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Bioavailability-Based In Situ Remediation To Meet Future Lead (Pb) Standards in Urban Soils and Gardens

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ABSTRACT: Recently the Centers for Disease Control and Prevention lowered the blood Pb reference value to 5 μg/dL. The lower reference value combined with increased repurposing of postindustrial lands are heightening concerns and driving interest in reducing soil Pb exposures. As a result, regulatory decision makers may lower residential soil screening levels (SSLs), used in setting Pb cleanup levels, to levels that may be difficult to achieve, especially in urban areas. This paper discusses challenges in remediation and bioavailability assessments of Pb in urban soils in the context of lower SSLs and identifies research needs to better address those challenges. Although in situ remediation with phosphate amendments is a viable option, the scope of the problem and conditions in urban settings may necessitate that SSLs be based on bioavailable rather than total Pb concentrations. However, variability in soil composition can influence bioavailability testing and soil amendment effectiveness. More data are urgently needed to better understand this variability and increase confidence in using these approaches in risk-based decision making, particularly in urban areas.

■ INTRODUCTION

Over the last 10 years, evidence has been accumulating that lead (Pb) exposure-related health effects occur at lower blood lead levels (BLLs) than previously thought.[1] Based on these data, the Centers for Disease Control & Prevention (CDC) concluded that there is no identified BLL without deleterious health effects in children.[2] The CDC lowered the definition of elevated BLL by setting a new BLL reference value based on the 97.5th percentile of BLL in the National Health and Nutrition Examination Survey (NHANES) distribution in children 1−5 years old. That value currently is 5 μg/dL and will be updated every four years;[2] the reference value will likely decline over time as efforts are increased to lower the BLL in children. This new reference value will have far-reaching impacts as researchers, policy decision makers, public health experts, and the private sector respond to the call to further reduce Pb exposures for children. In this paper, we discuss approaches and challenges to reducing Pb exposures in light of the new blood Pb reference value, focusing on soil Pb exposures in urban settings. In situ remediation with phosphate amendments based on bioaccessibility assessments is the best approach for these conditions. Research is urgently needed to increase confidence in using these approaches for science-based risk assessment and decision making in the context of urban gardening and land reuse activities.

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REDUCING SOIL PB EXPOSURES

Although Pb exposure has been reduced substantially through bans on the use of leaded gasoline and Pb-based paint,[3] the lowered BLL reference value motivates efforts to target additional sources and further reduce exposures. One of the major exposure pathways for children and adults is via ingestion of Pb from soil and dust,[4,5] and soil exposure has been linked to BLLs in children.[5−10] Soil Pb can transfer to humans through soil ingestion, consumption of Pb-contaminated foods, and inhalation of Pb-containing soil particles.[10] To further mitigate Pb exposure risks, renewed efforts will be needed to develop remediation strategies that reduce these exposures via soil.

The call to reduce soil Pb exposures is juxtaposed with increased interest in urban agriculture. Rising popularity of urban gardening and other repurposing of vacant lands is evident in postindustrial and/or historic cities, like Detroit and Cleveland, which are actively demolishing vacant buildings and leaving empty lots.[11] Community groups, urban planners, and developers are converting backyards into agricultural gardens, and empty lots into parks and playgrounds. This increased human contact with urban soils poses risks of exposure to Pb and other metal toxicants in the soils.[12−14]

Logistical constraints and the scope of the problem in urban areas present challenges for finding practical and effective approaches to remediation. There are three main types of remediation strategies to reduce soil Pb exposures: (1) dig and haul away contaminated soil followed by replacement with cleaner soil; (2) leave contaminated soil in place and cover with barriers that reduce exposures; and (3) treat soil in place (in situ) with amendments like phosphates to chemically change the Pb compounds in the soil so that they are less bioavailable for absorption by living organisms.[20−23] Excavating and replacing soil in dense urban communities is expensive, disruptive, and technically difficult. Furthermore, the volume of soil that may need to be remediated is substantial in some cities.[15−19] In this paper, we discuss in situ treatments to reduce bioavailable Pb as a viable option in the urban environment. The bioavailable fraction of Pb in soil is measured by feeding animals or humans soil samples, and then quantifying in vivo absorption in the body. The amount of bioavailable Pb can be estimated using in vitro bioaccessibility assessments in conditions that mimic the gastrointestinal environment.[22,24,25] For any given soil, only a fraction of total soil Pb is bioavailable, and that fraction varies substantially depending on the chemical composition of different soils.[25−28] Remediation options and bioavailability are discussed in more detail later in this paper.

We propose that generally the most practical approach for urban soils is to focus on bioavailability-based remediation and risk assessment and to treat soils in situ with amendments that reduce the amount of bioavailable Pb. However, more research is urgently needed to increase confidence in using these approaches to address the challenges of urban soils.

IMPLICATIONS OF LOWER BLL FOR PB REMEDIATION IN URBAN SOILS

The U.S. Environmental Protection Agency (EPA) maintains a soil screening level (SSL) of 400 mg/kg for Pb-contaminated soil at residentially designated areas,[29] but it is possible that the SSL may be lowered as regulators are now turning a closer eye to further reducing children's Pb exposures. Several recent studies highlight the challenge such efforts might face. In Toledo, Ohio, site-specific soil Pb data were used to predict BLLs using the U.S. EPA Integrated Exposure Uptake and Biokinetic (IEBUK) model[30] with a goal to identify geographic areas of higher risk for Pb poisoning in order to target education and outreach efforts. It was found that 8.6% of areas sampled had total soil Pb concentrations >400 mg/kg, but IEUBK modeling based on that data showed that 28.4% of sites sampled yielded predicted BLLs above 5 μg/dL for the 1−2 year old age group. These results suggest that about 20% of these sites met the SSL standard but posed a risk for BLL greater than 5 ug/dL in young children. The authors concluded that the current SSL is set too high in the context of the new BLL reference value. Clearly more studies are needed to understand what soil levels are needed to support Pb exposure and risk reduction strategies that would help more children meet the new blood reference value of 5 μg/dL.

Some states already have or are considering Pb cleanup levels of 150 mg/kg or less. For example, California's soil Pb cleanup numbers are 80 mg/kg for residential areas and 320 mg/kg for industrial areas, and can be applied voluntarily on a site-specific basis.[31] The Washington State Model Toxics Control Act (MTCA) mandatory soil cleanup standard, last updated in 2001, is currently 250 mg/kg for residential areas, but the Department of Ecology proposed lowering the standard to 100−150 mg/kg.[32] The department is exploring an update of the existing MTCA standard based on recent health risk data for BLLs <10 μg/dL, updates of EPA models of Pb exposure, and current EPA and CDC priorities to reduce Pb exposure.[32]

Such a change in the SSL will have profound implications for the remediation of Pb in soils. If the SSL were lowered to 150 mg/kg, it would present a substantial challenge for cleanup efforts because elevated soil Pb levels above 400 mg/kg are not uncommon, particularly in urban soils.[16−18,33−38] Examples of studies since the 1970s reported highly elevated soil Pb levels in many cities such as Chicago,[39] Cleveland,[33] New Orleans,[40,41] Sacramento,[42] Los Angeles,[43] Paris,[44] Beijing,[45] and New York City.[15,46,47] Background levels in some urban areas reach 150 mg/kg or higher and some over 1000 mg/kg.[15−18] These studies and others provide ample evidence that a large number of urban sites would demand attention should SSLs be lowered.

An important factor to consider in Pb remediation decisions is the amount of bioavailable Pb in the soil. The fraction of total soil Pb that is bioavailable can vary substantially among different soils. As mentioned in the Introduction, bioavailability can be measured directly using in vivo feeding studies.[22,24,25] In many cases, the amount of Pb absorbed after ingestion of soil is compared to a standard, which is the amount of Pb acetate absorbed after ingestion of a known quantity in water for Pb ingestion experiments. The ratio of soil:Pb acetate absorbed amounts is called relative bioavailability (RBA). RBA values have generally ranged from 1−85%.[25−27] For example, one study of 19 soil and soil-like materials from Superfund sites reported that six had <40% RBA, eight samples were within 40−80% RBA, and three had >80% RBA, as measured in swine.[28] Given the RBA variability among soils, it is apparent that total soil Pb concentration alone sheds only partial light on potential health risks.

CHALLENGES OF URBAN SOIL REMEDIATION

The urban setting creates unique challenges for soil Pb exposure risk mitigation. The typical approach is excavation and removal of the contaminated soil; however, this approach is not always practical or even feasible for addressing widely disseminated contamination in densely populated areas of

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Table 1. Types of Soil Amendments to Immobilize Pb in Contaminated Soils

amendments	mechanisms of Pb immobilization	limitations
	Organic	
bagasse from sugar cane, compost[21,72,139]	organic matter (OM) adsorption	pH dependent, OM decomposition
bark saw dust, other wood waste[21,139]	OM adsorption	pH dependent, OM decomposition lowers effectiveness over time
biosolids[21,139]	phosphate immobilization, OM adsorption, mineral oxide adsorption	phosphate solubility, odor, pH dependent, OM decomposition
poultry and other manure[21,139]	phosphate immobilization, OM adsorption	phosphate solubility can be high with concerns for phosphate in groundwater, odor, pH dependent, variable quality, OM decomposition
xylogen (paper mill waste)[21,139]	OM adsorption	pH dependent, OM decomposition
	Inorganic	
bentonite[72]	clay mineral adsorption	pH dependent
Fe, Mn, or Al oxides[27,79,140,141]	mineral oxide adsorption	pH dependent
fly ash and other coal combustion products[139,142]	OM adsorption, mineral oxide adsorption	pH dependent, fly ash may contain other contaminants of concern
hydroxyapatite (e.g., fish bone meal)[20,34,143−145]	phosphate immobilization	phosphate solubility can be low, odor, byproducts in fish bone may affect plants
lime[20,34,79,92,139]	pH adjustment to enhance adsorption and chemical precipitation	pH adjustment may affect plant growth, soil pH will revert to natural levels over time, and that may release Pb
rock phosphate[20,34,79,92]	phosphate immobilization	phosphate solubility can be low with concerns for limited immobilization
triple super phosphate (TSP)[20,34,79,92]	phosphate immobilization	phosphate solubility can be high
phosphoric acid[20,34,79,92]	phosphate immobilization	phosphate solubility can be high, significant soil pH reduction may affect plants

urban environments. Excavating and replacing soil in dense urban communities is cost prohibitive, highly disruptive, and technically difficult. Excavation and replacement is an unsustainable remediation approach because there are limited sources of clean soil, and its removal from the source site can have negative ecological impacts. Also, as SSLs move toward or below background levels, sources of soil that qualify as "clean" will become increasingly rare.

The anticipated scope of the problem makes soil excavation a daunting task in some cities. For example, a recent study of 68 urban vacant residential lots in Cleveland found soil Pb ranged from 20 to 2250 mg/kg with a median content of 228 mg/kg.[19] If Cleveland were to use excavation and replacement remediation strategies to a 150 mg/kg total Pb target level, the city would have to dig up more than half of the 16,000+ vacant lots. Strategies to reduce soil Pb exposure risks in urban environments must work within the constraints of these practical challenges.

IN SITU APPROACHES TO MITIGATING PB EXPOSURES IN URBAN SOILS

Many of the practical challenges associated with excavation and removal in urban environments can be overcome with in situ soil Pb exposure risk mitigation strategies. There are a number of approaches to risk mitigation from urban soils that have been reviewed in more detail elsewhere.[13,20,21,48] In this paper, we discuss strengths and limitations of different exposure mitigation methods in the context of the urban environment with the caveat that different approaches may be effective or ineffective depending on soil characteristics and application methodology.

Physical barriers work by covering the contaminated soil with a cap such as sod, clean soil with mulch, raised garden beds, or gravel that reduce soil dust and contact exposures.[49] Such barriers can be important for exposure risk mitigation because inadvertent ingestion of contaminated soil is the main pathway of exposure from soil.[37,50−52] One study suggests that clean raised beds can become recontaminated over time, though further research is needed to fully assess the extent of this possibility.[53] In addition, plants may serve as a physical barrier through phytostabilization of dust to reduce airborne distributions and exposures from highly contaminated mine tailings.[54] However, because any subsequent disturbance of physical barriers may reintroduce exposure to the contaminated soil below, it is advisible to use other remediation strategies such as in situ stabilization with soil amendments in conjunction with physical barrier approaches.

In the context of urban gardening, Pb accumulation by food-source plants is not considered a significant exposure risk, provided crops are adequately washed.[55−57] In fact, lead accumulation in plants is limited, and thus in general phytoextraction of Pb is not a viable remediation option.[58]

IN SITU SOIL AMENDMENTS TO IMMOBILIZE PB

In situ soil amendments are additives that can be mixed into soils to modify Pb compounds in a way that immobilizes Pb in the soil, limiting its bioavailability. These soil amendments can be as effective and much less costly than excavation and removal.[20,23,48] A variety of soil amendments have been tested for in situ Pb stabilization (Table 1). Amendments can be divided into two categories: organic (e.g., bark saw dust, xylogen, bagasse, poultry manure, compost, and biosolids) and inorganic compounds (e.g., lime, bentonite, fly ash, and various phosphorus containing compounds).[21] Studies suggest that repeated addition of organic matter in large quantities dilutes total Pb concentrations in soils and would therefore be beneficial.[55−57,59] However, questions remain about long-term effectiveness as the organic amendments decompose over time. Nanomaterials such as nanoscale zerovalent iron[60,61] and nanoparticulate apatite[62−64] have been used for in situ remediation of many contaminants, but the usefulness for Pb in soil is highly unlikely due to relatively high cost considering the sheer volume of urban soil that has to be treated. It is also generally regarded that the use of nanomaterials for in situ remediation should be highly cautioned as it may cause more issues, such as colloidal transport vectors, potential release of

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the contaminant should the nanomaterial dissolve, and uncertainty in ecosystem impacts.[65,66]

Inorganic amendments can bind to and immobilize Pb by forming minerals of varying bioavailability. For example, lead carbonates and oxides including Pb(II) oxide (PbO), and Pb(II) hydroxide ($Pb[OH]_2$) are more soluble and potentially have high bioavailability whereas Pb phosphates, Pb sulfide (PbS), iron (Fe)−Pb oxides, Fe−Pb sulfates, manganese−Pb oxides, Pb(II) chromate ($PbCrO_4$), and Pb(II) sulfate ($PbSO_4$) are less soluble and hence have low bioavailability.[67−70] The goal is to use inorganic amendments that favor formation of compounds with low bioavailability potential.

PHOSPHATE AMENDMENTS FOR REDUCING SOIL Pb BIOAVAILABILITY

While a number of studies have examined soil amendments to sequester Pb,[71−76] the strongest evidence for actual reductions in Pb bioavailability has been demonstrated for phosphates.[20,34,35,68,77−81] Phosphate promotes formation of highly insoluble Pb mineral species (e.g., pyromorphite) in soil that remain insoluble after ingestion and, therefore, less absorbed by the gastrointestinal (GI) tract and less bioavailable. Mechanisms of Pb immobilization are described elsewhere.[20] Pb phosphates are among the most stable Pb minerals known and their stability increases with aging time.[82] Another study demonstrated reduced Pb bioavailability in phosphate-treated soils as a function of increasing field treatment time indicating that once formed, pyromorphite in treated soils has long-term protectiveness.[83] Other studies have demonstrated that not only does pyromorphite become less soluble over time,[82,83] but also that Pb bioavailability decreases as aging time of the phosphate-amended soil increases.[34] These in situ approaches can be effective in reducing the bioavailable fractions with little if any change in total Pb concentrations.[20,68,81] Furthermore, reductions in blood Pb levels following in situ remediation approaches have been demonstrated in humans, swine, rats, and mice.[20,84−87]

Choosing the type of phosphate product as a soil amendment is very important for successful immobilization of Pb.[20] Soluble phosphate sources such as commercially available phosphate fertilizers and phosphoric acid can be effective in transforming Pb into Pb phosphates with low solubility.[88−90] Fertilizer phosphate sources are widely available (e.g., home improvement centers) and inexpensive. It is important to consider that variation in the quality and composition of urban soils can impact effectiveness of soil amendments;[20,34,91] variables include soil pH, water content, soil compaction, calcium content, soil organic carbon content, and chemical forms of Pb present in the soil.[20]

The use of phosphate amendments can have some drawbacks. Some phosphate sources, such as phosphoric acid, can significantly change soil pH to a point that inhibits plant growth, thus requiring liming agents to increase soil pH.[20] In addition, the type of phosphate amendment and the amount used can affect the amount of extractable phosphate that may migrate out of the soil in runoff, and present some risks of enhanced eutrophication of water bodies when higher phosphate levels in runoff may drain to surface waters or groundwater.[68,92] For example, fertilizer phosphate soil treatments can result in very high levels of extractable phosphate as compared to other less soluble phosphate sources (e.g., phosphate rock or synthetic apatites).[92] Leaching potential of phosphate from treated soils under certain conditions has been demonstrated in a few studies,[92−95] but more studies are urgently needed to better determine what treatments or conditions might be minimize these risks. Generally, phosphate treatment of contaminated urban soils is magnitudes smaller in scale than what is found in agricultural land and thus poses little risk to surface water quality.[97] An additional drawback to consider is that, as global phosphate demand has increased, supplies of rock phosphate are becoming more limited, and concerns for future availability and cost are rising.[98]

FACTORS INFLUENCING AMENDMENT EFFECTIVENESS

There is tremendous variation in soil composition in the environment, and the composition can influence soil amendment effectiveness. Urban soils are known for heterogeneous physical and chemical properties based on land use and cover, and these properties are influenced by the presence of large quantities of human transported materials.[99] Common soil quality issues associated with urban soils are soil compaction, poor drainage, shallow soils, stones and other debris, low organic matter, and low nutrient concentrations.[100] In particular, higher pH (7.0 or above) is often observed due to higher carbonate contents from concrete debris. Studies have shown that large portions of the Pb in soil could reside in the carbonate fraction and the organic matter fraction.[46] X-ray absorption data on two different urban sites showed that most Pb in this soil is either adsorbed to iron oxides or complexed with humic acids.[55,57]

In addition, variations in native soil microbial communities can have direct effects on soil and Pb chemistry that can in turn affect remediation processes.[101] Fungi in particular are known to interact with Pb in ways that may either increase or decrease Pb solubility and availability to both plants and animals.[102] Fungi can interact with Pb through hyper-excretion of low molecular weight organic acids such as oxalic, malic, and citric acids; these acids can alter the pH of their local environment and transform Pb into a variety of mineral and organic complexes that vary in solubility and reactivity.[103−105] Although several studies have documented these transformations under ideal laboratory conditions, it is not clear the extent to which these phenomena occur in situ within contaminated or remediated soil systems.[105] Additionally, it is also not currently known the extent to which various types of ammendment strategies may themselves alter microbial communities. However, while not specifically studied for this application, phosphate fertilization is well-known in agricultural systems to consistently have negative effects on arbuscular mycorrhizal fungal abundance,[106] and alteration of pH by liming is also likely to have broad effects given pH is often found to be a master variable in microbial community structure.[107]

Variations in cocontaminants in the soil can also affect in situ remediation processes because of competitive interactions with phosphate.[20] Possible cocontaminants in urban environments include arsenic, cadmium, chromium, nickel, and zinc. Phosphate amendments can immobilize metals such as cadmium, nickel, and zinc.[80,108,109] At the same time, these amendments can mobilize other cocontaminants. For example, some phosphate amendments and manures can mobilize arsenic in soil.[57,110−114] However, adjusting the soil pH may reduce this effect.[21] Furthermore, arsenic contamination is typically rare in urban soils so there is low concern for arsenic mobilization in most urban settings. In addition, antimony may be a concern in some circumstances, such as shooting ranges,

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Table 2. In Vivo and In Vitro Methods for Measuring Bioavailable and Bioaccessible Pb in Contaminated Soils

method/assay	form of soil Pb measured	type of method	key references
relative bioavailability assay (juvenile swine, rodent, primate monkey, and human exposure feeding studies)	bioavailable	in vivo	Casteel et al., 1996[146] Casteel et al., 2006[28] Smith et al., 2011[147] Juhasz et al., 2014[87]
Physiologically Based Extraction Test (PBET)	bioaccessible	in vitro	Ruby et al., 1996[131] Hettiarachchi et al., 2003[27] Attanayake et al., 2014[55] Defoe et al. 2014[56]
Relative Bioaccessibility Leaching Procedure (RBALP), also called Solubility/Bioavailability Research Consortium (SBRC) in vitro-gastric and in vitro-intestinal assays, U.S EPA Method 1340	bioaccessible	in vitro	Kelly et al., 2002[127] Drexler and Brattin, 2007[126] Juhasz et al., 2009[128] U.S. EPA, 2013[130]
Ohio State University In Vitro Gastrointestinal (OSU IVG) Method	bioaccessible	in vitro	Schroder et al., 2004[132]
Unified Bioaccessibility Research Group of Europe Method (UBM)	bioaccessible	in vitro	Denys et al., 2012[133]
Mehlich-3 test as a screening tool	estimate of bioaccessible	in vitro	Minca et al., 2014[19]

but, again, is generally not a concern in urban areas.[20] Supplementing phosphate amendments with iron oxide-rich soil amendments has been shown to reduce arsenic mobilization during phosphate treatments[115] but not in all cases.[59]

Given the number of variables that can influence the effectiveness of in situ remediation, it is clear that no single approach can work for all soils. For example, fish bone meal amendments were reported to be effective in EPA laboratory tests and at residential sites in Oakland, California,[116] but less so in laboratory tests of soils from contaminated mine waste sites.[117] Furthermore, most Pb bioavailability studies have been conducted on highly contaminated mining waste materials, mine-impacted soils, and shooting range soils[20,51,77,92,118] that can differ greatly from urban soils. Although the number of studies of urban sites is growing,[19,55,119−124] relatively little is known about bioavailability and in situ treatment effectiveness in urban soils at levels that may be relevant for the new BLL values.[20] Of all soil amendments, phosphates are the most effective treatment in reducing Pb bioavailability and bioaccessibility in Pb-contaminated soils.[20,35] Given these challenges in finding effective and feasible remediation strategies in urban soils, combined with looming pressures from the lowering of the blood Pb reference value, bioavailability assessments at individual remediation sites, even at the single garden level, become very important.

MEASURING SOIL Pb BIOAVAILABILITY IN VIVO

As stated earlier, typically only a fraction of total Pb in soil is bioavailable and poses potential human health and ecological risks.[20,35] Quantifying the amount of bioavailable Pb can be very valuable in deciding on remediation strategies. If cleanup levels were based on the bioavailable fraction rather than the total Pb concentration, remediation efforts may be substantially reduced or unnecessary if the concentration of bioavailable Pb were sufficiently low to protect human health. Minimizing remediation efforts would result in cost savings and thus potentially increase the scope and practicability of remediation efforts while also protecting human health.

Bioavailability can be measured directly in vivo or estimated using in vitro bioaccessibility assays.[22] Bioaccessibility will be discussed in the next section of this review. Bioavailability assessments measure the amount of a compound (e.g., Pb) that is absorbed in vivo after whole animal or human experimental feeding of a known amount of that compound (Table 2). The bioavailable fraction in soil is the amount absorbed as a fraction of the amount ingested. The RBA is calculated as the amount of Pb absorbed in vivo after ingestion of Pb in soil as compared to the amount absorbed after ingestion of Pb acetate in drinking water, a reference standard for unencumbered absorption.[20,25] Standard in vivo tests use the juvenile swine model, the adult mouse model, the primate monkey model, and, in very few cases, humans.[25,28,34,125] These in vivo tests can be cost prohibitive, particularly to communities, and take significant time to plan and implement. In vivo methods have been used to determine Pb RBA in highly contaminated sites (e.g., Superfund sites),[20,22,25,34,35] but there are scarce data for use on moderately contaminated urban soils.

VALIDATED METHODS FOR MEASURING BIOACCESSIBILITY IN VITRO

As mentioned above, an alternative to measuring bioavailability in vivo is bioaccessibility testing in vitro as an estimate of bioavailable Pb concentrations.[25] Bioaccessibility assessments measure the amount of Pb extracted from a given media (e.g., soil) in vitro into laboratory media that mimic extractability in gastrointestinal environments (Table 2). One of the more commonly used methods is the Relative Bioaccessibility Leaching Procedure (RBALP),[126,127] also called the Solubility/Bioavailability Research Consortium (SBRC) in vitro-gastric and in vitro-intestinal assays.[128] The U.S. EPA issued guidance for the adopted use of this method for risk assessment purposes at Superfund sites and named it EPA Method 1340.[129,130] RBALP, SBRC, and Method 1340 are the same assay. This method was positively correlated with bioavailable Pb concentrations from in vivo assessments of the same samples.[28,126] Other in vitro methods for measuring bioaccessibility have also been correlated with in vivo measurements (Table 2): the physiologically based extraction test (PBET) method,[27,131] OSU in vitro gastrointestinal method (OSU IVG),[132] and the Unified Bioaccessibility Research Group of Europe Method (UBM), also called the BARGE method.[133,134]

The most important criteria to validate an in vitro method are successful in vivo−in vitro correlation tests (IVIVC). In vitro methods that have not been evaluated against in vivo data are not acceptable for human risk assessment.[24] EPA guidance does not define the criteria for the "goodness of fit" parameters for the IVIVC regression.[24] However, Wragg et al.[134] reported

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goodness of fit parameters adopted from guidance developed by the U.S. Department of Health and Human Services Food and Drug Administration.[135] The criteria below may be applied to IVIVC and validation studies. Criteria include: (1) a linear relationship between in vivo and in vitro data with a correlation coefficient of (r) >0.8 and a slope >0.8 and <1.2 (for the initial correlation and subsequent validation data sets, respectively); (2) a within-laboratory repeatability of ≤10% relative standard deviation (RSD) for in vivo and in vitro assays; and (3) a between-laboratory reproducibility of ≤20% RSD for in vivo and in vitro assays. The three in vitro bioaccessible methods that meet these criteria are RBALP (at pH 1.5), PBET, and UBM.[27,126,133,134] Other methods have potential for use, including the Urban Soil Bioaccessibility Lead Test,[136] but must be evaluated against an appropriate animal model for use in urban soils according to U.S. EPA guidance.[24]

In addition to these validated methods, two other approaches to measuring bioaccessible Pb concentrations are being explored. The Mehlich-3 soil test, commonly used to screen soils for available nutrients in agricultural scenarios, might be useful as an inexpensive screening tool for Pb bioaccessibility; Mehlich-3 test results were highly correlated with RBALP measures of total Pb and bioaccessible Pb.[19] Another approach for screening combines in vitro bioaccessibility data with mathematical regression models to estimate bioavailability.[137]

Uncertainties need to be considered when performing bioaccessibility assessments. It is worth repeating that most of the studies listed previously were performed using nonamended highly contaminated soils; the accuracy of these tests in urban soils with lower Pb concentrations and in the context of soil amendments is less certain. Recent data suggest the RBALP method is not an accurate predictor of bioavailable Pb in soils amended with phosphate treatments.[25,34,138] While one study demonstrated an IVIVC correlation for an amended soil,[27] another study of phosphate-treated soils demonstrated that the RBALP method underestimated the ability of phosphate to reduce Pb bioavailability.[109] These and other data suggest that physical and chemical interactions of Pb and phosphate amendments during in vitro testing can inadvertently influence bioaccessibility test results,[19,20,55,119−121,123] but more research is needed to identify the exact mechanisms. Because there is a good possibility that urban soils will have been amended with phosphates through fertilization, these findings present a challenge for accurate assessment of RBA in urban soils. Therefore, although the RBALP/SBRC/1340 method is an excellent method for untreated soils, we need more studies to determine what method to use to predict Pb RBA in soils treated with amendments like phosphates.

One possibility to explore is using the RBALP under conditions of pH 2.5 instead of the currently accepted pH 1.5.[22,126] While developing the RBALP method, the researchers tested different in vitro conditions using untreated soils. The researchers selected pH 1.5 over pH 2.5 because of less variability at pH 1.5, although pH 1.5 and 2.5 both were statistically significant (R^2 of 0.85 and 0.75, respectively). They did not test RBALP with phosphate-amended Pb soils. Additional studies suggest that phosphate amendments can affect RBALP results depending on the in vitro conditions of the test. For example, soil amendments appeared to be largely ineffective in reducing IVBA Pb in two urban soils according to the RBALP using an extraction at pH 1.5, but reductions in IVBA Pb were observed when using an extraction at pH 2.5.[138] A significant negative linear relationship between reduction in IVBA Pb and Pb-phosphate formation was found only for pH 2.5. This difference in Pb extractability at pH 1.5 vs pH 2.5 for phosphate treated soils may be manifested in the pK_a values for phosphate for which pK_{a1} is 2.12, meaning below pH 2.12 phosphate prefers to be H_3PO_4, and above pH 2.12 phosphate prefers $H_2PO_4^{-1}$. A slight shift in extraction pH has a profound effect on phosphate chemistry. Therefore, a modified RBALP using pH 2.5 rather than 1.5 has potential to more accurately measure efficacy of phosphate soil amendments to reduce bioaccessible Pb. More research is urgently needed to develop a validated in vitro method that accurately measures reductions in IVBA Pb in amended urban soils.

Overall, it is clear that the method that provides the most confidence for determining Pb bioavailability in phosphate-treated soils is the use of an acceptable in vivo animal model. However, given that these tests are expensive and time-consuming, there is a dire need for validated, accurate, and cost-effective in vitro bioaccessibility assays for Pb in amended soils, particularly in urban soils. It is highly desirable to have a single in vitro method to predict reduction in RBA Pb from soil treatments so that multiple tests for each soil sample are avoided. It is also important to note that many urban gardeners faced with Pb contamination do not have extensive technical expertise or financial resources, so the tests need to be inexpensive and, ideally, amenable for the gardeners' own use.

■ RESEARCH NEEDS FOR INFORMED DECISION MAKING

Pulling together the information discussed above, it is clear that currently there are in vitro bioaccessibility testing methods that have been validated for a limited number of soils, and there are in situ amendments that have been shown to be effective for some soils. Combining bioavailability-based decision making with cost-effective on-site remediation options can be practical and cost-effective in urban environments. However, the use of bioavailability estimates in cleanup decision making has been slow in gaining acceptance. Risk assessments often rely on total soil Pb concentrations and the U.S. EPA default value of 60% RBA,[24] based on IEUBK modeling for the assessment of risks to children.[3] Bioavailability has been considered in setting remediation levels at major Superfund sites around the country, especially "mega-sites" dealing with mining, smelting, and other wastes.[21,22] Now, in the context of the lower blood Pb reference value, Pb bioavailability will likely be the most prominent factor in efforts to minimize costs of remediating and amending soils. The issue is very relevant for urban soils given the challenges and scope of problems in urban settings.

If there were more bioaccessibility testing at specific sites, RBA estimates derived from that data could be used instead of the default 60% RBA value[24] for a more accurate assessment of potential risks. In cases of low RBA estimates, for example, total soil Pb concentrations might be greater than the SSL but still determined to be protective of human health.[123] Such an analysis could reduce or even eliminate the need for remediation activities at the site. When RBA estimates are higher than the default 60% estimate,[24] we can better protect human health by using the more accurate estimate in remediation strategy decision making. Either way, the decisions will be data-driven and better informed.

There is much we need to know to increase confidence in using bioavailability estimates in order to gain more widespread acceptance of their use. Gaps in our knowledge stem primarily from the fact that soil composition can vary tremendously and

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that variation can impact in vitro bioaccessibility test results as well as soil amendment effectiveness.[19,20,55,119−121,123] It is abundantly clear that there is no "one size fits all" option for bioaccessibility testing or in situ remediation. Research is driving us toward developing customized approaches based on conditions at specific sites. We need to develop a broader knowledge base so that soil sample composition can inform the choice of in vitro bioaccessibility testing methods, the decision regarding needs for remediation, and the selection of appropriate remediation approaches.

To do this, we need to expand validation analysis of in vitro bioaccessibility testing methods using a wider array of soil sample types. Soil types should include samples containing levels of Pb lower than those found in highly contaminated sites, and soil samples containing amendments used for remediation (e.g., phosphate amendments). It is very important to emphasize again that it is only by validating in vitro bioaccessibility tests with animal feeding studies that we can be assured that the in vitro tests provide accurate estimates of RBA. The challenge is to identify which in vitro extraction methods work for which materials (e.g., different types of soils and different types of amendments) while keeping the number of extractions and thus the inherent experimental complexity to a minimum.

Another knowledge gap is the extent and duration of phosphate amendment effectiveness in a wider variety of soils. Current understanding is based predominantly on testing highly contaminated soils, and few studies have evaluated effectiveness over durations extending beyond several months to a year. Increasing potential for exposures to urban soils demands that more research focus on soils in urban areas, including urban gardens. The public needs science-based information to make informed decisions and help reduce their exposures to Pb. Currently that data-driven public information is sparse.

In light of the lower blood Pb reference value issued by the CDC juxtaposed with increased urban agriculture and public land use, effective bioavailability-based decisions and incorporation of in situ remediation strategies are urgently needed to reduce Pb exposures in urban areas. These approaches are particularly important given the challenges of remediating Pb in urban soils. If in situ remediation could achieve acceptable levels of bioavailable Pb, even if total Pb levels remain high, existing remediation methods could be effective at protecting public health. Future research should focus on characterizing soil conditions for accurate bioavailability estimates and effective soil amendment approaches because there is no singular solution that applies for all soils. Importantly, this information—that in situ amendments need to be tailored to particular soil type—should be conveyed to the public to inform their decision making. Together these efforts are essential for supporting healthy urban gardening and land reuse.

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Notes

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