Ecotoxicology (2021) 30:1029–1042
https://doi.org/10.1007/s10646-021-02443-0

Lead acetate ecotoxicity in tropical soils

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Accepted: 8 June 2021 / Published online: 30 June 2021

Abstract

Lead acetate (AcPb) is an important raw material used in chemical industries worldwide. The potential toxicity of AcPb is generally attributed to the presence of Pb. However, the effect of AcPb on the environment as a whole is still poorly known. This study aimed to evaluate AcPb toxicity on three standard species of soil invertebrates and two plant species using ecotoxicology tests. Three tropical soils (Oxisol, Inceptisol, and Tropical Artificial Soil (TAS)) were contaminated with different concentrations of AcPb and one dose of K-acetate (positive control). These soils were used in tests with *Eisenia andrei* (earthworm), *Folsomia candida* (springtail), *Enchytraeus crypticus* (enchytraeid), *Zea mays* (maize), and *Phaseolus vulgaris* (common bean). Dose-response curves obtained in the laboratory tests were used to estimate the EC_{50} values for each species. Among invertebrates, the highest sensitivity to AcPb was observed for *E. crypticus* in the TAS (EC_{50} = 29.8 mg AcPb kg^{-1}), whereas for *E. andrei* and *F. candida* the highest sensitivity was observed in the Oxisol (EC_{50} = 141.9 and 1835 mg AcPb kg^{-1}, respectively). *Folsomia candida* was the least sensitive invertebrate species to AcPb in all soils. Among plant species, *Z. mays* was less sensitive (EC_{50} = 1527.5 mg AcPb kg^{-1}) than *P. vulgaris* (EC_{50} = 560.5 mg AcPb kg^{-1}) in the Oxisol. The present study evidenced that the toxicity of AcPb should not be attributed uniquely to the presence of Pb, as the treatment containing uniquely Ac provoked the same toxicity as the highest dose of AcPb.

Keywords Toxicity · Soil invertebrates · Crops · Phytotoxicity · Lead

Highlights

- Lead acetate significantly affected all standard species tested.
- *Enchytraeus crypticus* was the most sensitive species in all tested soils.
- *Zea mays* was less sensitive to AcPb than *Phaseolus vulgaris*.
- K-acetate equivalent to the highest AcPb dose was as toxic as the highest AcPb dose.

Introduction

Soil pollution is a current worldwide challenge that has direct and/or indirect impacts on human health, food security, environmental quality, provision of ecosystem services, and the economy (FAO 2018). Among the main types of pollutants to the environment are heavy metals, such as lead (Pb), which stands out due to its potential harm and persistence in the environment (Wani et al. 2015; Frank et al. 2019; Verma et al. 2020).

Lead is an old and well-known public health hazard and is still responsible for poisoning hundreds of millions of children worldwide (Rees and Fuller 2020). The widespread number of sites contaminated by Pb is probably due to its historical and current broad use and human activities. For example, as a raw material in lead–acid batteries, some

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s10646-021-02443-0.

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paints, glazes, leaded glass and ceramics, as well as mining, smelting, refining, and recycling of lead (WHO 2019; Rees and Fuller 2020). When these activities and products/wastes are not properly managed, there is an increased risk of environmental contamination with severe lasting implications.

The solubility of Pb compounds can be quite different, with lead acetate, lead chloride, and lead nitrate being among the most soluble Pb salts (NTP 2016). These soluble Pb compounds have many industrial uses, e.g., lead acetate (AcPb) is used as a color additive in hair dyes; as a mordant in cotton dyes; in lead coating of metals; as a drier in paints; varnishes and pigment inks; and in medicines, such as astringents (NTP 2016; Pohanish 2017). Besides, AcPb has been used in the production of highly efficient perovskite solar cells (Li et al. 2018, 2020) and on lead-acetate test paper, a product designed to detect sulfur in different materials (Selwyn 2017). All the uses mentioned above make it a potential source of soil contamination when proper management is not assigned.

Although lead is an element that has been widely studied (Brown et al. 2016; Rehman et al. 2017; Entwistle et al. 2019; Alexandrino et al. 2020), the knowledge on the disposal and detailed information on the exposure to materials containing AcPb for soil organisms is still limited. Moreover, the majority of the studies conducted to date to evaluate the toxicity of Pb to plants, invertebrates, and soil microorganisms have used nitrates and chlorides as a source of Pb (Sobolev and Begonia 2008; Xu et al. 2009; Smolders et al. 2015; Chandrasekhar and Ray 2019; Zhang et al. 2019a; Dai et al. 2020). To the best of our knowledge, most studies using AcPb as a Pb source have been devoted to assessing its toxicity in animals (Ibrahim et al. 2012; Haouas et al. 2014). The few studies using AcPb in soils have been focused mainly on the toxicity of Pb (Päivöke 2002; Liao et al. 2007; Zeng et al. 2007; Cândido et al. 2020). Consequently, data on AcPb toxicity to soil organisms are lacking, a useful piece of information on the management of areas contaminated by this Pb source.

Several studies investigated the toxicity of AcPb and evidenced its potential harm in soils (Liao et al. 2007; Zeng et al. 2007; Cândido et al. 2020). For example, Liao et al. (2007) showed that AcPb (concentrations > 500 mg Pb kg^{-1}) caused a significant decline in soil microbial biomass. Zeng et al. (2007) reported that concentrations up to 900 mg Pb kg^{-1} as AcPb cause damage to rice plants, enzyme activity, and soil microbial biomass, and Cândido et al. (2020) found Pb concentrations of 2760 and 1788 mg Pb kg^{-1} (as AcPb) that decrease the shoot dry matter production by 50% in sorghum and soybean, respectively. The wide range of effective concentrations presented for these studies shows that Pb toxicity can be quite different, considering the soil, test organisms, and endpoints evaluated.

It is widely known that distinct soils can induce dissimilar toxicities for the same concentration of a specific contaminant due to its interaction with soil attributes (Kabata-Pendias and Mukherjee 2007). Also, the exposure mode and own protection and detoxification strategies of each species also contribute to diversify the toxicity values, which reinforces the need to obtain toxicity data for different soils, organisms, and endpoints.

Whereas there is a lack of knowledge on the toxicity of AcPb, mainly due to the stress caused by high concentrations of AcPb compared with acetate for plants and soil invertebrates, it becomes important to clarify the toxic effects of AcPb on these organisms. Ecotoxicological studies are needed to fill this gap and improve the understanding of AcPb effects on the environment, mainly for tropical soils, which may have physical and chemical attributes quite different from those found in temperate regions and standard substrates. Thus, this study aimed to evaluate AcPb and acetate toxicity in tropical soils through bioassays. It is expected that these results may clarify some aspects of AcPb toxicity in the tropical region.

Materials and methods

Test soils

In all experiments, two natural soils from areas of native vegetation with minimal anthropogenic interference of State of Minas Gerais, Brazil, were used: an Oxisol (Typic Hapludox) (21°17′10.3″ S and 44°47′45.5″ W) and an Inceptisol (Typic Dystrudept) (21°13′48.3″ S and 44°59′11.6″ W) (Soil Survey Staff 2014). Both soils were collected from the top 20-cm layer, air-dried, and sieved to 2 mm. These soils were selected because Oxisols and Inceptisols are relevant soil classes in tropical regions, covering approximately 20 and 9% of the total area of South America, respectively (Gardi et al. 2015).

In tests with soil invertebrates, in addition to the natural soils, a Tropical Artificial Soil (TAS; Garcia et al. 2004) composed of a mixture of 75% fine sand, 20% kaolinite clay, and 5% coconut fiber was used.

The physical and chemical properties of the natural soils are presented in Table 1. Briefly, soil pH was determined using a 1 mol L^{-1} KCl solution (1:5, w-v; ISO—International Organizations for Standardization 2005), cation exchange capacity (CEC) was calculated by the sum of exchangeable cations and potential acidity according to Teixeira et al. (2017), the particle-size analysis was performed using the pipette method (Day 1965), water holding capacity was measured according to ISO 11269-2 (ISO—International Organizations for Standardization 2005), and organic matter content was determined by the potassium

Table 1 Physical and chemical properties of the Oxisol, Inceptisol, and Tropical Artificial Soil (TAS) used in laboratory experiments

Attributes	Oxisol	Inceptisol	TAS
pH (KCl)	4.3	4.9	5.0
Cation exchange capacity at pH 7 ($cmol_c\ dm^{-3}$)	5.0	6.1	2.3
Water holding capacity (%)	40.0	59.0	49.0
Organic matter (%)	1.6	2.9	5.0
Texture clay (%)	23	46	20[a]
Silt (%)	3	19	5
Sand (%)	74	35	75[a]
Texture class	Sandy clay loam	Clay	

[a]Value determined by weighing

dichromate ($K_2Cr_2O_7$) method (Walkley and Black 1934). The soil pH and water holding capacity of TAS are 5 and 49%, respectively.

Higher plant growth test

To provide conditions for the development of plants, thirty five days before sowing, the pH of natural soils was adjusted to approximately 6.0 and the base saturation was increased to 50%, by the application of $CaCO_3$ and $MgCO_3$ in a 3:1 molar ratio, as recommended by Alvarez and Ribeiro (1999). Fifteen days before sowing, the soils were fertilized considering the critical levels of nutrients (Alvarez and Ribeiro 1999) and minimum levels of fertilization for plants in pots (Malavolta 1980). Both procedures were performed to avoid reductions in plant growth due to the lack of nutrients in the test substrate, which could mask toxic effects provoked by the presence of the test substance in the soil. A nutrient solution composed of 200 mg P kg^{-1}, 5 mg Zn kg^{-1}, 1.5 mg Cu kg^{-1}, 1 mg B kg^{-1}, and 3 mg Mn kg^{-1} prepared using analytical-grade ammonium dihydrogen phosphate, Zn-sulfate, boric acid, and Mn-sulfate was mixed in the soils. In both incubation periods and throughout the higher plant growth test, the soil moisture was kept at 60% of the water holding capacity.

The fertilized soils were air-dried immediately before receiving treatments. The same concentrations of AcPb and AcK were tested in both soils, comprising a gradient of increasing concentrations of AcPb composed of 0, 78, 157, 314, 628, 1256, 2512, 5024 mg $Pb(CH_3COO)_2.3H_2O$ kg^{-1} and a Pb-free acetate control (AcK; 5320 mg CH_3CO_2K kg^{-1}). The AcPb concentrations were defined following a multiplying factor of two and were prepared by the addition of different volumes of a stock solution of 91.5 g AcPb L^{-1} prepared in distilled water. The acetate concentration in the AcK control was used to have a treatment free of Pb but with an acetate concentration equivalent to the acetate concentration present in the 5024 mg AcPb kg^{-1} treatment (the highest AcPb concentration tested). The AcK control was used in the tests to evaluate the influence of the acetate itself in the final toxicity.

Higher plant growth tests using *Zea mays* (maize) and *Phaseolus vulgaris* cv. Carioquinha (common bean) were performed following ISO 11269-2 (ISO—International Organizations for Standardization 2005). These species were selected due to their relevance as staple crops. Each replicate corresponded to one pot (110 mm height, 120 mm diameter) containing 600 g of soil (dry weight equivalent; DW). Ten seeds were sown in each replicate up to 24 h after the soil spiking and the correction of soil moisture to 60% of its water holding capacity.

Four replicates were used per treatment and plant species. Plant tests were carried out in a growth chamber at 25 ± 2 °C with a photoperiod of 16:8 h (light: dark), using a light intensity of 8.000 ± 2.000 lux in the light periods. Soil moisture was reestablished by capillarity (each test pot was connected to an individual container filled with distilled water through a rope).

The test started after the emergence of 50% of the seeds in the control replicates. In all treatments, surplus plants were trimmed to leave only five plants per pot. During the experiment, the test replicates were randomly distributed within the growth chamber. The N and K nutrients were applied on the 7th and 14th days after starting the test on the soil surface, with a total of 300 mg N kg^{-1} applied as urea and 150 mg K kg^{-1} as a nutrient solution of analytical-grade KCl. After 21 days of the beginning of the test, plants were harvested at the stem base in all replicates. Then, the harvested plants were dried at 75 °C for 72 h and weighted to determine the shoot dry matter (SDM).

Ecotoxicological tests with soil invertebrates

Laboratory reproduction tests were performed using the three soils (Oxisol, Inceptisol, and TAS) without pH adjustment (Table 1) and the springtails *Folsomia candida*, the earthworms *Eisenia andrei*, and the enchytraeids, *Enchytraeus crypticus* as test organisms and following the ISO guidelines 11267 (ISO—International Organizations for Standardization 1999), 11268-2 (ISO—International Organizations for Standardization 1998) and 16387 (ISO—International Organizations for Standardization 2004), respectively.

The organisms used in the tests were grown in the laboratory, at a temperature of 25 ± 2 °C and a photoperiod of 16:8 h light: dark. Springtails were kept in plastic boxes (11 cm diameter and 4 cm height) containing a mixture of plaster of Paris and activated charcoal in a ratio of 11:1 (w:w), being fed weekly with dry granulated yeast. Earthworms were kept in plastic boxes (36 cm length, 22 cm

width, and 11 cm height) with a substrate containing a mixture of horse dung, previously defaunated through two freeze-thawing cycles of 48 h at −20 °C followed by 48 h at 25 °C, and peat in a proportion of 1:1, w-w. Moisture was kept between 40 and 60% of the water holding capacity of the mixture. Earthworms were fed twice a month with one spoon of horse dung. Enchytraeids were kept on Petri dishes (9 cm diameter and 1 cm height) filled with agar as described by Cesar et al. (2015b) and were fed weekly with finely ground autoclave-sterilized oat.

Natural soils were defaunated by two freeze-thawing cycles (48 h at −20 °C followed by 48 h at 25 °C), after which, their microbial community was restored by inoculation of 100 mL of elutriates per kg of fresh soil. The elutriates were obtained by stirring fresh and non-defaunated soil samples with water in a ratio proportion of 1:10 (w:v) for 30 min. After this procedure, both soils were stored for 10 days at room temperature in the dark before being spiked with AcPb or AcK in the laboratory for testing.

In each laboratory test, the invertebrate species were exposed to a concentration gradient composed of the following increasing concentrations of AcPb: 0, 314, 628, 1256, 2512, 5024, 10048, 20095 mg AcPb kg^{-1} soil dry weight and a Pb-free acetate control with 12,121 mg of CH_3CO_2K kg^{-1}. The concentrations selected for the reproduction tests were based on data from the available literature concerning the toxicity of Pb to *Eisenia fetida* (Neuhauser et al. 1985; Spurgeon et al. 1994; Davies et al. 2002, 2003), *Folsomia candida* (Sandifer and Hopkin 1997; Jie et al. 2009) and *Enchytraeus albidus* (Lock and Janssen 2003) using different lead salts as a source of contamination. For each treatment, soil aliquots were spiked through the addition of different volumes of a stock solution of 130.6 g AcPb L^{-1} or 135.2 g AcK L^{-1} (prepared with water) and water to obtain the desired concentration and soil moisture of 50% of its maximum water holding capacity. Soil spiking was performed immediately before the beginning of the laboratory tests. Tests with invertebrate species were performed at 25 ± 2 °C and under a photoperiod of 16:8 h (light: dark).

In the reproduction tests with *F. candida*, ten synchronized organisms 10–12 days old were used per replicate in a total of five replicates per treatment. Each replicate consisted of cylindrical plastic containers (7 cm diameter and 6 cm height) with 30 g of soil (fresh weight). During the experiment, the test organisms were fed by adding ca. 2 mg of dry granulated yeast in the test container at the beginning of the test and after 14 days of exposure. Once a week, the vessels were opened to allow aeration and to restore water losses by the addition of few drops of distilled water. After 28 days the test was finished and the content of each vessel was transferred to a larger container and filled with water. Drops of blue ink were added and the soil was gently stirred in the bottom of the vessels. Then, the water surface was photographed, and the number of juveniles and living adults was determined using the software ImageJ. Soil moisture and pH were measured at the beginning of the experiment in all treatments. An additional replicate without organisms was prepared per treatment for soil pH and moisture determinations at the end of the experiment.

In the reproduction tests with *E. andrei*, four replicates were prepared per treatment. Each replicate consisted of one plastic pot (11 cm diameter and 12 cm height) containing 500 g of soil (dry weight). Ten earthworms with fully developed clitellum, more than two months old, previously rinsed, and 386 ± 74 mg of individual weight (average ± standard deviation; $n = 1080$) were introduced in each replicate. Each test container was covered by a transparent lid with small holes to allow aeration. These covers were used to reduce water losses by evaporation and prevent the organisms from escaping. Fifteen grams of horse dung, previously defaunated, were added to each pot as food at the beginning of the experiment and at the 14th and 28th days of the test. On the 28th day, living adults were removed, counted, and weighted to determine the number of survivals and the percentage of initial biomass. On the 56th day of the experiment, the test ended and the experimental units were placed into a water bath at 50–60 °C to force the juveniles to raise in the soil surface, allowing to determine the number of juveniles in each test container.

In the reproduction tests with *E. crypticus*, replicates containing ten individuals of similar size and developed clitellum were used for each treatment. Four replicates were prepared per treatment, except for control (0 mg AcPb kg^{-1}) in which eight replicates were used. Each replicate consisted of cylindrical glass vessels (6 cm diameter and 9 cm height) with 20 g of soil (dry weight equivalent). Finely ground oats, 2 mg per replicate, were provided as food at the 0, 7th, 14th, and 21st days of the test. Once a week, test containers were opened to allow aeration, and water losses were restored whenever weight losses were higher than 2%. After a test period of 28 days, the organisms were killed by adding a few milliliters of an 80% ethanol solution in the replicates and stained with a few drops of a Rose Bengal solution (1% in ethanol). After 12 h, the soil was rinsed in a 0.25 mm-sieve, enchytraeids were transferred to a Petri dish and the total number of organisms was determined using a binocular magnifying glass (Chelinho et al. 2014). The number of adults could not be determined as the size of juveniles did not allow us to distinguish the surviving adults from some juveniles at the end of the test. Since the number of surviving adults (10 at most) was considerably lower than the number of juveniles at the end of the test, the total number of juveniles was determined by counting all Enchytraeids at the end of the test in each replicate. As for

Table 2 Lead acetate (AcPb) and lead (Pb) nominal concentrations and Pb actual concentrations (mean ± standard deviation; $n = 3$; expressed in mg kg^{-1}) in treatments of Oxisol and Inceptisol (and respective percentages of Pb nominal concentrations for each soil) used in the laboratory higher plant growth tests

Treatment	AcPb nominal	Pb nominal	Oxisol		Inceptisol	
			Pb actual	% of Pb nominal	Pb actual	% of Pb nominal
C0	0	0	4.1 ± 0.3	–	9.9 ± 0.4	–
C1	78	50	49 ± 2.5	98	55 ± 1.5	110
C2	157	100	119 ± 1.7	119	92 ± 2.5	92
C3	314	200	198 ± 2.6	99	188 ± 4.0	94
C4	628	400	412 ± 1.5	103	400 ± 3.1	100
C5	1256	800	796 ± 1.0	99.5	798 ± 2.1	99.8
C6	2512	1600	1599 ± 1.0	99.9	1591 ± 3.0	99.4
C7	5024	3200	3225 ± 0.6	100.8	3187 ± 4.5	99.6
AcK	5320 [a]	0	6.4 ± 0.2	–	8.1 ± 0.4	–

[a]Potassium acetate nominal concentration (in mg kg^{-1})

Collembola reproduction tests, soil pH and moisture were determined at the beginning of the test and an additional replicate without organisms was prepared per each treatment for soil pH and moisture determinations at the end of the experiment.

Chemical analyses

A composite sample was collected per treatment to determine Pb concentration, immediately after soil spiking with AcPb and AcK in all tests. Lead extraction was performed according to the USEPA 3051A method (USEPA 2007). Lead was determined by air-acetylene flame atomic absorption spectrophotometry, with detection and quantification limits of the method of 0.3 and 0.9 mg L^{-1}, respectively (Penha et al. 2017). The reference material BCR 142 R—light sandy soil (Community Bureau of Reference, Brussels) was used to verify the accuracy of Pb measurements. The recovery of Pb ranged between 90 and 110% of the reference material.

Statistical analyses

The shoot dry matter (SDM) of plants, the percentage of initial biomass of surviving earthworms, and the reproductive output of earthworms, collembolans, and enchytraeids were statistically analyzed by one-way ANOVAs followed by Dunnett's post hoc test (Dunnett 1955) to test for significance of the difference between the control and the AcPb contaminated soils and AcK control in each test. When the ANOVA assumptions of normality (Kolmogorov–Smirnov test for $p > 0.05$) and homoscedasticity (Bartlett test (Bartlett 1937), for $p > 0.05$) were violated, Kruskal–Wallis ANOVA by Ranks (Kruskal and Wallis 1952) followed by a multiple comparison test was used.

The effective concentrations—EC_{20} and EC_{50} values—and the respective 95% confidence intervals were calculated to estimate the concentrations that produce 20 and 50% change in the response (i.e., effects) on SDM in plants and reproduction of earthworms, collembolans, and enchytraeids. These values were estimated through non-linear regressions, using an exponential, Gompertz, or Logistic model (EC 2007). The model selected was the one that presented the highest determination coefficient (R^2) and the smallest 95% confidence interval. Non-linear regressions followed the method Levenberg–Marquardt and the assumptions of non-linear regressions were checked by the analysis of the normality of the residuals via Q–Q plots.

One-way ANOVAs and non-linear regressions were performed using the Statistica 7.0 software (Statsoft INC 2004). Significant differences between EC_{50} values of different test soils for the same species or between EC_{50} values of different species in the same soil were determined using a generalized likelihood ratio test.

Results

Lead concentrations in the soils of the control treatment (without the addition of Pb) were 4.1, 9.9, and 7.6 mg kg^{-1} in the Oxisol, Inceptisol, and TAS, respectively. These concentrations for natural soils (Oxisol and Inceptisol) are within the range of values considered normal for Pb *background* in the area (Guevara et al. 2018). The concentrations of Pb in the AcPb treatments in the Oxisol, Inceptisol, and TAS represented the added Pb concentration (Tables 2 and 3). Thus, chemical measurements confirmed that the test organisms (plants and soil invertebrates) were exposed to a gradient of increasing Pb concentrations. Since the actual concentrations showed a percentage of nominal concentrations close to 100%, the effective concentrations (EC_{50} and EC_{20}) were estimated based on the nominal concentrations of AcPb.

The AcK treatments were toxic to all test species (plant, springtails, enchytraeids, and earthworms), considering the

Table 3 Lead acetate (AcPb) and lead (Pb) nominal concentrations and Pb actual concentrations (mean ± standard deviation; $n = 3$; expressed in mg kg^{-1}) in treatments of Oxisol, Inceptisol and Tropical Artificial Soil (TAS; and respective percentages of Pb nominal concentrations for each soil) used in the laboratory reproduction tests with soil invertebrates

Treatment	AcPb nominal	Pb nominal	Oxisol		Inceptisol		TAS	
			Pb actual	% of Pb nominal	Pb actual	% of Pb nominal	Pb actual	% of Pb nominal
C0	0	0	4.1 ± 0.2	–	9.9 ± 0.3	–	7.6 ± 0.3	–
C1	314	200	193 ± 3.1	96.5	191 ± 2.1	95.5	186 ± 2.6	93
C2	628	400	395 ± 1.5	98.8	397 ± 2.6	99.3	392 ± 2.1	98
C3	1256	800	789 ± 2.1	98.6	798 ± 3.5	99.8	788 ± 4.4	98.5
C4	2512	1600	1598 ± 3.0	99.9	1593 ± 3.1	99.6	1596 ± 2.1	99.8
C5	5024	3200	3200 ± 1.0	100	3198 ± 1.5	99.9	3197 ± 4.2	99.9
C6	10,048	6400	6400 ± 1.7	100	6404 ± 2.0	100.1	6437 ± 3.8	100.6
C7	20,095	12,800	12,800 ± 1.2	100	12,790 ± 5.6	99.9	12,807 ± 3.6	100.1
AcK	12,121[a]	0	5.1 ± 0.3	–	9.1 ± 0.3	–	10.3 ± 0.3	–

[a]Potassium acetate (AcK) nominal concentration (in mg kg^{-1})

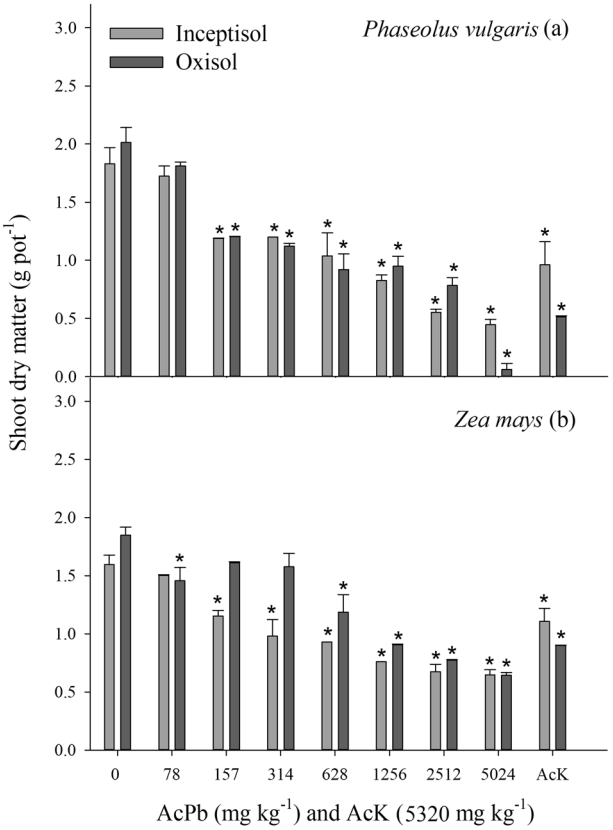

Fig. 1 Shoot dry matter production (average ± standard deviation, $n = 4$) of *Phaseolus vulgaris* (**a**) and *Zea mays* (**b**) when exposed to an Oxisol and an Inceptisol spiked with increasing concentrations of lead acetate (AcPb) or potassium acetate (in a concentration of 5320 mg kg^{-1}; AcK) in a higher plant growth test. *—Shoot dry matter significantly different from respective control (0 mg kg^{-1}; Dunnett's test, $p \leq 0.05$)

Oxisol and Inceptisol for SDM (Fig. 1) and Oxisol, Inceptisol, and TAS for the number of juveniles, and the initial percentage of biomass (Figs. 2 and 3). As expected, Pb chemical measurements in the Oxisol, Inceptisol, and TAS showed that AcK treatments had Pb concentrations (mg kg^{-1}) similar to that of control treatments without application of Pb, for the tests with plants (Oxisol—6.4 ± 0.2 and Inceptisol—8.1 ± 0.4) and soil invertebrates (Oxisol —5.1 ± 0.3, Inceptisol—9.1 ± 0.3 and TAS—10.3 ± 0.3).

In the higher plant growth tests, all validity criteria defined in the abovementioned protocols were met. The percentage of emergence in the control treatment was 80 and 81% for *Z. mays* and 81 and 83% for *P. vulgaris* in the Oxisol and Inceptisol, respectively. For *P. vulgaris*, SDM was significantly affected in both natural soils (Oxisol and Inceptisol) by concentrations higher than or equal to 157 mg AcPb kg^{-1} and in AcK treatment (Fig. 1a). In the Inceptisol, concentrations greater than or equal to 157 mg AcPb kg^{-1} significantly affected *Z. mays* SDM. The same was observed for AcK at 3200 mg kg^{-1} (Fig. 1b). It was observed a significant effect on SDM when *Z. mays* plants were grown in the Oxisol with concentrations higher than or equal to 628 mg AcPb kg^{-1} (628, 1256, 2512, and 5024 mg kg^{-1}), except for the 78 mg AcPb kg^{-1}, which also had a significant effect. A significant decrease was also observed in the AcK treatment (Fig. 1b).

In the laboratory tests with soil invertebrates, all validity criteria were met. In the control treatment, the percentage of adult survival of *E. andrei* and *F. candida* were 98, 100, 100 and 84, 82, 82% in the Oxisol, the Inceptisol, and the TAS, respectively. The mean of juveniles (and associated coefficient of variation) produced in control treatment in the Oxisol, the Inceptisol, and the TAS were, respectively, 41 (20%), 61 (30%), and 44 (10%) for *E. andrei*; 412 (24%), 713 (28%), and 775(29%) for *F. candida*; 573 (37%), 1228 (17%), and 1204 (15%) for *E. crypticus*.

Effects on *F. candida* reproduction were observed in concentrations higher than or equal to 2512 mg kg^{-1} in natural soils, and higher than or equal to 5024 mg AcPb kg^{-1} in the TAS soil (Fig. 2a). The exception was the 314 mg kg^{-1} concentration in the Inceptisol in which significant effects

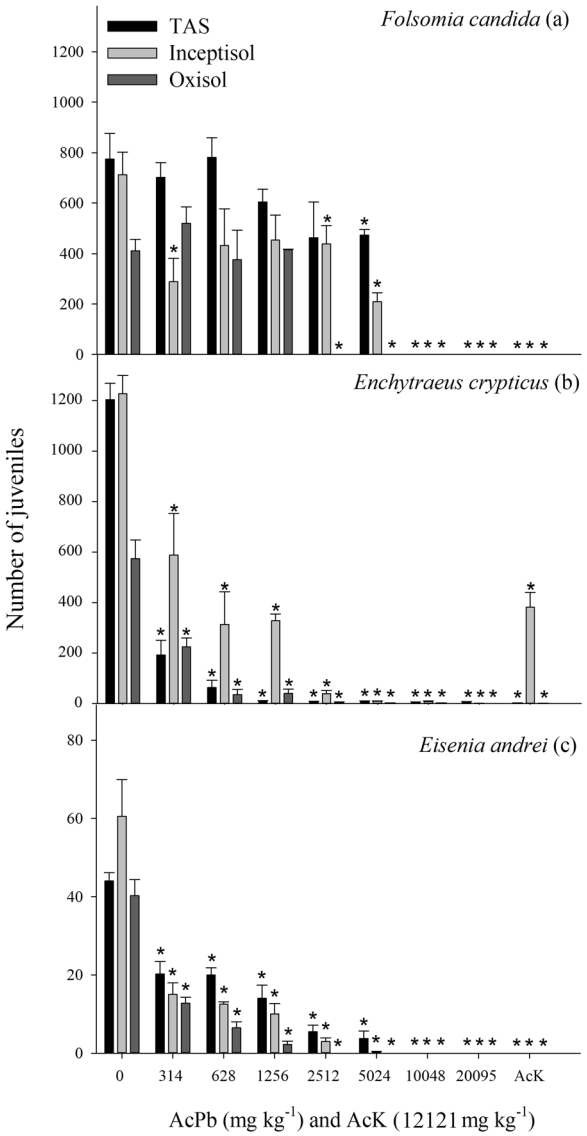

Fig. 2 Number of juveniles (average ± standard deviation, $n = 4$–5) of *Folsomia candida* (**a**), *Enchytraeus crypticus* (**b**), and *Eisenia andrei* (**c**) when exposed to an Oxisol, an Inceptisol, and a Tropical Artificial Soil (TAS) spiked with increasing concentrations of lead acetate (AcPb) or potassium acetate (in a concentration of 12121 mg kg^{-1}; AcK) in laboratory reproduction tests. *—Number of juveniles significantly different compared from respective control (0 mg kg^{-1}; Dunnett's test, $p \leq 0.05$)

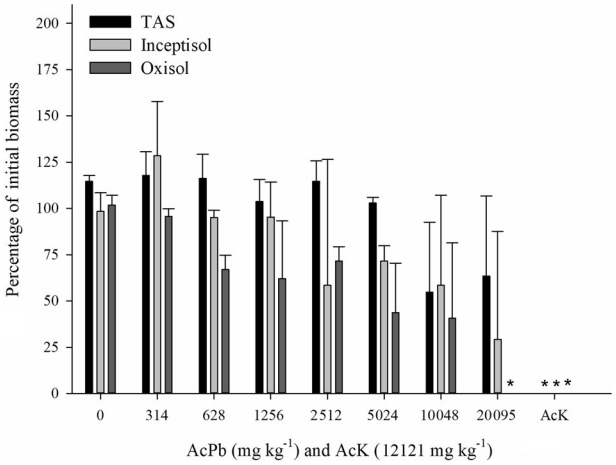

Fig. 3 Percentage of the initial biomass (average ± standard deviation, $n = 4$) of surviving adults of *E. andrei* after being exposed to an Oxisol, an Inceptisol, and a Tropical Artificial Soil (TAS) spiked with increasing concentrations of Pb acetate (AcPb) or potassium acetate (AcK) in laboratory reproduction tests. *—Percentage significantly different from the respective control (Dunnett's test, $p \leq 0.05$)

were observed (Fig. 2a). However, this decrease was not consistent with the reproductive pattern observed over the concentration gradient used in the test. Living adults of *F. candida* were not observed in concentrations higher than or equal to 2512 mg AcPb kg^{-1} in both the Oxisol and the Inceptisol, and in the TAS in concentrations higher than 10048 mg AcPb kg^{-1} (Fig. 2a).

For *E. crypticus* and *E. andrei*, effects on reproduction were observed in concentrations greater than or equal to 314 mg AcPb kg^{-1} (Fig. 2b, c).

Effects of AcPb on *E. andrei* initial biomass were observed only for the highest AcPb (20095 mg AcPb kg^{-1}) concentration in the Oxisol (Fig. 3).

The EC_{50} values for AcPb calculated for the five test species are presented in Table 4. The monocotyledonous *Z. mays* showed a sensitivity significantly lower than that of the dicotyledonous *P. vulgaris* in the Oxisol. In the Inceptisol, the average EC_{50} values for *P. vulgaris* were also lower; however, the confidence interval does not confirm the difference between the EC_{50} values of *Z. mays* and *P. vulgaris*. For the three species of soil invertebrates, in general, the sensitivity decreased in the following order: *E. crypticus* > *E. andrei* > *F. candida*.

Discussion

The toxicity of AcPb changed according to soil type and composition. An increased soil pH can contribute to a reduced concentration of Pb in soil solution, owing to the lower solubility of AcPb (Harter 1983; Alloway 2013). Conversely, the reduction of soil pH following the application of AcPb in the natural tropical soils can be explained by the strong affinity between Pb^{2+} and Fe oxides, namely hematite (Pierangeli et al. 2001a, b), on which the specific adsorption of Pb^{2+} may release H^{+} and cause soil acidification. The influence of pH on Pb toxicity and availability was reported by other authors (Bur et al. 2012; Ardestani et al. 2014; Romero-Freire et al. 2015). The pH reduction following the AcPb addition was not observed in the TAS most probably because this soil is not rich in Fe oxides. Thus, the attributes of natural soils provided greater

Table 4 EC_{50} and EC_{20} values (and respective 95% confidence intervals) for the effects on growth of *Z. mays* and *P. vulgaris* and reproduction of *E. andrei*, *F. candida*, and *E. crypticus* exposed to an Oxisol, an Inceptisol, and a Tropical Artificial Soil (TAS) spiked with increasing concentrations of Pb acetate (AcPb). Values are expressed in mg of AcPb kg^{-1} of soil

Species	Soil	EC_{20}	EC_{50}
		---------mg kg^{-1}---------	
E. andrei	Oxisol	68.8 (5–132)	141.9 (48–235)
	Inceptisol	NV[a]	177.4 (113–245)
	TAS	73.6 (10–138)	370.5 (209–534)
F. candida	Oxisol	NV	1835 (36–3633)
	Inceptisol	NV	3606 (1129–6089)
	TAS	2050.3 (651–3451)	4601.5 (2879–6325)
E. crypticus	Oxisol	NV	52.3 (30–75)
	Inceptisol	NV	72.2 (35–109)
	TAS	NV	29.8 (22–38)
Z. mays	Oxisol	1078.5 (568–1587)	1527.5 (893–2162)
	Inceptisol	NV	1229.3 (490–1967)
P. vulgaris	Oxisol	NV	560.5 (251–871)
	Inceptisol	100.5 (9–191)	802.2 (413–1192)

[a]NV—data not validated by nonlinear regression models ($p < 0.05$)

sensitivity to soil invertebrates exposed to AcPb. Moreover, the results obtained evidenced that the use of TAS could underestimate the toxicity of the test substance, which seems to make the TAS less suitable to assess toxicity of AcPb. This fact gives strength to the use of local natural soils in the assessment of chemicals toxicity, at least in tropical regions. Despite that, the use of an artificial standard soil (i.e. TAS) is still advisable (even when not representing a worst-case scenario) to allow the comparison of toxicity data between laboratories.

Besides pH (Pierangeli et al. 2001a), Pb availability in soils is affected by specific adsorption to soil solid phases (Pierangeli et al. 2001b), precipitation of poorly soluble compounds, and formation of relatively stable complexes and chelates with soil organic matter. Lead sorption is also dependent on the distribution of soil particle-size fractions, owing to their varying reactivity and specific surface area (Romero-Freire et al. 2015; Zhang et al. 2019b). This can explain the increased toxicity observed in the Oxisol compared with the Inceptisol, as the latter has increased clay and organic matter contents relatively to the Oxisol, and these attributes are related to greater Pb retention capacity.

According to Zhang et al. (2019b), soil pH is the main predictive factor for Pb toxicity to enchytraeid reproduction. In that study, *E. crypticus* individuals were exposed for 21 days to the natural standard soils Lufa 2.1, Lufa 2.2, Lufa 2.3, Lufa 2.4, and Lufa 5 M (Speyer, Germany) and a grassland soil, all contaminated with $Pb(NO_3)_2$ (Zhang et al. 2019b). The EC_{50} values for *E. crypticus* reproduction ranged between 81.4 and 1008 mg of Pb kg^{-1}. The lowest value was observed for the Lufa 2.1 soil (OM = 1.3%; CEC = 2.2 $cmol_c$ kg^{-1}; pH = 4.8) and the highest value for the LUFA 5 M soil (OM = 2.6%; CEC = 10.1 $cmol_c$ kg^{-1}; pH = 6.9). The conclusion of Zhang et al. (2019b) was attributed after finding similar EC_{50} values in soils with different properties (CEC, OM content, and clay content), but with approximate values of pH (LUFA 2.4, LUFA 5 M, and grassland soil), indicating that pH was the main factor describing the toxicity of Pb on enchytraeid reproduction. Along with pH, CEC and Ca concentration in porewater were identified as the factors determining EC_{50} and EC_{10} based on total Pb concentration (Zhang et al. 2019b). The three soils used in the present study presented pH around 6.0 after the application of carbonates and the EC_{50} values observed in the natural soils (Oxisol 33.3 mg Pb kg^{-1} and Inceptisol 46 mg Pb kg^{-1}) for *E. crypticus* reproduction were lower for the Oxisol (OM = 1.6%; CEC = 5.0 $cmol_c$ kg^{-1}) than for the Inceptisol (OM = 2.9%; CEC = 6.1 $cmol_c$ kg^{-1}), indicating that the difference of toxicity is probably also related to differences in OM content. Literature data support the high influence of OM content on EC_{50} values (Fig. S1).

The organic matter content in the TAS (5.0%) may have contributed to diminishing the toxic effects of AcPb on soil organisms. However, this was not observed for *E. crypticus*, with an EC_{50} value of 19 mg Pb kg^{-1} being the lowest average EC50 value for the species (plants and soil invertebrates). The different EC_{50} values for *E. crypticus* reproduction in both natural soils (Oxisol and Inceptisol) may be also related to Ca^{2+} concentrations in each soil. It is known that Ca^{2+} outruns Pb^{2+} for specific absorption sites in living organisms (Zhang et al. 2019b). This may have contributed to the reduced toxicity of AcPb in the Inceptisol, as it presented a higher EC_{50} value and higher Ca^{2+} concentration compared with the Oxisol.

The survey of EC_{50} data (Table 5) in the literature for Pb shows how soil chemistry (pH, OM, and Ca), Pb salt used, invertebrate, and plant species influence Pb toxicity (Cheyns et al. 2012; Smolders et al. 2015). In a study with springtails (*F. candida*) exposed to an artificial soil (10% Sphagnum peat, 20% kaolinite clay, and 70% quartz sand) contaminated with $Pb(NO_3)_2$, Menta et al. (2006) did not observe effects from concentrations lower than 500 mg Pb kg^{-1}, and decreased reproduction (16%) was only observed at the 1000 mg kg^{-1} concentration. These results are consistent with the present study since significant decreases in reproduction were not observed in AcPb concentrations lower than 1256 mg kg^{-1} (800 mg Pb kg^{-1}), except for the dose 314 mg kg^{-1} of AcPb (200 mg Pb kg^{-1}) in the Inceptisol. The salt used as a source of contamination may itself influence the performance of the assays. For instance, $Pb(NO_3)_2$ is more toxic to *F. candida* than $PbCl_2$ (Fountain

Table 5 EC_{50} values for the effects on growth of plants and reproduction of soil invertebrates. Values are expressed in mg of Pb kg^{-1} of soil

Site	Soils	Soil properties				Species	EC50 mg kg^{-1}	Pb source	Reference
		pH	CEC cmolc kg^{-1}	OM %	OC %				
Brazil	Oxisol	6.1	5.0	1.6	–	*E. andrei*	90	Pb acetate	Present study
	Inceptisol	5.7	6.1	2.9	–		113		
	TAS[a]	6.0	–	5.0	–		236		
Spain	Calcic Luvisol	7.4	14.3	–	1.2	*E. fetida*	480	Pb chloride	Smolders et al. (2015)
United Kingdom	Dystric Luvisol	6.1	26.5	–	4.3		2400		
		6.1	26.5	–	4.3		4530		
Belgium	Haplic Luvisol	6.2	8.4	–	1.0		1710		
Netherlands	Lufa 2.1[b]	4.9	2.2	1.3	–	*E. crypticus*	81	Pb nitrate	Zhang et al. (2019b)
	Lufa 2.2	5.7	7.6	3.7	–		238		
	Lufa 2.3	5.4	4.0	1.4	–		205		
	Lufa 2.4	6.9	20.1	5.4	–		948		
	Lufa 5 M	7.0	10.1	2.6	–		1008		
	Grassland soil	6.9	20.0	12.8	–		991		
Brazil	Oxisol	6.1	5.0	1.6	–	*E. crypticus*	33.3	Pb acetate	Present study
	Inceptisol	5.7	6.1	2.9	–		46		
	TAS	6.0	–	5.0	–		19		
	Oxisol	6.1	5.0	1.6	–	*F. candida*	1169		
	Inceptisol	5.7	6.1	2.9	–		2297		
	TAS	6.0	–	5.0	–		2931		
Spain	Calcic Luvisol	7.4	14.3	–	1.2	*F. candida*	712	Pb chloride	Smolders et al. (2015)
China	–	6.5	20.1	–	1.6	*F. candida*	2361	Pb chloride	Xu et al. (2009)
China	Forest soil	5.1	15.2	1.21	–	*F. candida*	1244	Pb nitrate	Dai et al. (2020)
Brazil	Oxisol	6.1	5.0	1.6	–	*Z. mays*	973	Pb acetate	Present study
	Inceptisol	5.7	6.1	2.9	–		783		
	Oxisol	6.1	5.0	1.6	–	*P. vulgaris*	357		
	Inceptisol	5.7	6.1	2.9	–		511		
	Rhodic Acrudox	5.7	11.7	4.0	–	*S. bicolor* L.	2359	Pb acetate	Cândido et al. (2020)
	Typic Hapludox	6.3	6.1	2.1	–		2760		
	Typic Hapludox	6.3	6.1	2.1	–	*G. max* L.	1788		
EUA	Udic Argiustolls	4.8	4.1	–	0.4	*L. perenne* L.	785	Pb nitrate	Anderson and Basta (2009)
	Typic Hapludults	5.5	4.1	–	0.7		961		
	Udertic Paleustolls	6.3	14.2	–	1.4		856		
	Aridic Argiustolls	7.8	27.9	–	0.7		2693		
	Typic Endoaquolls	6.1	25.7	–	2.4		4191		
Spain	Calcic Luvisol	7.4	14.3	–	1.2	*L. esculentum*	2900	Pb chloride	Smolders et al. (2015)
United Kingdom	Dystric Luvisol	6.1	26.5	–	4.3		6140		
Belgium	Haplic Luvisol	6.2	8.4	–	1.0		1240		
Spain	Arable land	7.4	14.7[c]	–	1.4	*L. esculentum*	6000	Pb chloride	Cheyns et al. (2012)
United Kingdom	Grassland	6.5	27.1[c]	–	3.1		6500		
Belgium	Arable land	6.7	8.7[c]	–	1.0		2200		
Denmark		5.7	4.2[c]	–	1.5		2700		
Denmark	Grassland	5.2	7.6[c]	–	2.1		1600		
Netherlands		4.7	41.7[c]	–	31.0		5400		
Belgium	Arable land	6.7	8.7[c]	–	1.0	*H. vulgare*	4900		

Table 5 (continued)

Site	Soils	Soil properties				Species	EC50 mg kg^{-1}	Pb source	Reference
		pH	CEC cmolc kg^{-1}	OM %	OC %				
Denmark	Grassland	5.2	7.6[c]	–	2.1		1900		
Netherlands		4.7	41.7[c]	–	31.0		8300		
Spain	Calcic Luvisol	7.4	14.3	–	1.2	*H. vulgare*	2380	Pb chloride	Smolders et al. (2015)
	Dystric Luvisol	6.1	26.5	–	4.3		6750		
	Haplic Luvisol	6.2	8.4	–	1.0		1710		
Australia	Tenosol	7.0	20.9	–	3.0	*C. sativa* L.	4200	Pb nitrate	Kader et al. (2016)
		7.8	7.4	–	5.5		3840		
		6.3	24.1	–	8.4		6250		
		8.7	5.8	–	1.8		3490		
	Ferrosol	5.2	5.3	–	3.5		2240		
		5.3	11.7	–	5.0		4380		
	Vertosol	8.1	24.2	–	1.1		5240		
	Kurosol	5.1	7.3	–	1.5		5590		
	Dermosol	7.4	29.1	–	3.9		5570		
	Calcarosol	8.1	19.3	–	3.5		2560		
Spain	Leptic Cambisol (eutric)	6.7	9.9	–	0.6	*L. sativa*	3479	Pb nitrate	Romero-Freire et al. (2015)
Spain	Leptic Regosol (eutric)	7.2	25.9	–	8.2		6240		
Spain	Leptic Regosol (distric)	5.9	3.8	–	0.5		1303		
Spain	Cutanic Luvisol (chromic)	7.0	15.5	–	0.7		1765		

Values are expressed in mg of Pb kg^{-1} of soil

[a]TAS—tropical artificial soil

[b]LUFA—Landwirtschaftliche Untersuchungs- und Forschungsanstalt, Speyer, Germany

[c]CEC—effective cation exchange capacity at soil pH

and Hopkin 2005) for the same Pb amount. Thus, results from different sources of contamination may not be directly comparable. Nevertheless, the EC_{50} values for *F. candida* reproduction in this study, using AcPb, are consistent with the ones reported generically for Pb (580 to 3160 mg kg^{-1} at 20 °C—ISO 11267:1999; Fountain and Hopkin 2005). The toxicity of AcPb varies among soil invertebrates due to different routes of exposure to the contaminant. Both species *E. andrei* and *E. crypticus* have soft bodies and are directly exposed through their derma, which favors the absorption of contaminants present in the soil solution (Cesar et al. 2015a). *F. candida* has an exoskeleton and, unlike the soft-bodied species, it absorbs the contaminant with water through specialized organs (Peijnenburg et al. 2012). These different exposure pathways may have contributed to the increased sensitivity in the soft-bodied organisms (*E. andrei* and *E. crypticus*) compared with the hard-bodied ones (*F. candida*) (Fig. 2). Generally, *F. candida* organisms have a subcylindrical or spherical body, very fragile, with a cuticle coating their exoskeleton. The exoskeleton molts can eliminate substances accumulated on the body surface, such as metals (Peijnenburg et al. 2012). Besides the dermal contact with the contaminant, the ingestion of contaminated soil organic matter should be also considered as another exposure pathway (Briones 2018).

Shoot dry matter (SDM) is the most relevant variable in toxicity tests with plants (ISO—International Organizations for Standardization 2005). It was observed that *P. vulgaris* SDM was the most sensitive to AcPb exposure in the Oxisol (Tables 4 and S2). It is known that the toxic effects of Pb may be due to its action in vital processes in plants, such as photosynthesis inhibition and nutrient absorption. Also, Pb may impair water balance, hormone status, and membrane permeability and structure (Sharma and Dubey 2005). Furthermore, several factors influence the absorption of metals such as Pb by plants, leading to different toxicity effects among plant species. According to Chlopecka (1994), the absorption of metals by plants is not only

affected by contaminant concentration and form, or by soil physical and chemical attributes, but also by the characteristics of the tested plant species, nutrition, and growth stage. As most of these factors were standardized in the toxicity assays, the main differences are due to traits related to Pb absorption and translocation in soils (root system) and due to the attributes of the tested soils. However, it is worth remembering that little is known about the effects of acetate (in different concentrations) on the absorption of Pb in different plant species.

The higher EC_{50} values for *Zea mays* in the Oxisol (Tables 4 and S2) can be explained by the increased tolerance to Pb concentrations in soil presented by the species (Gupta et al. 2013). Some plant species, such as *Brassica pekinensis* and *Pelargonium* sp. "Frensham," present defense mechanisms when exposed to Pb, with internal pathways for detoxification, including selective absorption, excretion, complexation by specific ligands, and compartmentalization (Arshad et al. 2008; Pourrut et al. 2011). Some species, including *Z. mays*, tolerate Pb by complexation and inactivation, with Pb deposits in cell walls and vacuoles (Wierzbicka and Antosiewicz 1993). On the other hand, plant species with increased sensitivity, such as *Brassica napus* and *Phaseolus vulgaris*, have some metabolic routes blocked by Pb (Gupta et al. 2013).

Exposure to Pb reduces the capacity of nutrient absorption in plants such as *Zea mays*, *Oryza sativa*, *Brassica oleracea*, *Raphanus sativus*, and *Medicago sativa* (Pourrut et al. 2011). Divalent cations, including Zn^{2+}, Mn^{2+}, Mg^{2+}, Ca^{2+}, and Fe^{2+}, are some of the nutrients that can have their uptake reduced by Pb exposure. However, factors associated with the reduction in nutrient absorption are not fully understood (Sharma and Dubey 2005; Pourrut et al. 2011). In the literature, there are reports on the several adverse effects of Pb on plant tissue at the subcellular level, namely chloroplasts disorganization, cell wall damage, and presence of osmiophilic bodies in stems and leaves harvested at the physiological maturity stage (Ferreyroa et al. 2017). Although these parameters were not evaluated in this study, they may have caused the observed phytotoxic effects of AcPb.

Contrasting EC_{50} values were found in different soils contaminated with Pb-nitrate and cultivated with *Lolium perenne* L. (ryegrass; Anderson and Basta 2009). The authors reported EC_{50} values between 795 and 4191 mg Pb kg^{-1} and attributed these differences within soils to clay, Fe oxides, and organic matter contents. The phytotoxic limit for total Pb in soil, i.e., Pb present in all soil fractions, is highly variable, ranging from 100 to 400 mg Pb kg^{-1} (Kabata-Pendias 2004). In most cases, Pb bioavailability is low, which explains the relatively high total concentrations required to induce toxicity. The variation within toxicity limits reflects differences in sorption–desorption in soils, absorption processes in the root–soil solution interface, and the sensitivity of varying species.

The acetate concentration used in the tested soils had a significant saline/toxic effect on soil invertebrates and plant species, which was proved by the AcK treatments. On the other hand, the presence of acetate as a source of organic C may exert a stimulant effect on soil invertebrates (Briones 2018) and may even be beneficial to *Lens culinaris* (lentil) plants under copper stress, with a test in 0.3 and 3.0 mmol L^{-1} Cu concentrations and addition of 10 mmol L^{-1} Na acetate (Hossain et al. 2020). Possibly, at lower concentrations, acetate will also present beneficial effects on Pb stress, and in this study the acetate concentration tested was only related to higher concentrations (acetate) that were added with Pb, 20095 and 3200 mg kg^{-1} for invertebrates and plants, respectively. Acetate can also improve drought tolerance in plants (Kim et al. 2017), as shown with acetate environmental concentrations between 20 and 30 mmol L^{-1} in the soil causing enhanced drought tolerance in both monocots and dicots, such as rice, wheat, maize, and rapeseed plants, being presented as a basic and simple biochemical compound, which connects fundamental metabolism, epigenetic regulation, and hormone signaling. The absence of the benefits of acetate (AcK treatment) in this study can be explained mainly by the high acetate levels added in this treatment.

Considering the effects of AcPb in soils, invertebrates, and plant species, the composition and disposal of products containing AcPb should be carefully evaluated. Disposal of waste containing AcPb may represent a source of environmental contamination. The evaluation of Pb concentrations in plant tissue and invertebrates was not considered in the present study, but Pb uptake by plants and soil invertebrates likely happened, taking into consideration their reduced production, reproduction, and survival.

Conclusions

Lead acetate concentrations tested in the soils showed toxicity to at least one of the tested species (*E. crypticus*, *E. andrei*, *F. candida*, *P. vulgaris*, and *Z. mays*).

The acetate concentrations of 5320 and 12,121 mg kg^{-1} showed toxicity for plants and soil invertebrates, respectively. The effect of various acetate concentrations and its interaction with plants (including bioaccumulation phenomenon) needs to be better understood.

The lower organic matter content associated with smaller CEC in the Oxisol with increasing AcPb concentrations seem to potentiate toxicity to the studied species comparatively to the Inceptisol and the TAS.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Acknowledgements The authors would like to thank the National Council of Technology and Scientific Development (CNPq), the Coordination for the Improvement of Higher Education Personnel (CAPES), and the Foundation for Research Support of the State of Minas Gerais (FAPEMIG) for financial support for this study. Authors also acknowledge the Environment Foundation of Minas Gerais (FEAM) and Universidade Federal de Lavras (UFLA) via cooperation term FEAM–UFLA n° 209101050013, as well as Universidade de Coimbra for the infrastructure and professionals involved in this study. Lastly, the authors thank Juliano Fernandes Mota and Paulo Roger for helping with field and laboratory activities.

Author contributions All authors contributed to the conceptualization, investigation, data analysis, and writing of the manuscript. RCSA: conceptualization, data curation, methodology, formal analysis, writing—original draft, and writing—review and editing. FRDL: writing—original draft and writing—review and editing. GCM: writing—original draft and writing—review and editing. TN: supervision, writing—original draft, and writing—review and editing. JPS: supervision, writing—original draft, and writing—review and editing. LRGG: funding acquisition and writing—review and editing. JJM: conceptualization, funding acquisition, supervision, writing—review and editing, and methodology.

Funding This study was funded by FAPEMIG, The State of Minas Gerais Research Foundation (Grant number APQ 1084/15).

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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