S2 Appendix.

Results

Elemental composition by XRF

The compositions of fittings tested by XRF (in triplicate) are presented in Table 3. Scans of the GS spouts revealed undetectable (<LOD) levels of Cd, Cu, and Ni, trace amounts (<0.1%) of Cr and Fe, 88% Zn, and 0.64% Pb. Scans for the three replicate spouts yielded some differences: two of the GS spouts had 0.86% Pb while the third had 0.20%. Scans of the brass taps revealed undetectable Fe, trace amounts of Cd and Cr, 0.77% Ni, high amounts of Cu (50%) and Zn (45%), and 1.3% Pb. The SS spouts had undetectable Cd and Pb, minor amounts of Cr (5.2%), Cu (6.3%), and Zn (1.5%), and high amounts of Fe (14%) and Ni (70%). The SS taps had undetectable Cd, trace amounts of Pb (0.01%) and Zn, minor amounts of Cu (0.27%) and Ni (3.5%), and high amounts of Cr (17%) and Fe (44%). The PVC pipes had undetectable Cd, Cr and Pb and trace amounts of Cu, Fe, Ni, and Zn.

Table 3. XRF results for Galvanized Spouts, Brass Taps, Stainless-steel Spouts and taps, and PVC Pipes.

1	Element	Cd	Cr	Cu	Fe	Ni	Pb	Zn
Galvanized Steel Spouts	Average Weight (%)	<LOD	0.02	<LOD	0.06	<LOD	0.64	88
	Standard Deviation	-	1.2x10^{-4}	-	6.7x10^{-4}	-	3.8x10^{-3}	7.7x10^{-3}
Brass Taps	Average Weight (%)	0.01	0.02	50.	<LOD	0.77	1.3	45.
	Standard Deviation	5.8x10^{-5}	5.8x10^{-5}	0.01	-	3.0x10^{-4}	8.5x10^{-4}	8.9x10^{-3}

Stainless-steel Spouts	Average Weight (%)	<LOD	5.2	6.3	14	70	<LOD	1.5
	Standard Deviation	-	$9.8x10^{-3}$	0.01	0.03	0.03	-	$2.7x10^{-3}$
Stainless-steel Taps	Average Weight (%)	<LOD	17	0.27	44	3.5	0.01	0.08
	Standard Deviation	-	0.03	$3.7x10^{-3}$	0.16	0.05	$7.1x10^{-5}$	$5.2x10^{-4}$
PVC Pipes (control)	Average Weight (%)	<LOD	<LOD	0.02	0.09	0.02	<LOD	0.08
	Standard Deviation	-	-	$1.5x10^{-4}$	$4.9x10^{-4}$	$7.1x10^{-5}$	-	$7.0x10^{-4}$

Water lead concentrations and Q test statistic values (per NSF 61 test protocol)

The first draw sample concentrations for each component are presented in Fig 1 and Table 4. Fig 1 shows the WLLs for all five components from each sampling day with 95% confidence interval error bars. Because the data for SS spouts, SS taps, and PVC controls are superimposed at values near 0 µg/L, and therefore nearly indistinguishable at the Y-axis scale needed to include data for GS spouts and brass taps, a separate, re-scaled graph of just the former three components is presented as S3 Fig for clarity. The 16-hour stagnation sample data, with the three replicates for each component, is provided in S4 Dataset. The resulting Q test statistics for tested components, along with descriptive statistics, are presented in Table 5.

Fig 1. Samples of first draw lead concentrations obtained for components tested according to NSF 61 protocols with 95% CI error bars.

Table 4. First draw Pb concentrations (µg/L) for components tested according to NSF 61 Protocols.

2Sample Day	3	4	5	10	11	12	17	18	19
Galvanized Spouts									
First draw Average	39	34	34	35	27	37	34	33	35
Std Dev	29	26	25	30	19	26	23	23	25
Brass Taps									
First draw Average	292	315	301	188	129	189	105	105	109
Std Dev	50	67	47	23	5	18	9	8	9
Stainless-steel Spouts									
First draw Average	0.2	0.1	0.4	<0.1	<0.1	0.1	<0.1	<0.1	<0.1
Std Dev	0.1	<0.1	0.2	0	0	0.1	0	0	0
Stainless-steel Taps									
First draw Average	0.4	0.3	0.5	0.6	0.3	0.2	0.2	<0.1	0.3
Std Dev	0.2	0.3	0.3	0.6	0.2	0.2	0.2	0	0.3
PVC Pipes									
First draw Average	<0.1	0.1	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	1.0
Std Dev	0	<0.1	<0.1	0	0	0	0	0	1.5

Table 5. Descriptive Statistics of WLLs (µg/L) for components tested according to NSF 61 protocols.

3Water System Component	Galvanized Spouts	Brass Taps	Stainless-steel Spouts	Stainless-steel Taps	PVC pipes
Minimum	27	105	<0.1	<0.1	<0.1
Maximum	39	315	0.4	0.6	1.0
Average	34	192	0.1	0.3	0.2
Geometric Mean	34	175	0.1	0.3	0.1
Standard Deviation	3	89	0.1	0.1	0.3
Test Statistic Q	577	225	0.2	0.9	0.2

Lead concentrations for tested SS parts did not exceed 1.2 µg/L in any sample or test. Brass taps produced the highest first draw aqueous lead concentrations, which declined from a maximum of 315 µg/L on Day 4 to a minimum of 105 µg/L on Days 17 and 18. The first draw concentrations of lead leached from GS spouts remained roughly consistent during the 3-week test period, with a maximum of 39 μg/L on Day 3 and a minimum of 27 μg/L on Day 11. The discontinuous reduction in lead concentrations on Day 11 was observed for both GS spouts and brass taps. The SS spouts, SS taps, and PVC control produced negligible lead leaching in comparison to the former two parts.

Discussion

The SS spouts, SS taps, and control PVC pipes conformed with both lead composition (NSF 372) and lead leaching (NSF 61) standards. India Mark II handpump GS spouts, as well as brass taps (of a type commonly used for standpipes and other piped water supply systems in many LMIC settings) failed to meet both composition and leaching standards. It is notable that one replicate of the GS spouts had a much lower lead content than the other two examples tested; this spout's lower lead content could be a function of varying lead concentrations in the zinc bath used during manufacture of the components in one or more different facilities, batches, and/or manufacturers. The resulting WLLs for the spout with lower measured lead content were also an order of magnitude lower than the other two spouts, indicating that lower surface lead content corresponded to much lower WLLs.

The SS spouts, SS taps, and PVC pipes leached low concentrations of lead (all <1.2 μg/L), which was expected due to the low levels of lead reported in XRF scans for these components and materials. The levels of lead quantified in leaching tests were in fact low enough that some or all of the measured lead could possibly have been introduced in the sodium bicarbonate used to prepare the synthetic NSF 61 test water. Since this reagent was certified to have lead concentrations < 5 ppm (although previous laboratory testing for determining background Pb levels suggests that reagent-grade sodium bicarbonate typically has lead levels far below the upper limit certified by the manufacturer) and was used at concentrations as high as 1:1000 in NSF 61 test water. By contrast, the GS handpump spouts and brass taps had compositions exceeding allowable lead levels under international composition standards such as NSF 372, and leached lead at levels exceeding those permissible according to lead leaching standards such as NSF 61. For both the GS spouts and brass taps, all averaged first draw samples over the nine sample collection days had WLLs above the WHO guideline value of 10 µg/L. The stagnation of the corrosive water increases the contact time with the lead-containing materials, increasing the potential to leach lead into the water. Flushing the water before use can theoretically reduce WLLs, though the results from this work did not indicate a reduction of lead leaching to levels that could be reasonably considered to approach background concentrations of lead in drinking water in the absence of leaded plumbing components. For example, the American Academy of Pediatrics recommends that drinking water supplies for children in schools and daycares not exceed lead concentrations of 1 µg/L [18], a threshold exceeded by samples in contact with brass taps and galvanized spouts in all samples. The long-term leaching behavior of understudied components such as those used in this work may merit additional study with variation in stagnation time, water chemistry, and frequency of flushing.

The test statistic, Q, was calculated according to the NSF 61 standard protocol to determine which water system components met certification standards of $Q \leq 1$ µg/L. The SS spouts, SS taps, and PVC control met this value having Q statistics of 0.2, 0.9, and 0.2 µg/L, respectively. The brass taps had a Q test statistic of 225 µg/L and the GS handpump spouts had a Q test statistic of 577 µg/L. According to the Q test statistic, these results indicate that with 90% confidence, 225 µg/L should be the highest amount of lead leached from 75% of leaded brass taps produced and 577 µg/L is the highest amount of lead leached from 75% of GS handpump spouts produced on a first draw basis. In both cases, these values indicate the potential of these components to leach lead at levels of concern. If an estimated four million India Mark II galvanized hand spouts are in use worldwide [15] and are in contact with water that is as aggressive as the test water used in this study, the Q test statistic findings in this study imply that as many as 1 million of those systems may leach lead from GS spouts at first draw levels greater than 577 µg/L around the time of their initial installation and commissioning, and may continue to leach lead over the course of their design life. Furthermore, India Mark II handpumps may contain other GS steel and brass parts capable of leaching lead at levels of concern, a possibility that would be consistent with the findings of high lead leaching in field water samples from India Mark II handpumps in three West African countries: Ghana, Mali, and Niger [6]. It should also be noted that, since the Q test statistic calculation exponentiates the standard deviation, a large variation in triplicate samples increases the standard deviation, potentially inflating the results, especially for the galvanized spouts in this study.

In the absence of health-based guidance on lead in plumbing materials and for drinking water supply, operational definitions such as those embedded in the NSF standards can provide useful benchmarks for assessing the safety of plumbing materials and components. However, the process of evaluating materials with respect to such standards can be cumbersome, may require costly instrumentation and substantive laboratory capacity, and produces results that are only actionable in the context of clear and enforceable national policies.

As a result, lead content and leaching behavior is not routinely assessed for a variety of water system components that are primarily manufactured for and used in LMIC settings. These “understudied” components may include handpump parts and faucets manufactured or imported and installed in LMIC settings. Worldwide, an estimated 0.6-1 billion persons in LMICs use water from an India Mark II handpump [15]. An estimated 300 million (or 55% of urban population in Sub-Saharan Africa without piped water) rely on standpipes with taps as their primary water source [19,20]. Anecdotal evidence suggests many such taps in LMIC water systems are made from brass. The findings from this study evaluating lead content and leaching from these understudied parts could have profound implications for water safety in LMICs.

Taken together and in the context of prior literature, our experimental findings provide compelling evidence that leaded brass taps and GS fittings of the type studied in this work, which fail to meet both the NSF 61 and NSF 372 standards, are unsuitable for drinking water supply systems, and may leach unsafe levels of lead into drinking water. A previous study [6] found that 72% of drinking water system brass components tested in three West African countries exceeded the NSF 372 limit of 0.25% wt/wt. Drinking water systems with one or more brass components produced water samples with 3.8 times the measured lead concentration of samples from systems with no brass components. Findings from that previous study and this study strengthen the case that leaded brass and GS components that fail to conform to NSF 372 and/or NSF 61 standards should not generally be installed in new drinking water systems, particularly new systems without corrosion control, and lead-free alternatives such as non-leaded SS components should be sourced instead wherever possible. The use of lead-leaching components in new rural water supply systems in LMICs unnecessarily exposes water system users to levels of lead harmful to their health. Corrosion control could be implemented for existing or new systems which contain leaded components, though there is a lack of feasibility due to the requirements of constant chemical dosage for consistent water chemistry which may be logistically difficult due to the added costs and transport into these rural areas.

Consistent with World Health Organization guidelines [21], nothing reported in this study should in any way be necessarily used to justify closing or decommissioning existing drinking water systems with leaded brass or stainless steel components in rural LMIC settings, since the harms of reducing or impeding access to drinking water that is safely managed with respect to fecal contamination and other microbial hazards can be extreme [22]. Rather, the results of this work provide further evidence for the importance of ensuring that non-leaded ("lead-free") components and materials are used in the construction of new drinking water systems. In many cases, action to strengthen regulatory frameworks and/or protect supply chains may be helpful in achieving this objective.

This study has several limitations. To meet the NSF 61 Section 9 synthetic test water alkalinity parameters, sodium bicarbonate (MCB Reagents, Cincinnati, Ohio) was used which likely contained heavy metals, including lead stating "Heavy Metals (as Pb) – 5 ppm". A limited sample size was used which skewed the results significantly with the galvanized spouts since one out of the three had a quarter of the lead content than the other two. The potential error could be reduced if a larger sample size of components were tested from different batches, or if greater homogeneity in the composition of replicate components was confirmed prior to testing. Furthermore, while NSF 61 can provide a useful preliminary assessment of water system components, it may not be the most representative measure of what is occurring in the field. Variability of product manufacturing can skew results, while inevitable variability in water chemistry, water temperature, exposure times, and installation conditions (including variation in the extent to which brass components are heated and thus modified with respect to lead lability and mobilization) will inevitably produce variations unlikely to be captured in a standard laboratory test protocol.

The strengths of this study included being able to test alternatives of commonly used water system components in a controlled environment using replicable conditions following the NSF 61 protocol. By following these protocols, it helps provide a baseline for whether the tested products would be safe to be used in rural water systems. Though useful for preliminary compliance results, the study highlighted how NSF 61 may need to be used in junction with another standard or experimental test since variability in components' material composition exacerbates the uncertainty of lead release.

Future work may seek to quantify the added lead exposure attributable to such unsuitable water system components at a population level. Biokinetic modeling could be applied using more accurate groundwater quality parameters and lead leaching data to address these questions and begin to assess the associated preventable burden of disease. Future studies will test additional scenarios with varying combinations of test water, component type (of material, supplier, and models), heat pretreatment (if any), and sample collection frequency/schedule to address some of the above limitations. Nonetheless, these limitations do not contribute sufficient uncertainty to the results of our study to prevent us from making strong recommendations that leaded brass and galvanized steel components failing to conform to NSF 372 and/or 61 standards should be avoided in the construction of new drinking water systems. In LMIC settings, where routine end-user testing of components with respect to lead leaching may be challenging, the use of components that are certified by an independent 3rd party as conforming to NSF 372 or a similar composition standard may be a useful first step for many implementers towards eliminating leaded products from their drinking water infrastructure supply chains. Further verification of composition for a random subset of imported components (e.g., XRF screening at ports of entry) may be a relevant additional measure for implementers where such screening is feasible, cost-effective, and aligns with implementer priorities and regulations. In all cases, however, standards without robust monitoring and enforcement mechanisms are unlikely to be impactful, and in these cases WHO guidance on policy options to prevent lead in drinking water may prove valuable to implementers and policymakers seeking to advance progress in this area [21]. Where unsuitable materials and components such as the leaded brass and galvanized steel parts in our study continue to contaminate drinking water infrastructure supply chains, our study provides compelling evidence that these parts and materials may continue to leach lead into potable water at levels that pose a public health threat.

Lead-containing components can go undetected in the rural water system supply chain. These components are sometimes sold as “lead-free”. Implementers source these parts and install them without realizing they contain lead and have the potential to leach high levels of lead. Implementers should shift away from procuring or using leaded brass taps and leaded galvanized components that fail to meet NSF 61 and 372 in drinking water systems. Results from this study and future studies can help inform policy recommendations in countries where such lead-containing water system components are being installed, to better prevent their sale and use in drinking water systems. Governments could broadly adopt NSF 372, which has the maximum weighted average lead content requirement of 0.25%. The handpump spouts and leaded brass taps were both over this lead content and expectedly leached WLLs higher than the WHO guideline values.

Conclusion

Leaded brass taps and galvanized handpump spouts procured from Ghana, and indicative of the types of components routinely found in tap stands and handpumps serving rural communities in LMIC settings failed to meet the NSF 372 and NSF 61 standards for use in drinking water systems. These components leached lead into simulated test water at levels of health concern in all tests, and at levels far exceeding the WHO guideline value on a first draw basis. Alternative products, such as stainless-steel spouts and taps conforming to NSF 372 and NSF 61 standards, offer safer alternatives and should be preferentially sourced and installed for drinking water applications, particularly those without corrosion control.

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S1 Appendix. Calculation of the Q Test Statistic.

S2 Appendix. Synthetic Water Quality Parameter Data.

S3 Figure. First draw lead concentration leaching from stainless-steel and PVC components.

S4 Dataset. Samples Data and Q Test Statistic Calculation.

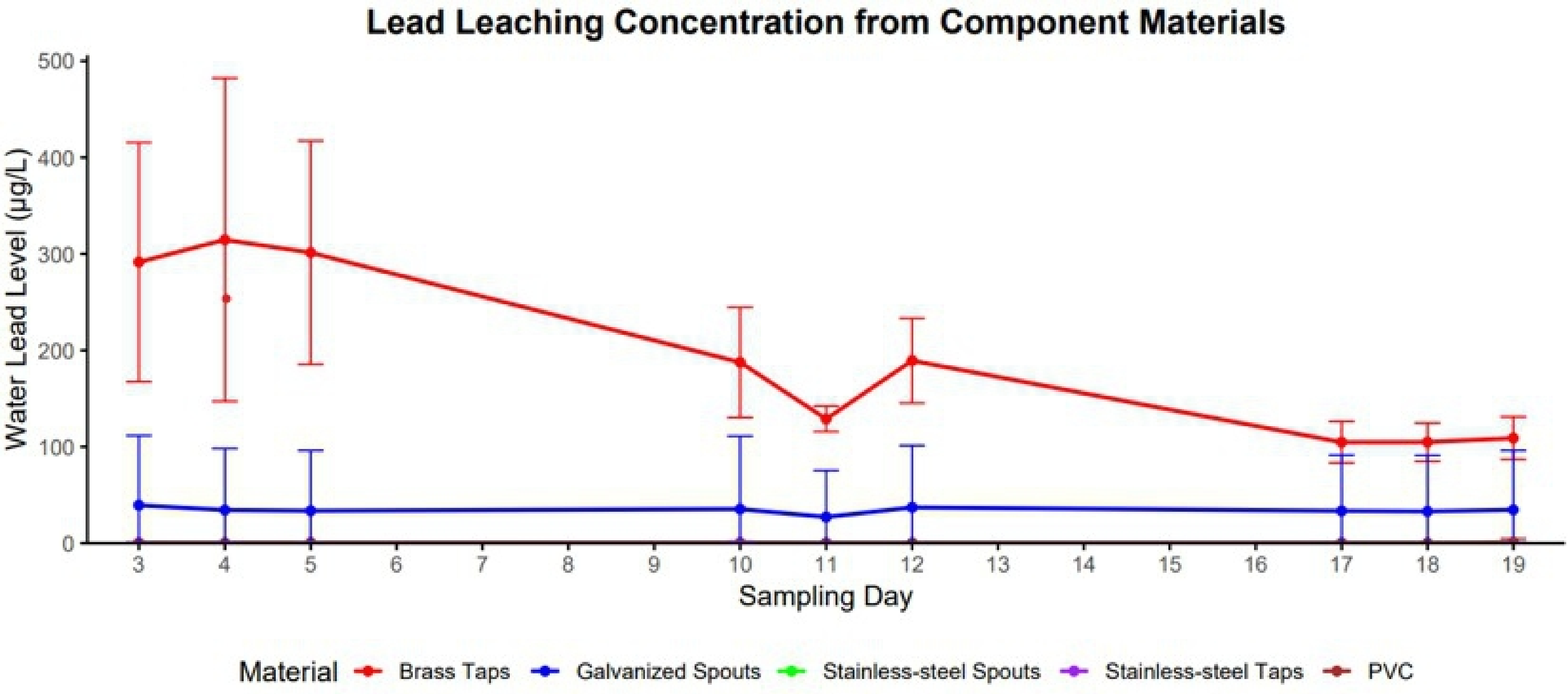
Lead Leaching Concentration from Component Materials
500
400
300
200
100
0
Water Lead Level (µg/L)
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Sampling Day
Material
Brass Taps
Galvanized Spouts
Stainless-steel Spouts
Stainless-steel Taps
PVC

Fig 1