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The influence of bioavailable heavy metals and microbial parameters of soil on the metal accumulation in rice grain

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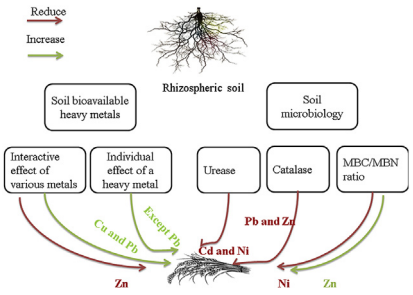
HIGHLIGHTS

- RDA shows that bioavailable metals and microbiology explains 68.9% of the eigenvalue.
- The bioavailable metals measured by BCR method are better for predicting rice metals.
- Soil bioavailable Cd, Cr and Ni enhance Cu and Pb, but reduce Zn in rice grain.
- MBC/MBN, urease and catalase activities are the key parameters affecting rice metals.
- Heavy metals in rice grain decreases by 15.7%–80.5% with sampling distance.

GRAPHICAL ABSTRACT



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ABSTRACT

A field-based study was undertaken to analyze the effects of soil bioavailable heavy metals determined by a sequential extraction procedure, and soil microbial parameters on the heavy metal accumulation in rice grain. The results showed that Cd, Cr, Cu, Ni, Pb and Zn concentrations in rice grain decreases by 65.9%, 78.9%, 32.6%, 80.5%, 61.0% and 15.7%, respectively in the sites 3 (far-away), compared with those in sites 1 (close-to). Redundancy analysis (RDA) indicated that soil catalase activity, the MBC/MBN ratio, along with bioavailable Cd, Cr and Ni could explain 68.9% of the total eigenvalue, indicating that these parameters have a great impact on the heavy metal accumulation in rice grain. The soil bioavailable heavy metals have a dominant impact on their accumulation in rice grain, with a variance contribution of 60.1%, while the MBC/MBN has a regulatory effect, with a variance contribution of 4.1%. Stepwise regression analysis showed that the MBC/MBN, urease and catalase activities are the key microbial parameters that affect the heavy metal accumulation in rice by influencing the soil bioavailable heavy metals or the translocation of heavy metals in rice. RDA showed an interactive effect between Cu, Pb and Zn in rice grain and the soil bioavailable Cd, Cr and Ni. The heavy metals in rice grain, with the exception

Abbreviations: BCR, Community Bureau of Reference; SBR, soil basal respiration; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; SOC, soil organic carbon; STN, soil total nitrogen; CEC, cationic exchange capability.

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Redundancy analysis
Rice grain

of Pb, could be predicted by their respective soil bioavailable heavy metals. The results suggested that Pb accumulation in rice grain was mainly influenced by the multi-metal interactive effects, and less affected by soil bioavailable Pb.

1. Introduction

The bioavailable fraction of a heavy metal in soil plays a vital role in its accumulation in plants. A number of studies have demonstrated that heavy metal uptake by plants is positively associated with the bioavailable concentration of soil heavy metals (Zhao et al., 2010; Zeng et al., 2011; Monterroso et al., 2014). For the evaluation of the bioavailability of heavy metals, various single-step extraction methods are frequently used because of simplicity and ease of operation, and DTPA, EDTA, $CaCl_2$, and $NaNO_3$ have all been adopted as extractants (Feng et al., 2005; Arain et al., 2008). Nevertheless, the reported values of the bioavailable fraction of heavy metals have varied among studies due to the different extraction procedures used, which are operationally based (Prasad, 2013). In addition, according to Mendoza et al. (2006) 's study, single-step extraction might underestimate the heavy metal bioavailability. An alternative approach is the use of a sequential extraction scheme, which permits a more specific extraction, for the analysis of soil heavy metals. One such scheme is the BCR (Community Bureau of Reference) sequential extraction procedure which has been applied widely in the estimation of heavy metal mobility and bioavailability in soils and sediments. For example, Zhong et al. (2011) studied the mobility and bioavailability of soil heavy metals using the sum of the first three fractions of the BCR sequential extraction and which are regarded as being bioavailable. Xiao et al. (2017) reported that the reducible fraction of Cd played an important role in the accumulation of heavy metals in rice grain. Tokalioğlu et al. (2006) noted that the acid soluble and oxidizable fractions of soil heavy metals were positively associated with their concentrations in vegetable. These studies indicate that the first three fractions of the BCR sequential extraction are all bioavailable. The application of a standardized and comprehensive method to evaluate soil bioavailable heavy metal and its influence on heavy metal concentrations in plants could improve understanding of the mechanism of heavy metal accumulation in plants. Thus, this study has evaluated the bioavailable heavy metals by using the first three fractions of BCR sequential extraction, and used this data to investigate the influence of soil bioavailable metals on the heavy metal accumulation in rice grain.

The effects of bioavailable heavy metals on the heavy metal accumulation in plants involve the individual effect and the interactive effect of the soil bioavailable heavy metals on their accumulation in plants (Huang et al., 2009). Generally, the studies investigating the individual effect of soil bioavailable heavy metals on their respective accumulation in plants were conducted on the basis of field investigation (Chang et al., 2014; Li et al., 2014). Nevertheless, with regard to the interactive effect of soil bioavailable heavy metals on their accumulation in plants, most of the previous studies employed pot based experiments (Saifullah et al., 2016; Wang et al., 2016). Gao et al. (2016) also indicate that much research on bioavailable heavy metals in paddy soils and the heavy metal accumulation in plants has been undertaken by means of pot experiments. They note, however, that field conditions are rather more complex and results may differ from those obtained by means of pot experiments and that at the regional scale the association between heavy metals in soils and rice has had little investigation (Gao et al., 2016). There is a research gap for field-based investigation of heavy metals in the soil-rice system. Apart from that, most of the previous studies only concerned the interactive effect between Cd and Zn accumulation in plants, while few studies considered the interactive effect of other heavy metals (Xiao et al., 2017). In addition, the studies regarding the interactive effect of Cd and Zn accumulation in plants have obtained different results. For example, Ma et al. (2017) reported that increasing the Zn ions in soil could restrict the uptake of Cd by rice. However, the study of Green et al. (2016) indicated that increasing Zn supply does not inhibit Cd accumulation by rice. Therefore, there is a need to explore the interactive effect of the soil bioavailable heavy metals on the accumulation of various heavy metals in plants under the real-world field conditions.

Soil microorganisms can affect the soil environment and plant growth through their growth and metabolism (Li et al., 2013, 2017). For example, Li et al. (2013) demonstrate that soil pH increases due to enzymatic reaction in soil and which could change the bioavailability of soil metals, whilst Guo and Chi (2014) found that some plant growth-promoting rhizobacteria can increase the bioavailability of Cd in soil. In addition, Nadeem et al. (2014) indicate that crop productivity could be enhanced by the presence of mycorrhizae and plant growth promoting rhizobacteria under conditions of soil contamination by heavy metals, which could affect the accumulation of heavy metals in plants. Rice is the most important agricultural crop, which accounts for 55% of all cereals consumed annually in China, while heavy metal accumulation in rice grain has posed a threat to food safety and human health (Zhou et al., 2015; Gao et al., 2016; Khan et al., 2017; Rehman et al., 2017). However, the effect of microorganisms and in particular, the influence of the indigenous enzymes and microbial biomass, on heavy metal accumulation by rice grain has not been sufficiently studied, let alone the comprehensive effect of soil microbial parameters and bioavailable heavy metals on the concentration of heavy metals in rice grain. Therefore, there is a need to analysis the influence of soil microbial parameters and bioavailable fractions of heavy metal together in order to better our understanding.

Based upon the above, this field-based study had the following objectives: 1) to assess heavy metal accumulation in rice grain and describe its spatial variation; 2) to analyze the influence of the soil bioavailable heavy metals obtained by a BCR sequential extraction on the heavy metal concentrations in rice grain; 3) to identify the comprehensive impacts of soil microbial parameters, such as microbial biomass and the activities of various enzymes and the soil bioavailable heavy metals on the accumulation of various heavy metals in rice grain.

2. Materials and methods

2.1. Study site description

Area A, area B and area C respectively, were located in Huizhou, Jiangmen and Zhaoqing counties of Guangdong Province (114°30′-114°53′E, 22°26′-22°32′N; 111°59′-113°15′E, 21°27′-22°51′N; 111°21′-112°52′E, 22°47′-24°24′N, respectively), in South China. The region experiences a subtropical monsoon climate with an