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Effects of biochar addition on toxic element concentrations in plants: A meta-analysis

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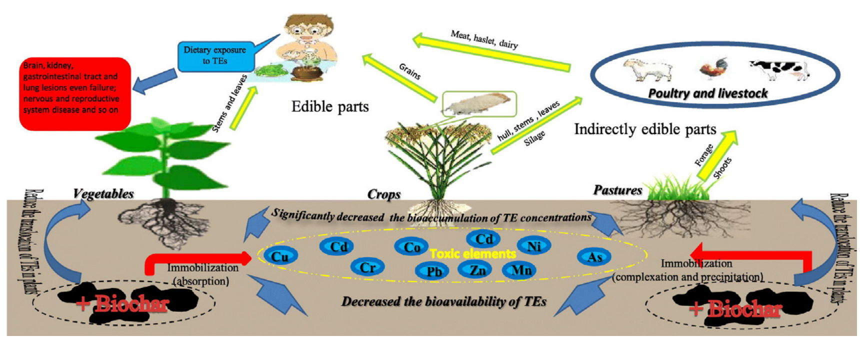
HIGHLIGHTS

- Biochar addition to soil noticeably decreased TE concentrations in plants.
- Feedstock and pyrolysis temperature were main controlling factors.
- Biochar addition significantly decreased TE concentrations in edible parts.
- Mechanisms were hypothesized based on the observed effects of biochar addition.

GRAPHICAL ABSTRACT



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ABSTRACT

Consuming food contaminated by toxic elements (TEs) could pose a substantial risk to human health. Recently, biochar has been extensively studied as an effective soil ameliorant in situ because of its ability to suppress the phytoavailability of TEs. However, despite the research interest, the effects of biochar applications to soil on different TE concentrations in different plant parts remain unclear. Here, we synthesize 1813 individual observations data collected from 97 articles to evaluate the effects of biochar addition on TE concentrations in plant parts. We found that (1) the experiment type, biochar feedstock and pyrolysis temperature all significantly decreased the TE concentration in plant parts; (2) the responses of Cd and Pb concentrations in edible and indirectly edible plant parts were significantly more sensitive to the effect of biochar than the Zn, Ni, Mn, Cr, Co and Cu concentrations; and (3) the biochar dosage and surface area, significantly influenced certain TE concentrations in plant tissues as determined via correlation analysis. Moreover, the only exception in this study was found for metalloid element (i.e., As) concentrations in plants, which were not significantly influenced by biochar addition. Overall, the effects of biochar on TE concentrations in plant tissues were negative, at least on average, and the central trends suggest that biochar has a considerable ability to mitigate the transfer of TEs to food, thereby reducing the associated health risks. Our results provide an initial quantitative determination of the effects of biochar addition on multifarious TEs in different plant parts as well as an assessment of the ability of biochar to reduce TE concentrations in plants.

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1. Introduction

Soil contamination with toxic elements (TEs) has become a global and widespread problem, and it is primarily caused by anthropogenic activities (Tóth et al., 2016; Li et al., 2014; Duruibe et al., 2007; Zhang et al., 2009). Common TEs in soil include arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), nickel (Ni) and zinc (Zn) (Shu et al., 2016; Williams et al., 2009; Nannoni et al., 2016). All of these TEs pose a great risk to human health because of most of them or their compounds are highly toxic carcinogenic substances, especially As, Cd, and Pb. These highly carcinogenic substances, accumulate in various human organs, and can induce organ (e.g., brain, kidney, gastrointestinal tract and lung) lesions and even failure after long-term intake, even at levels below the acceptable daily intake (Satarug and Moore, 2004; Horiguchi et al., 2013; Landrigan et al., 2002 Türkdoğan et al., 2003; Fu and Boffetta, 1995). Chromium, Co, Cu, Mn, Ni and Zn are essential trace elements that are linked to human metabolism at strictly limited concentrations (Nielsen, 1990; Chowdhury and Chandra, 1987; Fraga, 2005). Such TEs accumulate in soil and are transferred into the human body through soil-plant (i.e., crop and vegetable) food chains or soil-plant (i.e., residuum of crops, including the hull, stems, leaves, and some grasses utilized for silage or forage)-poultry/livestock food chains (Hang et al., 2009; Fu et al., 2008). Inhibiting the TEs in food to minimal concentrations is desired for highly toxic elements (e.g., Cd, As, Pb) and to maximum permissible concentrations for toxic but essential elements (e.g., Cu, Zn). Biochar, which is an effective, low-cost and eco-friendly soil ameliorant, has received increasing attention because of its ability to immobilize TEs and reduce their bioavailability in soil, which suppresses the bioaccumulation of TEs (Malińska et al., 2017). Biochar is a carbon-rich porous material that can be derived from agricultural waste or forestry biomass and treatment plant residuum via thermolysis in the absence of oxygen (Lundberg and Sundqvist, 2011). Biochar is recognized for its ability to improve soil properties and safely sequester carbon (Woolf et al., 2010).

Biochar has been investigated to determine its ability to reduce the bioaccumulation of TE concentrations through several mechanisms. For example, in terms of soil, biochar can enhance the immobilization of TEs in soil by altering soil physical and chemical conditions, and such changes decrease the bioavailability of TEs, thereby reducing plant bioaccumulation of TEs (Jiang et al., 2012; Khan et al., 2014; Gul et al., 2015). Previous studies (Bruun et al., 2008; Lundberg and Sundqvist, 2011; Lehmann and Joseph, 2009) have shown that the immobilization of TEs in soil via biochar relies on several factors: (1) the feedstock, ash content and constituents, which refer to the mineral fraction; (2) preparation conditions, particularly the pyrolysis temperature; and (3) soil properties. From the perspective of plants, biochar additions reduce the translocation of TEs in plants, thereby decreasing the TE concentrations in different plant tissues. Moreover, experimental conditions (e.g., biochar application rate, experimental type and duration) also influence the uptake of TEs by plants (Rizwan et al., 2016; Beesley et al., 2011). Thus, numerous experimental studies have been performed to determine the response of different TE concentrations in various plant species and different parts to biochar treatments (derived from various feedstocks with different pyrolysis temperature). However, considerable differences and even contradictory findings have been observed among these studies.

For instance, herbal biochar has been shown to increase Cd concentrations in plant tissues (Prapagdee et al., 2014; Hossain et al., 2010; Moreno-Jiménez et al., 2016), though the same type of biochar decreased Cd bioaccumulation in plants, even drastically (Cui et al., 2011; Jones et al., 2016). Some have also reported that biochar has no significant effect on Cd bioaccumulation in plants (Xu et al., 2016a, 2016b), and inconsistent results have been observed for several TEs (e.g., Pb, As) (Gartler et al., 2013; Houben et al., 2013; Moreno-Jiménez et al., 2016). Biochar application has been frequently reported to increase certain TEs and decrease others under the same experimental conditions. For example, in field applications, herbal biochar (850 °C) could decrease Zn and Cd concentrations and increase Cu and Pb concentrations in plants (Wagner and Kaupenjohann, 2015), whereas biowaste biochar (500 °C) had insignificant effects on Pb, Cu, and Ni concentrations in plants but caused a significant decrease in Cd (Bian et al., 2014). All these results suggest that it is crucial to evaluate the effects of moderator factors (i.e., feedstock, pyrolysis temperature, soil properties, plant species, and experimental conditions) to better understand and utilize biochar to decrease the bioaccumulation of TEs.

Currently, a knowledge gap is observed regarding whether the effects of all types of biochar (mainly affected by feedstock or pyrolysis temperature) on the bioaccumulation of TEs in plants may or may not be significantly negative and whether the magnitude of the response of TE concentrations in different plants and plant parts varies according to the biochar additions. Moreover, an overall perspective on the ability of biochar to the decrease the bioavailability of different TEs in soil and reduce the bioaccumulation of TEs in plants is difficult to obtain because of the different or contradictory datasets.

In this study, the mean effect of biochar addition on the bioaccumulation of TEs was quantitatively analyzed using data extracted from primary studies. We applied a comprehensive meta-analysis and synthesized data from 97 articles. The main objective of our study was to determine and compare the magnitude of the direct effects of biochar additions on different TE concentrations in plants and to ascertain the underlying mechanism based on different types of biochar. The mechanisms were evaluated according to how the biochar addition influenced the bioavailability of TEs in soil. Furthermore, because TEs threaten human health through the food chain, we also evaluated the effect of biochar addition on the bioaccumulation of TEs in different plant parts in terms of their edibility. In particular, the response of the bioaccumulation of TEs (including As, Cd, Pb, Cr, Co, Cu, Ni, Mn, and Zn) in plants to experimental biochar addition was evaluated. We hypothesized that (1) TE concentrations in plants would be significantly reduced by biochar addition; (2) the ability of biochar to decrease the bioaccumulation of TEs would not be influenced by higher pyrolysis temperatures; and (3) the effects of biochar addition on TE concentrations in plants would be significantly influenced by moderator variables (e.g., experimental conditions).

2. Methods

2.1. Data compilation

Peer-reviewed articles evaluating the effects of biochar additions on the bioaccumulation of TEs were identified by searching the *Web of Science* and *Google Scholar* on 23 December 2016 using the keywords “biochar”, “trace element”, “heavy metal”, “TE”, and “bioaccumulation”, and Chinese searches were conducted using *CNKI* (Chinese National Knowledge Infrastructure). There were no restrictions on the publication year. To minimize publication bias as much as possible, the following criteria were applied to the primary studies: (i) the treatment and control groups were the same in all aspects except biochar application; (ii) experiments used a randomized design; (iii) the standard deviation (SD) was provided directly or could be calculated by the standard error (SE); and (iv) the culture medium was soil. After extraction, 97 published articles were included in our database.

Measurements from the last sampling period were collected if multiple measurements were performed throughout the experimental period in the same primary study, because this criterion was required for the statistical assumption of independence among each observation in the meta-analysis (Hedges et al., 1999). Different biochar application rates and/or TEs and/or plants species and/or plant parts under treatment and control conditions were considered individual variables; therefore, several effect sizes were often obtained in a single primary study, even though such effect sizes may not be independent.

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