Accuracy of a Commercial Lead Test Kit

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Abstract

Background
Up until 1960s, lead was widely used for constructing plumbing systems, and a residual amount of lead is still detected within water systems today. Due to the wide availability, low-cost, and ability to produce an instant result, commercial lead test kits have been known for their convenience. However, considering that small lead exposures can pose serious health concerns to those who are vulnerable, inaccurate results may cause a potential health hazard. This study investigated the accuracy of a commercial lead test kit called "10-in-1 Drinking Water Test Kit" by Baldwin Meadows and compare its findings to instrumental analysis.

Methods
Concentration of standard lead solutions with known concentrations of blank, 10 ppb, and 30 ppb were measured using ICP-MS and Baldwin Meadows lead test kit. Then, statistical analysis was used to determine if there was a significant difference between the two analytical methods. In addition, the obtained data was compared to Health Canada's and U.S. EPA's maximum allowable concentration (MAC) for lead to determine if the two methods are capable of detecting safe level of lead in drinking water.

Results
The concentration of lead measured with ICP-MS was slightly greater than the target values with 8.69% error. The colorimetric analysis from Baldwin Meadows lead test kit did not show any color change at 10 ppb and measured a mean value of approximately 1 ppb at the 30 ppb level resulting in 96.72% error. The statistical analysis indicated that there is a significant difference between the lead concentration measured with Baldwin test kit and ICP-MS.

Conclusion
The findings of this study suggest that Baldwin Meadows commercial lead test kit failed to detect lead greater than both Canada's and U.S. EPA's MAC. Therefore, it is concluded that it is not capable of measuring the safe level of lead in drinking water. Although this study does not represent all commercial DIY lead test kits available on the market, it implies that lead test kits may present false negative results and cause accidental consumption of lead contaminated water.

Keywords: *lead, drinking water, maximum allowable concentration (MAC), commercial lead test kit, Baldwin Meadows lead test kit, ICP-MS,*

Introduction

Lead is one of the most common heavy metal found in the earth's crust, mainly used to produce lead acid batteries, solder, alloys, rust inhibitors, and plastic stabilizers (WHO, 2011). Up until 1960s, due to its properties of corrosion resistance, malleability, and low cost, it was widely used for constructing plumbing systems (Flegg, n.d.). It was only 1975 when the health effects of lead were recognized and led to the revision of the National Plumbing Code of Canada to ban using lead-containing materials for new pipes (Flegg, n.d.). However, despite the effort of replacing lead-containing old service lines with newer materials, the residual amount of lead is still detected from the distribution line as of today (Alberta Health, 2013).

Due to the wide availability, low-cost, and ability to produce an instant result, commercial lead test kits have been known for their convenience. Lead test kits are particularly useful to consumers in rural areas where the water service lines are not maintained by municipalities, thereby they may be more vulnerable to lead contamination of drinking water (Delpla *et al.,* 2015). The question that remains to be asked is how accurate and reliable the lead test kits are in terms of determining the safe level of lead in drinking water.

Literature Review

Health Effects

According to Schedule 1 of the Canadian Environmental Protection Act, lead is categorized as a toxic substance that bioaccumulates in the human body (Department of Justice, 2020). Upon exposure to lead, red blood cells act as vehicles that transport lead to soft tissues of the brain, liver, kidneys, and bones (WHO, 2011). Younger populations are the ones more susceptible to lead exposure because the same amount of lead exposure takes a more significant proportion of their body mass compared to adults (WHO, 2011). Also, the biological half-life of lead is known to be considerably longer in children than adults; therefore, the condition of chronic exposure to lead can lead to a steady distribution of lead to various organs over a long period of time (WHO, 2011).

While lead can affect various organs, it is also a well-recognized developmental neurotoxicant. Research on young primates found that lead exposure poses significant damage to the central nervous system, resulting in behavioural and cognitive deficits (WHO, 2011). In addition to the research done on primates, another finding which investigated the correlation between lead ingestion from drinking water and mental retardation of children discovered a directly proportional relationship between blood lead concentration and neurological damage (Lead and Mental Retardation, 1975). The study was done with 154 children between the ages of two and five who were attending clinics in Glasgow. The first group was attending the clinic due to retardation of mental development, and the other group was attending for other health concerns that are unrelated to mental retardation. The author reported that the amount of lead in blood as well as the amount of lead in drinking water of group with mental impairment was significantly higher than the control group.

In addition to the lead susceptibility of younger populations, another vulnerable group is pregnant women because lead is capable of crossing the placental membrane to the fetus. Carpenter (1974) claimed that lead is able to pass through the placental membrane rapidly and in significant amounts even at low maternal blood levels. Therefore, even a small exposure to lead during pregnancy can harm the prenatal neurological development of infants.

Previous Exposures

There has been an ongoing debate on whether Canada's drinking water is safe from lead exposure. For example, a study conducted by a previous BCIT student investigated the risk of lead exposure in childcare facilities in Metro Vancouver (Quach 2017). The result indicated that almost all the investigated facilities had much lower lead concentration than Health Canada's maximum allowable concentration (MAC) of 0.005 mg/L (Health Canada, 2019). He also noted that the lead level could easily be controlled by removing the stagnated water with pre-flushing.

However, despite the simple control measure as 'pre-flushing' can reduce the lead concentration in drinking water, two news media reported that over 640 Ontario schools and over 120 BC schools failed to meet the provincial standards of lead in drinking water between 2016 to 2017, and 2016 to 2018 respectively (Cruickshank *et al.*, 2018; Poisson *et al.*, 2017). The data showed that proportions of the investigated schools were found to have 100 to 300 times higher concentration of lead than the provincial standards. The reporter also underlined that only 5 percent of all the facilities during the Ontario investigation have submitted the lead tests and emphasized the significance in monitoring practices to screen possible elevation of lead in drinking water.

BC Legislation and Guideline

The British Columbia *Drinking Water Protection Act* outlines the requirements and responsibilities for water suppliers to comply with and explains the authority of drinking water officers to exercise their powers. Although the *Act* does not mention the need of routine lead tests for water suppliers, it indirectly addresses the responsibility of water suppliers to conduct lead tests in their drinking water sources. As per Section 4 of the *Act,* drinking water officers must follow directives and exercise their power in accordance with guidelines established by the Ministry of Health (Drinking Water Protection Act, 2001). Likewise, under Section 8 of the Drinking Water Protection Regulation (2003), a water supplier must provide a potable water source to users with respect to the procedures established by a drinking water officer. Therefore, it is ultimately a water supplier's responsibility to monitor the elevation of lead in drinking water in accordance with directives provided by health officers.

Both Health Canada's Guidelines for Canadian Drinking Water Quality and above BC guideline established by the Minister state that lead tests must be conducted in a laboratory capable of using analytical methods to measure lead (Health Canada, 2019; Drinking Water Protection Act, 2001). Health Canada (2020b) indicates that the maximum allowable concentration (MAC) of lead is 0.005 mg/L. However, since there is no safe level of lead exposure that is known to be without harmful effects (WHO, 2011), Health Canada (2020a) recommended to be kept as low as reasonably achievable.

For cases of individual residences, there is no enforceable legislation that requires lead in drinking water to be tested (Health Protection Branch, 2019). Therefore, it is solely homeowners' responsibility to test the lead concentration. Although the BC Building code now bans usage of lead-containing materials to be used for construction, buildings that are built prior to the revision of the 1989 BC Building Code still possess the potential of lead exposure in drinking water service lines (Alberta Health, 2013). Furthermore, Barn *et al.* (2013) stated that the lead leaching may significantly vary by water use patterns, water chemistry, and plumbing characteristics. Hence, a systematic monitor of lead concentration at the water supplier's tap does not guarantee the safe level at supplied residences. To accurately represent lead exposure of a given population, lead should be tested at both residential and non-residential water sources (Health Protection Branch, 2019).

Lead Exposure in Rural Areas

Followed by the recognition of health effects associated with lead in drinking water, the Canadian National Plumbing Code eliminated the usage of lead-containing materials for new water service lines

(Health Canada, 2016). With municipalities' efforts to replace the existing lead service lines and continuous actions to control corrosion, test water quality, and implement mitigation strategies led to a gradual decrease in lead intake for Canadians (Health Canada, 2020a). According to the Canadian Health Measures Survey (2020) that conducted biomonitoring of major toxic substances to humans, lead exposure for Canadians has decreased by 80% over the past 40 years.

However, even though the accumulated lead exposures in average Canadians have gradually decreased over time, not all Canadians are reflected in the above survey. An investigation conducted by Delpla *et al.* (2015) found that the risk of lead in drinking water was higher in rural municipalities as a result of a deprived socioeconomic status. The study examined 593 rural municipalities in Quebec and compared the lead exposure level to wealthier municipalities. While deprived municipalities often used groundwater as their potable water sources, most of their water sources did not have any treatment system in place or only had the basic treatment system which solely relies on chlorination. The author pointed out that the probable causes of poor water quality of existing water treatment plants in the deprived municipalities were due to lacked financial, technical, and management support as a result of insufficient economic status. In addition to Delpa *et al.*'s investigation, another study explored conditions of drinking water infrastructure in U.S. (Vanderslice, 2011). The study observed that lead service lines were more common in older communities which were often categorized as low income and minority.

As noted above, routine lead tests are significant to screen for possible elevation of lead level in drinking water systems. To minimize the lead consumption in drinking water, the public must be able to identify the exposure and implement mitigation strategies. However, considering the circumstances in rural areas where the access to laboratories is limited and time-consuming, widely available low-cost lead test kits that give instant result are generally preferred.

Previous Studies on Lead Test Kits

With the ongoing debates on whether consumer lead test kits provide an accurate and reliable result, a study (Schock & George, 1993) evaluated colorimetric commercial test kit called "Lead-Trak" by Hach Chemical Co for accuracy and chemical interferences by comparing its result to graphite flame atomic absorption spectroscopy (GFAAS). GFAAS is a laboratory instrument that is capable of detecting concentration of various heavy metals in water samples. While the study showed that the test kit provided a relatively higher detection limit of 4 μg/L compared to GFAAS's detection limit of 0.2 μg/L, both results were within 99% confidence level, indicating very good statistical agreement between the two analyses (Schock & George, 1993). Moreover, the study's examination of chemical interferences concluded that varying concentration of Zn, Fe(II), polyphosphate, and orthophosphate showed significant bias (up to ±10%) of lead concentration, and presence of Cl^-, and Al(II) in the water sample may contribute to a reduction in the precision of the test kit (Schock & George, 1993).

Another study (Cartier *et al.,* 2012) examined the performance of a portable lead testing instrument called Anodic Stripping Voltammetry (ASV), a device often used for estimation of lead during onsite field inspections. The experiment showed comparable results with inductively coupled plasma mass spectrometry (ICP-MS), a standard laboratory technology used to measure lead concentration, between the range of 2 – 50 ppb. While ICP-MS offers a significantly low detection limit down to parts per trillion, it requires sample preparation step which includes chemical digestion and sensitive optimization of the instrument. Thus, ICP-MS requires the analysis to be conducted in a laboratory setting by fully trained personnel. By having to detect lead concentration without proper chemical digestion and instrumental analysis, the portable ASV suits the purpose of onsite field inspections where only rough estimation is sufficient. Nonetheless, despite the advantages of portable ASV lead analyzers, it is not appropriate for the purpose of measuring lead in residential settings. The author noted that due to ASV's capability of detecting a trace level of heavy metals, it requires very careful management and calibration of the device which still requires users to be fully trained. More importantly, portable ASV lead analyzers are primarily made for field operators who practice building technology. Hence, the device can be very costly compared to other commercial test kits.

Currently, there are limited numbers of literatures that address on the accuracy of consumer lead test kits. In order to accurately measure lead exposure in drinking water, an investigation of the accuracy of lead test kits is necessary.

Research Question

The purpose of this research is to measure the accuracy of a commercial lead test kit called "10-in-1 Drinking Water Test Kit" by Baldwin Meadows (Baldwin Meadows, n.d.). As mentioned above, lead test kits are particularly more useful and practical to those in rural settings who suffer from socioeconomic inequalities and limited laboratory resources. Considering that small lead exposures can pose serious health concerns to those who are vulnerable, inaccurate results which may produce false negatives may cause a potential public health disadvantage. Successful identification of accurate lead test kits would allow health officers to either recommend or discourage using the test kits. If lead test kits turn out to be inaccurate to a significant degree, there should be policies and legislations enforcing manufacturers to put warning labels mentioning the inaccuracy of the product as well as the user liability.

Materials and Methods

Materials Used

The commercial lead test kit used in this experiment is called "10-in-1 Drinking Water Test Kit" by Baldwin Meadows, purchased from Amazon.ca (Baldwin Meadows, n.d.). Baldwin Meadow test kit comes in a form of a strip that performs colorimetric analysis of multiple chemical parameters including lead. The strip changes its color in the presence of a substance in question, where the intensity of color change is based on the concentration of the substance. Then, the changed color is compared with the color chart provided by the manufacturer to find the concentration of the substance.

While the majority of consumer lead test kits provide qualitative test results based on U.S. EPA's drinking water maximum allowable concentration (MAC) of 15ppb, Baldwin Meadows test kit advertises to provide quantitative result between 0 to 50 ppb, more specifically at 0, 5, 15, 30, 50 ppb (U.S. EPA, n.d.). Therefore, the quantitative results can be interpreted based on both Health Canada's MAC of 5 ppb and

U.S. EPA's MAC (Health Canada, 2020b; U.S. EPA, n.d.).

In addition to the test kit used, inductive coupled plasma mass spectrometry (ICP-MS), was used to verify the lead concentration of standard solutions. ICP-MS is a standard laboratory technology used to measure lead in drinking water which provides a detection limit down to 0.01 to 0.1 parts per trillion (Thermo Elemental, n.d.). The instrument model used for this experiment was Agilent 8900 ICP-MS/MS.

Reagents

Calibration and sample standards used in this experiment was provided by a manufacturer, Fisher Chemical, with lead reference of SL21-500 (Fisher Chemical, n.d.). This included calibration standards of blank, 0.5 ppb, 1.0 ppb, 10 ppb, 50 ppb, and 100 ppb, and three sample standards of 10 ppb, and 30 ppb.

Instrumental and Commercial Lead Test Kit Analysis

The instrumental analysis which included preparation of calibration and sample standards, calibration of ICP-MS, and sample standard analysis was conducted in BCIT's chemistry lab at SW-3, room 4635 by Dr. Hsin Kuo.

The sample standard solution analysis using Baldwin Meadows lead test kit was conducted outside of chemistry laboratory. Total of 195 Baldwin Meadows lead test kits were analyzed and the colorimetric assessment was done visually under a white background.

Inclusion and Exclusion Criteria

Baldwin Meadows lead test kit provides shelf life of two years. Therefore, the experiment was conducted before the proposed expiry date of Baldwin Meadows test kits. Since lead test kit is sensitive to moisture, purchased products were checked to ensure that the caps were tightly sealed, and containers were properly packaged and contained desiccators. When conducting the experiment, colored test areas of reagent strips were kept away from touch and any sources of moisture.

Results

Descriptive Statistics

In this experiment, numerical data was collected on a continuous and ratio scale (Heacock, H., personal communication [One-Sample, Two-Sample, Paired T-Tests], 2020). Then, the collected data from each standard test was used to calculate descriptive statistics as shown in Table 1.

Table 1. Summary of descriptive statistics of ICP-MS and Baldwin Meadows test kit measured in 10 ppb and 30 ppb of lead standard solutions.

Target Conc.	Variable	Count	Mean	Median	S.D.	Max.
10 ppb	ICP-MS	2	10.935	10.935	0.0737	10.987
	Baldwin Meadows Test Kit	65	0.000	0.000	0.0000	0.000
30 ppb	ICP-MS	2	32.606	32.606	0.4432	32.920
	Baldwin Meadows Test Kit	65	0.985	0.000	1.9324	1.463

The concentration of lead in standard solutions were measured to be slightly greater than the target value when analyzed using ICP-MS for both 10 ppb and 30 ppb of standard solutions. Nonetheless, the colorimetric analysis from Baldwin Meadows lead test kit did not show any color change at 10 ppb, therefore was indicated as zero lead concentration, and mean value of approximately 1 ppb was measured at 30 ppb.

Figure 3. illustrates a visual representation of accuracy of Baldwin Meadows test kit compared to ICP-MS. At 30 ppb, while the mean value obtained

from ICP-MS resulted in 8.69% error, the mean value from the test kit resulted in 96.72% error.

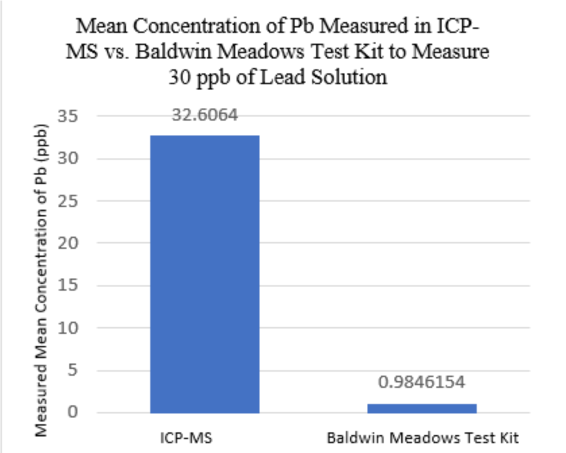

Figure 1. Obtained mean concentration of Pb measured with ICP-MS vs. Baldwin Meadows Test Kit to measure 30 ppb of lead solution.

Inferential Statistics

NCSS, a statistical software package, was used to analyze the obtained dataset (NCSS 2021 Statistical Software, 2021). Two-sample t-test was used in this experiment to determine the significance of the mean difference between the two-independent analysis of ICP-MS and Baldwin test kit. Note that for both standards of 10 ppb and 30 ppb, two-tailed test was conducted.

The summary of inferential statistics is shown in the table below.

Table 2. Summary of inferential statistics

H_0 and H_A	Lead standard	Test used	Result	Conclusion (alpha or beta error, if relevant), power
H_o: there is no statistically significance difference between concentrations of lead measured with Baldwin Meadows lead test kit and concentrations of lead measured with ICP-MS.	10 ppb	Two-sample t-test	P = 0.00303	Reject null hypothesis and conclude that the lead test kit measures statistically significantly different level of lead at the standard concentration of 10 ppb. Power (α = 0.01) = 99.903%, suggesting very low chance of having type II (beta) error and there truly is a difference between the lead concentration measured with the test kit and ICP-MS. As p-value is very low (<0.01) it is very unlikely for type I (alpha) error to occur.
H_A: there is a statistically significant difference between concentrations of lead measured with Baldwin Meadows lead test kit and concentrations of lead measured with ICP-MS.	30 ppb	Two-sample t-test	P = 0.00130	Reject null hypothesis and conclude that the lead test kit measures statistically significantly different level of lead at the standard concentration of 10 ppb. Power (α = 0.01) = 100%, suggesting no type II (beta) error and there truly is a difference between the lead concentration measured with the test kit and ICP-MS. As p-value is very low (<0.01) it is very unlikely for type I (alpha) error to occur.

Discussion

According to the descriptive statistics, the overall mean concentration of lead obtained by Baldwin Meadows commercial lead test kit was found to be significantly lower than ICP-MS measurement. As shown in Table 1, despite the manufacturer's specification claiming the detection limit of lead from 10 to 50 ppb, the test kit did not detect any level of lead at 10 ppb of standard solution and very small amount of lead was measured (mean = 0.98 ppb) at 30 ppb, demonstrating 100 percent of false negative result. Although the colorimetric analysis might contain some level of bias as the quantification of color change relied heavily on subjective observation, the observer bias itself is not sufficient to explain such a substantial degree of error.

Similarly, the data analyzed by inferential statistics suggested the same implication. The p-values obtained from both parameters of 10 and 30 ppb were analyzed to be 0.00303 and 0.00130, respectively. The low p-values indicate that the chance of the null hypothesis being true, as well as likelihood of alpha error, are low. As shown in Table 2, inferential statistics described that the null hypothesis was rejected and concluded that the lead concentration measured with the test kit and ICP-MS showed a significant difference. Also, powers of both parameters were analyzed to be very high, indicating a very low likelihood of statistical analysis representing a false positive result.

The result from this study not only disagreed with the manufacture's specification, but also contradicted Schock *et al.* (1993). Despite the precision of the test kit examined by Schock *et al.* varied with concentration, the test kit still showed comparable results to GFAAS analysis with an average precision of ±3 μg/L throughout the parameters of 10 to 100 μg/L (Schock & George, 1993). Moreover, the study showed that colorimetric analysis of lead is subject to chemical interference in a presence of certain chemical compounds such as zinc, iron (II), phosphate and orthophosphate species, chlorine, and aluminum (III). However, considering that the lead standard solutions to examine Baldwin Meadows test kit were made with ICP-MS standard, the likelihood of samples containing contaminants that interferes with the analysis was very low. While GFAAS only provides a detection limit of 0.2 μg/L (ppb) to measure the concentration of lead in water, ICP-MS is a more advanced technology that is capable of measuring lead concentration down to 0.01 to 0.1 ng/L (ppt) which has a detection limit of 2,000 to 20,000 times better than GFAAS (Schock *et al.*, 1993; Thermo Elemental, n.d.). Due to the lower detection limit and highly sensitive nature of ICP-MS, to minimize background elements and other potential contamination, ICP-MS standard solution is prepared using ultrapure-deionized water and ultrapure nitric acid whereas GFAAS uses deionized water and regular grade nitric acid. Hence, the likelihood of ICP-MS solutions containing chemical interferences is very low.

Since chemical compositions responsible for the colorimetric analysis for both test kits were unknown, it is difficult to say that the chemical interferences from Schock *et al.* directly relate to interferences of Baldwin Meadows lead test kit. Nonetheless, the proposed chemical interferences in Schock *et al.* (1993) do exist in the environment and may present in a drinking water system. Thus, in order for commercial lead test kits to effectively measure the presence of lead in water, they must have a sufficiently high level of accuracy to neglect the potential interferences.

Although this study did not examine possible sources of error that are responsible for false negative result of Baldwin Meadow test kit, as per Gutknecht et al (2008) which investigated limitations of quantitative lead test kits used for lead paints, the strength of lead extraction reagent may be a factor that hinders the test kit from resulting in color reaction. If extraction reagents used for the kit are too weak, the test kit would not have a sufficient capability to draw lead out of a lead solution, making colorimetric reagents unable to react with lead especially at concentration as low as ppb level.

Limitations

The initial project design was to determine the accuracy of various brands of commercial lead test kits. However, due to a budget constraint, only one type of lead test kit was analyzed. Baldwin Meadows lead test kit was chosen over other types of kits because it contained larger quantities of test strips and was relatively inexpensive. Therefore, Baldwin Meadows test kit only represents lower grade of lead test kits and does not reflect the accuracy of all available commercial test kits.

One factor that may have affected the result is the method of colorimetric measurement. As noted above, the change in color intensity of the test kit was determined by visual observation followed by a comparison to a color chart provided by the manufacturer. If more budget were allowed, the change in color intensity would have measured using a colorimetric instrument such as a spectrophotometer that can read the intensity of light and translate it in a measurable unit. Although this would not produce drastic changes in the result, it would allow to quantify the magnitude of the test kit’s measurement to a higher degree.

Another consideration that may have improved the reliability of the study is a lot number. All the lead test kits were purchased at around the same time and had the same lot number. Products with the same lot number are made in the same manufacturing process in a certain time period. This implies that if any errors were made during a manufacturing process, all the products with the same lot number would likely have the same error. To increase the reliability of the study, for the purpose of a future study, it is recommended to use products with different manufactured numbers.

Knowledge Transition

The result from this study indicates that Baldwin Meadows lead test kit does not provide a sufficient level of accuracy to measure the safe level of lead in drinking water. However, since this study only examined one type of commercial lead test kit, it does not provide sufficient scientific evidence for health authorities and other regulatory agencies to ban using commercial lead test kits. Nonetheless, environmental health officers should inform the findings to the public and provide recommendations on better ways to detect lead in drinking water, especially for those who are more exposed to lead in drinking water such as private water system users.

While the accuracy of the overall commercial lead test kits still remains to be inconclusive, this study can serve as reference material for agencies such as BCCDC and Health Canada to conduct more detailed research. Once future studies provide strong scientific evidence on the accuracy of commercial lead test kits, the findings must be translated to regulatory frameworks such as legislations, guidelines, and policies to prohibit the use, require approval for sale, or enforce labeling requirements that mention user liability, and detailed specifications of a product including accuracy and precision.

Future Research

Some potential areas of study to fill in knowledge gaps of this study include:

- Analysis of various brands of commercial lead test kits.
- Comparison of accuracy and precision between qualitative and quantitative lead test kits.
- Comparison of accuracy and precision between manufacturer’s internal standard data, test kit, and various types of laboratory instrumentations.

Conclusion

The findings of this study suggest that Baldwin Meadows commercial lead test kit failed to detect lead greater than both Canada's MAC of 5 µg/L and U.S. EPA's MAC of 15 µg/L, therefore conclude that it is not capable of measuring the safe level of lead in drinking water. Although this study does not represent all commercial DIY lead test kits available in the market, it implies that lead test kits may present false negative results and cause accidental consumption of lead contaminated water. To minimize the accidental exposure of lead in drinking water, environmental health officers should take initiatives to inform test kit users about its potential risk, and other agencies to conduct detailed research to build strong scientific evidence regarding the accuracy of commercial lead test kits. This would allow the implementation of findings to regulatory frameworks such as legislations, policies, and guidelines to address the problem of commercial lead test kits.

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Competing Interest

The author declare that they have no competing interests while conducting this study.

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