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Review

Measurement of soil lead bioavailability and influence of soil types and properties: A review

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HIGHLIGHTS

- Key parameters influencing *in vitro* measurements of Pb bioaccessibility in soils and uncertainties are summarized.
- Soil type, soil properties and metal concentrations influence lead bioavailability.
- Differences in *in vitro* methods and Pb source limit statistical analysis of soil factors influencing Pb bioavailability.

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ABSTRACT

Lead (Pb) is a widespread heavy metal which is harmful to human health, especially to young children. To provide a human health risk assessment that is more relevant to real conditions, Pb bioavailability in soils is increasingly employed in the assessment procedure. Both *in vivo* and *in vitro* measurements for lead bioavailability are available. *In vivo* models are time- consuming and expensive, while *in vitro* models are rapid, economic, reproducible, and reliable while involving more uncertainties. Uncertainties in various measurements create difficulties in accurately predicting Pb bioavailability, resulting in the unnecessary remediation of sites. In this critical review, we utilised available data from *in vivo* and *in vitro* studies to identify the key parameters influencing the *in vitro* measurements, and presented uncertainties existing in Pb bioavailability measurements. Soil type, properties and metal content are reported to influence lead bioavailability; however, the differences in methods for assessing bioavailability and the differences in Pb source limit one's ability to conduct statistical analyses on influences of soil factors on Pb bioavailability. The information provided in the review is fundamentally useful for the measurement of bioavailability and risk assessment practices.

Contents

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Abbreviation

ABA	absolute bioavailability
AUC	Area under curve
BA	bioavailability
BAc	bioaccessibility
BW	body weight
CEC	cation exchange capacity
G-phase	gastric phase
IEUBK	Integrated Exposure Uptake Biokinetic model
I-phase	intestinal phase
IV	intravenous
IVG	In Vitro Gastrointestinal (IVG) Method
IVIVC	correlation between *in vivo* and *in vitro* methods
OM	organic matter
PBET	A Physiologically Based Extraction Test
RBA	relative bioavailability
RBALP	Relative Bioavailability Leaching Procedure
RIVM	In Vitro Digestion Model (RIVM)
SBRC	Solubility Bioaccessibility Research Consortium assay
S:L ratio	solid:liquid ratio
TOC	total organic carbon
UBM	Unified BioAccessibility Research Group Europe (BARGE) method
US EPA	U.S. Environmental Protection Agency

1. Introduction

Exposure to lead (Pb) is of increasing concern due to the global scale of its occurrence in the environment and adverse health effects (U.S. Environmental Protection Agency, 2014). Oral ingestion of Pb contaminated soil is a major pathway for exposure to humans especially children (U.S. Environmental Protection Agency, 2014). Ingestion of Pb contaminated soils by children is of particular concern due to their hand-to-mouth activities and higher metabolic rate (Gulson et al., 1995; Oomen et al., 2003; U.S. Environmental Protection Agency, 2007a), which will result in a permanent influence on children's development of neuronal systems, cell function and a decrease of children's intelligence quotient (Shannon, 1998). Even at a low blood lead level, a range of neurocognitive, behavioural and other specific issues have been reported as being linked to Pb exposure (Benetou-Marantidou et al., 1988; Dietrich et al., 1990). The U.S. Environmental Protection Agency (EPA) indicates that there is no safe threshold for children exposed to Pb (U.S. Environmental Protection Agency, 1994, 2007a).

Total Pb concentration in contaminated soils contributes to Pb exposure and influences blood lead level in children; however, an increasing number of investigations have indicated that using total Pb concentration may overestimate the risks from Pb exposure (C. R. Janssen et al., 2000; Oomen et al., 2006; U.S. Environmental Protection Agency, 2007a; Li et al., 2014; Wijayawardena et al., 2014), since only a fraction of Pb in ingested soil can cause adverse effects to human health due to the influence from soil properties and sources, Pb distribution and metabolism of Pb in organisms (Ruby et al., 1996; Oomen et al., 2006). Usage of the 'effective' fraction of total ingested Pb is recommended to assess risks and adverse effects from Pb exposure to humans especially children (Ruby et al., 1996; Oomen et al., 2006). Bioavailability (BA), as a linkage parameter between total concentration and the 'effective' fraction for exposure assessment, holds promise for determining a more realistic basis for environmental risk assessment and remediation (Belfroid et al., 1996). The term BA in this study is defined as the fraction of an ingested dose that crosses the gastrointestinal epithelium and becomes available for distribution to internal target tissues and organs (U.S. Environmental Protection Agency, 2007b).

Extensive research efforts have been made for Pb BA measurement; however, it continues as a challenge due to the existence of a large number of uncertainties, inadequate information, and lack of reliable predictive models (U.S. Environmental Protection Agency, 2014). Although the U.S. EPA has established that relative bioavailability (RBA) of Pb in soil is 60% in the Integrated Exposure Uptake Biokinetic (*IEUBK*) model, Pb RBA has been reported to be wide-ranging. For example, Casteel et al. (2006) reported RBA of Pb using a swine model ranging from 6% to 105%.

Numerous research attempts have been made on measuring Pb BA via *in vivo* models such as in swine (*Sus scrofa*), rats (*Rattus*), mice (*Mus*), monkeys (*Cercopithecidae*), rabbits (*Oryctolagus cuniculus*); however, limited data and information are available due to time- consuming and cost-factors as well as ethical issues (Juhasz et al., 2007; U.S. Environmental Protection Agency, 2007a). Moreover, challenges exists when extrapolating data from *in-vivo* studies to human health due to the physiological differences and species diversity between humans and the experimental animal models (Ruby et al., 1999). A potential alternative approach to supersede *in vivo* studies is the use of *in vitro* tests to measure Pb bioaccessibility (BAc) (i.e. the fraction that is soluble in the gastrointestinal environment and is available for absorption), which are