



Selenium spatial distribution and bioavailability of soil-plant systems in China: a comprehensive review

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Abstract Selenium (Se) has a dual nature, with beneficial and harmful effects on plants, essential for both humans and animals, playing a crucial role in ecosystem regulation. Insufficient Se in specific terrestrial environments raises concerns due to its potential to cause diseases, while excess Se can lead to severe toxicity. Thus, maintaining an optimal Se level is essential for living organisms. This review focuses first on Se transformation, speciation, and geochemical properties in soil, and then provides a concise overview of Se distribution in Chinese soil and crops, with a focus on the relationship between soil Se levels and parent materials. Additionally, this paper explores Se bioavailability, considering parent materials and soil physicochemical properties, using

partial least squares path modeling for analysis. This paper aimed to be a valuable resource for effectively managing Se-enriched soil resources, contributing to a better understanding of Se role in ecosystems.

Keywords Selenium · Soil properties · Bioavailability · Spatial distribution

Introduction

Selenium (Se) is proven to be a vital micronutrient that is essential for both animal and human health (Zeng et al., 2023; Brummer et al., 2013; Zhang et al., 2010). It plays a pivotal role in disease prevention by bolstering antioxidant defenses, preventing blood clot formation, enhancing nervous system functions, modulating immune responses, aiding in cancer prevention, and displaying antimicrobial and antiulcer properties (Alcantara et al., 2022; Clark et al., 1996; Hawkes et al., 2001; Joseph, 2013; Kumar et al., 2010). However, the impact of Se exhibits a biphasic concentration-dependent pattern. Inadequate Se intake can lead to the development of Keshan disease (KD) (Broadley et al., 2006; Natasha et al., 2018), while too much Se consumption can cause adverse effects such as skin lesions, nail and hair loss, and even fatality (Li et al., 2011). Although Se is not a mandatory nutrient for plant growth, the primary source of Se for the human body is the food chain. Hence, the soil Se content significantly influences

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human Se intake (Wang et al., 2017a, 2017b). However, numerous people in some countries suffer from suboptimal levels of Se in their diet, including New Zealand, Finland, and the United Kingdom. Approximately 15% of the global population, totaling between 500–110 million people, is affected by Se deficiency (Tan et al., 2016). China, as reported by the world health organization (WHO), also faces Se deficiency (Dinh et al., 2018). A survey about nutrition reveals that more than 105 million people in China suffer from serious health issue effects due to living in areas lacking Se (Xu et al., 2012).

The Se content in soil is primarily controlled by the properties of parent materials in the earth's crust. Soil Se distribution has a profound impact on its absorption and accumulation in plants, thereby influencing human health through the food chain to the Se intake (Carina et al., 2015). It is worth noting that previous studies have reported instances where crops grown on Se-enriched land still exhibited Se deficiency (Gandin et al., 2018; Lin et al., 2002). Hence, the Se concentration in plants is influenced by the total Se content in soil and the soil Se bioavailability (Wang et al., 2019; Wen & Carignan, 2007). Several studies suggest that soil Se bioavailability is influenced by numerous factors, including soil pH, soil organic matter (SOM) content, amorphous iron, and mineral composition (Antoniadis & Golia, 2015; Chen, 2012; Wang et al., 2018).

China encompasses a Se-deficient geological belt that extends from the northeast to the southwest, where soil Se content falls below 0.125 mg/kg (Tan, 1989). Conversely, regions with high soil Se concentrations are characterized by local Se-rich rock formations, often leading to endemic selenosis (Li et al., 2012). Furthermore, Se distribution, content, ecological impacts and bioavailability exhibit considerable variation in both Se-excessive and Se-deficient areas (Cao et al., 2013; Tian et al., 2016; Yuan et al., 2012). In Se-deficient regions like Qinling Mountain, Loess Plateau, the Taihang Mountain, and the eastern Tibetan plateau, soil Se content remains below 0.2 mg/kg. In contrast, areas such as Enshi, Hubei and Ziyang, Shaanxi can boast soil Se content as high as 36.69 and 79.08 mg/kg, respectively (Li et al., 2009).

This paper aimed to provide a comprehensive review of total Se content and distribution in crops and soil to enhance our understanding of Se distribution in the environment. Additionally, it examines the

influence of parent materials on soil Se bioavailability and identifies key determining factors.

Data and methods

Data collection

Se data for topsoil and paddy fields were systematically gathered from published sources across China. Simultaneously, additional chemical properties of soil at corresponding locations were collected. This rigorous data collection process adhered to specific criteria outlined as follows and was conducted using two prominent databases, namely, the China National Knowledge Infrastructure and Web of Science: (1) Inclusion of data sourced from the Multi-Purpose Regional Geochemical Survey (MPRGS) took precedence. (2) Soil samples extracted from depths within the range of 0 to 20 cm were considered. (3) Publications were required to include a declaration regarding their quality assurance and control systems. (4) The research in question needed to furnish descriptive statistical information pertaining to Se concentrations in soil. (5) Sampling points were carefully chosen in agricultural areas while maintaining a considerable distance from landfill sites and sites undergoing pollution remediation. (6) The publication time was set from January 1, 2005 to March 31, 2024. This meticulous screening process yielded a total of 129 peer-reviewed papers, encompassing data from 116 distinct cities or regions across China.

Soil and paddy Se content classification

The categorization of Se-enriched land varies depending on different criteria. In China, the delineation of Se content in the ecological landscape was established through investigations into the Keshan disease zone and low Se environments. One classification, for instance, designates soil with Se content falling within the range of 0.175 to 0.450 mg/kg as indicative of sufficient Se levels (Tan, 1996). Another standard designates soil with Se concentrations exceeding 0.4 mg/kg as Se-enriched (Li et al., 2000). Cultivated land characterized by soil Se content within the range of 0.4 to 3 mg/kg is typically classified as Se-enriched land (Ministry of Land & Resources of the People's Republic of China, 2016). In this particular study, the

grading criterion for Se-enriched land was defined as falling within the range of 0.4 to 3 mg/kg, as detailed in Table 1. For Se-enriched paddy fields, the evaluation standard stipulates Se content within the range of 0.04 to 0.3 mg/kg according to General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China and Standardization Administration of the People’s Republic of China (2009).

Bioconcentration factor (BCF)

The BCF for Se was determined using Eq. (1), which quantifies the accumulation of soil Se by plant (Chen et al., 2009; McBride et al., 2014).

$$BCF = \frac{Se_{crop}}{Se_{soil}} \tag{1}$$

where BCF represents a dimensionless factor specific to crops, Se_{crop} denotes the total Se concentration in the crop (mg/kg), and Se_{soil} represents the soil Se concentration (mg/kg).

Partial least squares path modeling (PLSPM)

In this study, we employed PLSPM to validate the connections among soil Se content, grain Se content, and soil characteristics. Latent variables were constructed from four distinct components, namely heavy metals, pH, nutrients, SOM, and soil Se. The latent variable "heavy metals" encompassed Cd, Pb, Cr, As, Cu, and Zn. Additionally, we considered P, N and K_2O as nutrient-related factors. Due to the non-normal distribution of the manifest variables, PLSPM was employed to ascertain the relationship between grain Se and soil properties.

Table 1 Classification standard of soil Se content

Content (mg/kg)	Classification
≤0.125	Serious deficiency
0.125~0.175	Slight deficiency
0.175~0.4	Appropriate
0.4~3.0	Enriched
>3.0	Toxic

Statistical analysis

Using IBM SPSS Statistics v22.0 to obtain descriptive statistics. Spatial distribution maps were generated using ArcGIS v10.3 by Esri (USA). Bar plots and box plots were created using Origin v2022. The PLSPM analysis was performed using the PLSPM package (Sanchez et al., 2017) in R version 3.6.2, developed by the R Core Team in 2019.

Results and discussion

Soil Se geochemical characteristics

Five different forms of Se are found in the soil environment, including Se (0), selenate (VI), selenite (IV), selenide (-II), and organic Se (Krofflic et al., 2016; Santos et al., 2015). Organic Se encompasses methylselenides, trimethylselenium ions, and Se-containing amino acids. These various forms of Se are considered critical factors that influence its toxicological, chemical characteristics, and bioavailability (Galić et al., 2021; Santos et al., 2015). Se bioavailability can be ranked from strong to weak as follows: selenate>organic Se>selenite>Se>selenide (Fordyce, 2013). The speciation and transformation of Se in soil are affected by soil mechanical components, pH levels, and redox conditions. Three primary mechanisms, namely (1) reduction–oxidation, (2) precipitation-dissolution, and (3) sorption–desorption processes, determine the mobility and migration of Se in the soil. These processes involve interactions between Se and other soil constituents such as clay minerals, iron and manganese oxides, and organic matter (Allaway, 1968). Selenite and selenate are the predominant Se forms in soil, both of which are water-soluble. Selenate, particularly, is highly bioavailable and mobile in alkaline soils with good aeration. In contrast, in acidic and reducing conditions, selenite dominates in the deeper layers of the soil (Cao et al., 2001). Selenite exhibits a stronger affinity for metal oxides and soil organic matter (Brown et al., 1999; Levesque, 1974). Se (0) and selenide (-II) are not directly accessible to plants due to their water insolubility (Fernández-Martínez & Charlet, 2009). Seleno-amino acids, on the other hand, display high bioavailability and can be utilized in Se-amended organic fertilizers in soil (Eich-Greatorex

et al., 2007). When seleno-amino acids are introduced in hydroponic plant growth, they lead to greater plant Se accumulation compared to inorganic Se at equivalent concentrations (Bañuelos et al., 2015; Kikkert & Berkelaar, 2013). Soil microbial communities play a pivotal role in Se migration and transformation (Chasteen & Bentley, 2003). Selenate can undergo reduction to Se (0) through soil microbial processes, involving organisms such as *Bacillus selenatarse-natis*, *Escherichia coli*, *Enterobacter cloacae*, and *Thauera selenatis*, under both aerobic and anaerobic conditions (Nancharaiiah & Lens, 2015). Additionally, various soil microbial species like *Burkholderia fun-gorum*, *Stenotrophomonas maltophilia*, and *Escheri-chia coli* have the capability to reduce selenite to Se (0) (Jong et al., 2015).

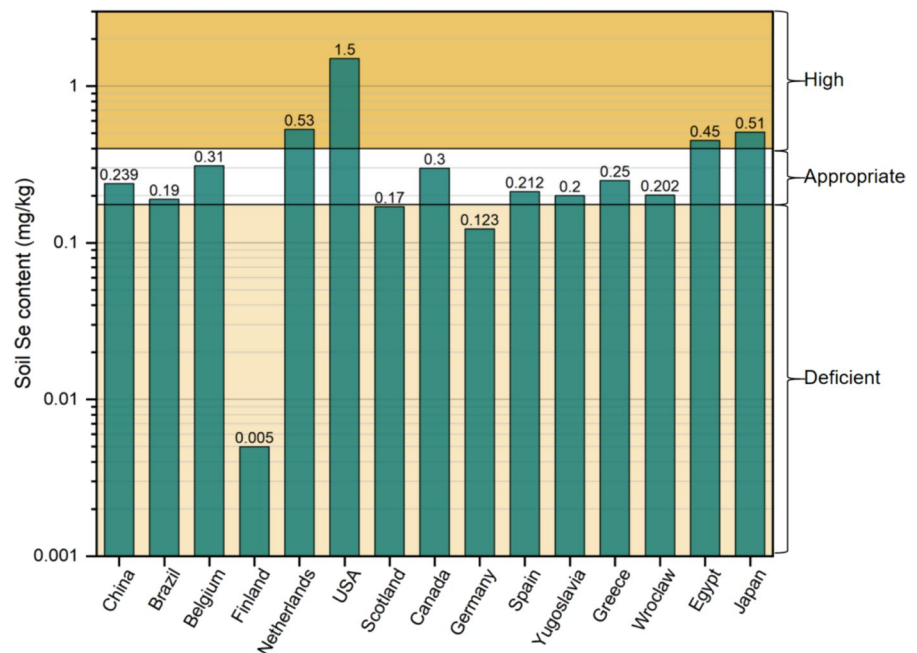
According to binding strength and extractability, Se can generally be partitioned into five fractions: residual Se, organic matter (OM)-bound Se, exchangeable Se, iron (Fe)/manganese (Mn) oxide-bound Se, and water-soluble Se (Feng et al., 2013; Wang & Chen, 2003). These fractions exhibit varying degrees of bioavailability and mobility. In natural settings, exchangeable and water-soluble Se are highly mobile and are less prone to adsorption onto soil particles (Hu et al., 2014; Kulp & Pratt, 2004; Zhao et al., 2005). Although OM-bound Se has lower

bioavailability than the water-soluble and exchange-able forms, it can be stored in the soil and gradually released into the soil solution (Abrams et al., 1990). In contrast, residual Se and Fe/Mn oxide-bound Se exhibit the lowest bioavailability, as they are strongly bound to soil components.

Spatial distribution of soil Se concentration in cultivated areas across China

Numerous countries around the world, including some European nations (Yang et al., 2022), grapple with Se deficiency. The global spatial distribution of Se content in soil is presented in Fig. 1. As depicted in Fig. 1, Se concentrations exhibit significant regional disparities, with areas experiencing deficiency (e.g., Finland, Scotland, and Germany), regions with adequate levels (e.g., China, Brazil, Belgium, Canada, Spain, Yugoslavia, Greece, and Wroclaw), and a few areas with high Se content (e.g., Netherlands, USA, Egypt, and Japan). Notably, China is among the countries facing Se deficiency, with approximately 72% of its territories classified as Se-deficient. This study covers Se research in agricultural soils across 28 provinces in China. We examined the number of research cases conducted in each province, revealing that Guizhou Province (18) had the highest number

Fig. 1 Global soil Se content. Data are from various global studies: Gabos et al., (2014), Temmerman et al., (2014), Mora et al., (2015), Supriatin et al., (2015), Gutenmann et al., (1979), Ure et al., (1979), McKeague and Wolynetz (1980), Diaz-Alarcon et al., (1996), Maksimovic et al., (1992), Eliopoulos et al., (2020), Patorczyk-Pytlik and Kulczycki (2009), Elsokkary (1980), Yamada et al., (2009)



of soil Se research cases, followed by Guangxi (15), Sichuan (9), Anhui (7), Fujian (7), Shandong (7), Guangdong (5), Heilongjiang (5), Jiangxi (5), Shaanxi (5), Hubei (4), Yunnan (3), and Zhejiang (3). Other provinces had fewer than 3 cases, and no cases were retrieved from Taiwan, Macao, Shanghai, Beijing, Shanxi, or Liaoning.

In this study, the average concentration of Se in soil is 0.45 mg/kg, which is higher than the Clark value of 0.13 mg/kg (Rudnick & Gao, 2003). The soil Se concentration of the cases retrieved are above the Clark value in most cases, with only two cases lower than 0.13 mg/kg. Se-enriched arable land is defined as having Se concentrations between 0.4 and 3 mg/kg. Soil Se levels, illustrated in Fig. 2, is based on mean values reported in previous research. The data reveal

that 4.3% of cases fall into the categories of slight and severe deficiency, while 43.1% are classified as adequate, and 52.6% as rich in Se. Generally, Se-enriched cases are concentrated in the southeastern regions of China, primarily encompassing Guangxi and Guizhou Province. In contrast, the North and Northeast regions of China generally exhibit soil Se content below the rich Se grade. Consistent with prior studies, the Se deficiency zone in China extends from northeast to southwest, spanning regions such as Heilongjiang, Jilin, Liaoning, the Loess Plateau, Sichuan, Yunnan, and the eastern Tibetan Plateau. The average Se content within this belt is only 0.1 mg/kg, significantly lower than other areas in China. In the southeastern region of the belt, soil Se content gradually increases in yellow soil, red soil, laterite, and paddy

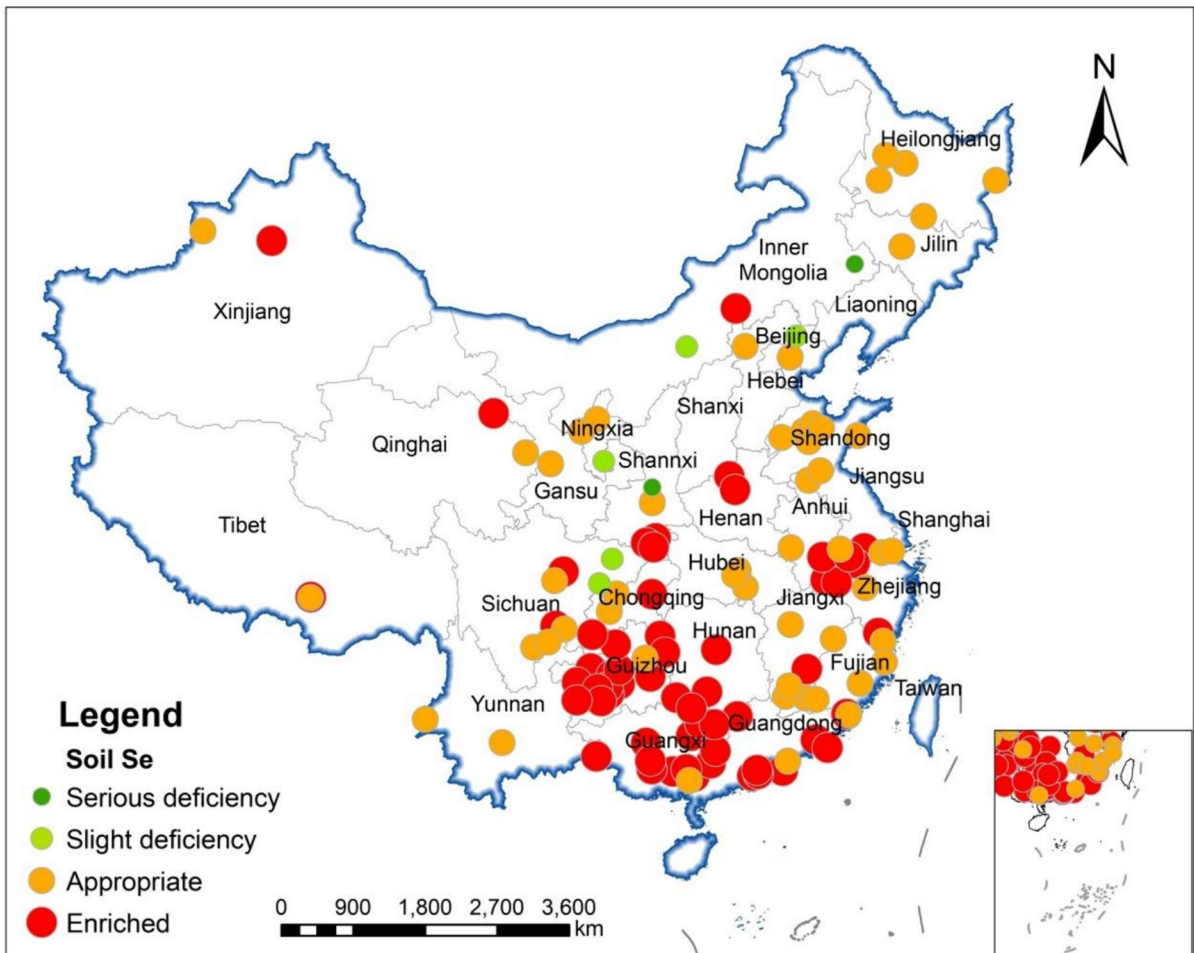


Fig. 2 Spatial distribution of soil Se concentration in China

soil. Conversely, in the northwest region of the belt, soil Se content declines in chernozem, chestnut soil, sierozem, and desert soil. This spatial pattern of soil Se distribution resembles a saddle-shaped trend surface, with low content in the central region and higher content in the southeast and northwest regions. To assess the distribution of heavy metal pollution in cultivated land, the MPRGS was conducted in China. Up to 2014, the survey identified Se-enriched cultivated land covering approximately 34,960 km², primarily concentrated in Fujian, Guangdong, Hainan, Hunan, Hubei, Anhui, Guizhou, Jiangsu, Zhejiang, Shanghai, Shanxi, and Henan Province (China Geological Survey, 2015).

Table S2 and Fig. 3 present Se concentrations originating from different parent materials, highlighting their significant role as the primary Se source in natural soil ecosystems (Yang et al., 2022). Se concentrations vary across geological origins, with quaternary sediment ranging from 0.13 to 0.84 mg/kg (average: 0.38 mg/kg), clasolite-derived soil ranging from 0.14 to 0.95 mg/kg (average: 0.44 mg/kg), carbonatite-derived soil ranging from 0.13 to 0.96 mg/kg

(average: 0.51 mg/kg), intermediate and acid rock-derived soil ranging from 0.15 to 0.67 mg/kg (average: 0.36 mg/kg), basic and ultrabasic rock-derived soil spanning from 0.053 to 1.51 mg/kg (average: 0.53 mg/kg), metamorphic rock-derived soil varying from 0.18 to 0.60 mg/kg (average: 0.37 mg/kg), coal measures-derived soil covering a wide range from 0.35 to 2.51 mg/kg (average: 1.08 mg/kg), and black shales-derived soil extending from 0.05 to 0.89 mg/kg (average: 0.50 mg/kg). In summary, the hierarchy of Se concentration in soil from different parent materials can be succinctly summarized as follows: coal measures > basic and ultrabasic rock > carbonatite > clasolite > black shales > quaternary sediment > intermediate and acid rock > metamorphic rock. This observed trend underscores the significant influence of parent materials on soil Se concentrations, in line with the previous findings of Layton-Matthews et al. (2013), and supported by empirical data and prior research.

By statistical comparison, the Se content showed some differences between different soil types as follows (Table S3 and Fig. 4): red soil (average:

Fig. 3 Se concentration in soil derived from different parent rock materials

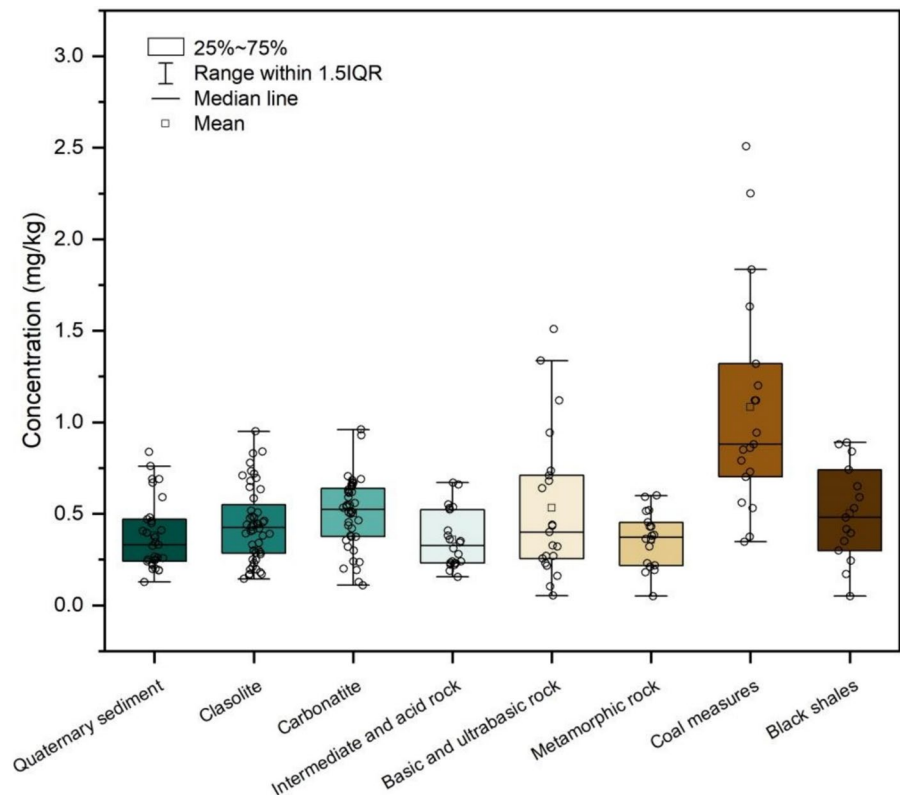
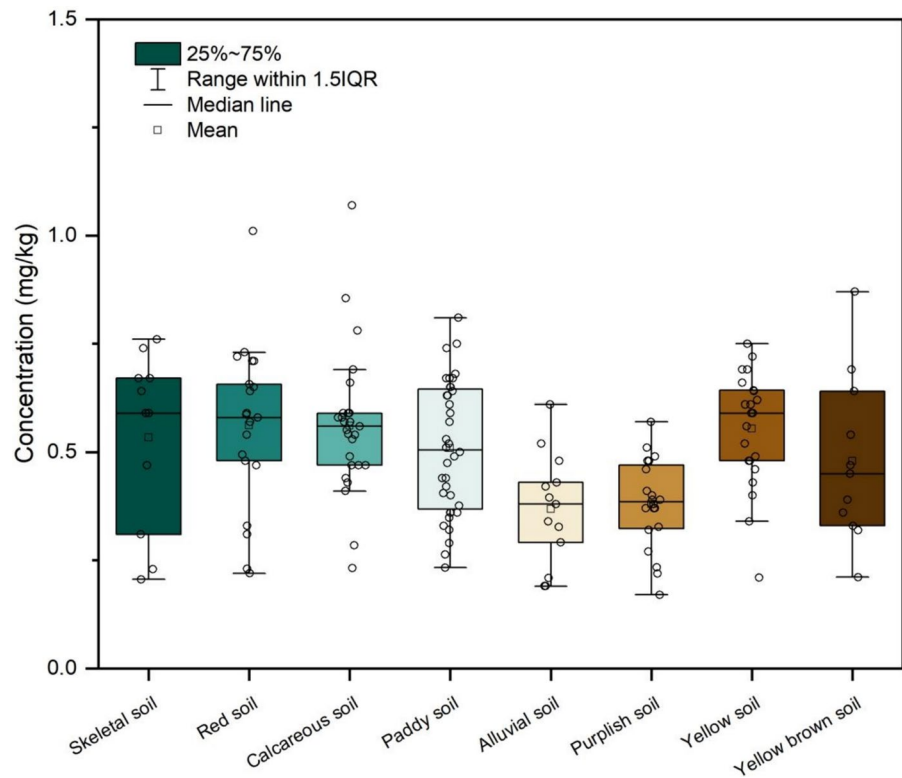


Fig. 4 Se concentration in different soil types



0.562 mg/kg) > calcareous soil (0.561 mg/kg) > yellow soil (0.554 mg/kg) > skeletal soil (0.534 mg/kg) > paddy soil (0.509 mg/kg) > yellow brown soil (0.479 mg/kg) > purplish soil (0.381 mg/kg) > alluvial soil (0.368 mg/kg). Under the alternating action of redox reduction, paddy soil has high acidity and strong water and fertilizer retention ability, which is conducive to the accumulation of organic matter and selenate. Purplish soil is developed from the weathering of purple sand shale, which is prone to soil erosion. Purplish soil belongs to sandy loam soil, which may be the reason for the low content of Se.

China, with its vast territory encompassing diverse parent materials, exhibits variable Se concentrations in soil across different regions, as mentioned above. The prominent role of coal measures in governing soil Se content has been consistently demonstrated in numerous studies. For instance, the Se content in Ziyang County, Shaanxi Province, is predominantly influenced by black shale series, carbonaceous slate, and siliceous slate from the Cambrian era (Long & Luo, 2017). Enshi Tujia and Miao Autonomous Prefecture, characterized as a typical coal measures

region, boasts soil Se levels reaching up to 1.49 mg/kg (Li et al., 2017).

Spatial distribution of Se in crop across China

Rice and wheat are the predominant cereal crops in China, and their Se content exhibits regional variations. For spring wheat, the average Se content is distributed as follows: northwest > north > northeast. For winter wheat, the average Se contents rank as follows: northwest > east > southeast > central > south. Overall, wheat grains in northwest China tend to have relatively high Se content. Conversely, southeastern China exhibits elevated Se levels in rice grains (Fig. 5). On average, wheat contains 0.0571 mg/kg of Se, while rice contains 0.061 mg/kg. It is worth noting that previous research has highlighted wheat as a highly efficient accumulator of Se, which accounts for its higher Se content compared to rice (Christophersen et al., 2013; Gupta & Gupta, 2017). The discrepancy between our study's findings and others can be attributed to regional variations in soil Se content across China. As previously mentioned, the southeastern region of China has higher Se

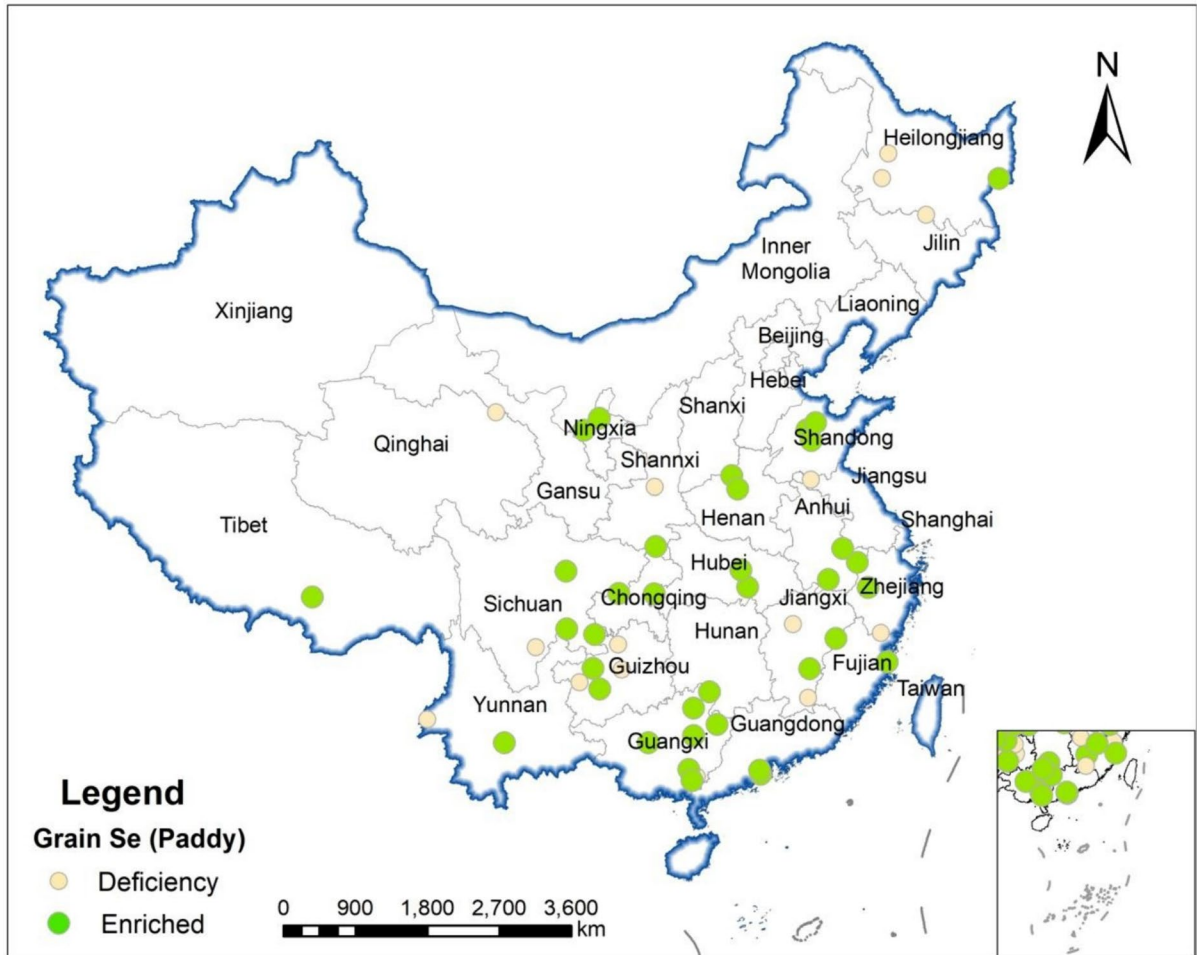


Fig. 5 Spatial distribution of Se concentration in paddy grains in China

content, particularly in areas where rice is primarily cultivated. Additionally, the cultivation of wheat is observed in regions traditionally characterized by selenium deficiency. (Dinh et al., 2018; Higuchi, 2014). However, it is crucial to acknowledge that the Se content in soil alone does not solely determine the Se content in rice; the bioavailability of Se also plays a non-negligible role (Statwick & Sher, 2017). There are also some related researches reveal that the difference of rice varieties also leads to the difference of Se content in crops. In one experiment, *Oryza sativa* L. low grain Se cultivar *Hefengzhan* and high grain Se cultivar *Fengbazhan* were used as test materials. The results showed that the grain Se content of high Se varieties was significantly higher than that of low Se varieties (Zhang et al., 2019). The content of Se

in different parts is quite different. The content of Se in each part was root > leaf > stem \approx seed, indicating that during the transfer process of Se in soil to crops, a considerable part of Se was enriched in the roots and leaves of rice, and the content of Se in the edible part was less.

The Se content in rice grains extending from 0.012 to 0.241 mg/kg. Notably, in Se-rich industrial areas of China, such as Enshi and Ziyang, the Se content in rice greatly surpassed the global averages, reaching levels of 2.11 mg/kg and 0.71 mg/kg, respectively, compared to the global average of 0.095 mg/kg (Williams et al., 2009). Furthermore, in Ziyang, Se content in rice grains surpassed the threshold of Se-toxicity established by Tan (1989) at 1 mg/kg. However, across most regions of China, the average Se content

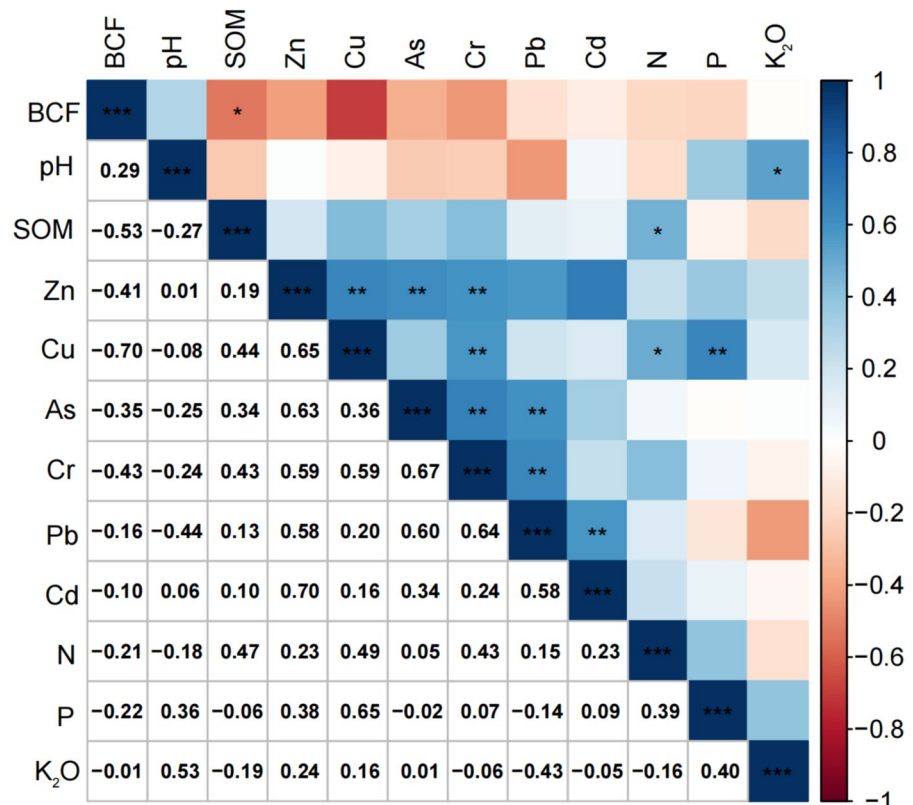
in rice either remained lower than or comparable to global levels. The WHO (2004) proposed a Se-deficiency limit in grains at 0.05 mg/kg, a threshold that some Se-deficient regions in rice production did not meet, registering levels below 0.05 mg/kg. Additionally, regional variations were observed in the average Se content of wheat, ranging from 35.9 to 119.8 mg/kg (Cui et al., 2017). Comparatively, in northeast, central, and south China, the Se content in wheat fell below the threshold of Se-deficiency outlined by the WHO (2004) at 0.05 mg/kg.

Correlation between BCF and soil physicochemical properties

The total Se content in the soil is a fundamental indicator of potential plant Se uptake. However, numerous studies have illustrated that plant Se acquisition is not solely dependent on the overall Se concentration but is also strongly associated with the soil Se bioavailability. Therefore, certain regions may exhibit high Se concentration in the soil but not in the grains (Zhu et al., 2008). BCF

provides a measure of soil Se bioavailability to some extent. A Pearson correlation analysis demonstrates a robust negative association between BCF and SOM ($r = -0.53, P < 0.05$), consistent with the findings of Xing et al. (2015) (Fig. 6). Previous research has indicated that Se availability in the soil is influenced by various physicochemical soil properties, including the content of OM (Qin et al., 2012; Wang et al., 2018). OM-bound Se represents a potential source of Se available for plant uptake as it can be released into the soil solution through mineralization processes (Antoniadis & Golia, 2015; Dhillon et al., 2019; Kulp & Pratt, 2004). In natural soils, OM-bound Se encompasses Se bound to humic acid (HA) and fulvic acid (FA), constituting over 50% of total Se content in natural soils (Wang et al., 2017a, 2017b). Se associated with FA in lighter forms can readily undergo mineralization into inorganic Se and seleno-amino acids. In contrast, Se bound to HA is more stable and presents challenges for plant uptake (Chang et al., 2019; Coppin et al., 2006). Interestingly, Beguería et al. (2013) observed a positive correlation between

Fig. 6 Correlation between BCF and soil physicochemical properties. Statistical significance levels are denoted by *, **, and *** for $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively



Se bioavailability and soil organic carbon. This relationship may be linked to the transformation between OM-bound Se and water-soluble Se during the decomposition of SOM (Natasha et al., 2018; Supriatin et al., 2015). Overall, SOM exerts a dual influence on the bioavailability of Se.

The findings reveal a slight positive correlation ($r=0.29$) between BCF and soil pH, although this relationship was not statistically significant. This aligns with previous research that acknowledges the typical decrease in Se bioavailability in soil as pH levels decrease (Frost & Griffin, 1977). pH plays a pivotal role in Se adsorption onto clay minerals and oxy-hydroxides, thereby affecting Se bioavailability in soil. An increase in pH results in a reduction in positive surface charge on clay minerals and oxy-hydroxides, leading to decreased Se adsorption onto these minerals (Deng et al., 2015; Shand et al., 2010; Wiederhold, 2015). Thus, the bioavailability and Se content in acidic soil are lower compared to neutral or alkaline soils.

Amorphous iron, a colloidal mineral in soil with a positive charge and active iron oxide characteristics, can form stable complexes with SeO_4^{2-} and precipitate alongside iron hydroxides (Wadgaonkar et al., 2018). This coexistence of iron hydroxides and amorphous iron likely reduces the availability of Se (Jia et al., 2019). It is noteworthy that the soil's pH plays a crucial role in controlling the adhesion of iron oxides to Se, with greater adsorption capacity as soil pH decreases (He et al., 2018). For the correlation between Se and some heavy metals, there are some researches reveal that Se is a non-metallic element, and its chemical properties are similar to sulfur (S), phosphorus (P). Se usually combined with heavy metal elements to form compounds in rock. In the process of rock weathering to form soil, Se and heavy metals are released together, and the spatial distribution of the two is closely related, so it can also be judged that Se in the surface soil comes from the parent material of the soil to a certain extent. On the other hand, Se mainly exists in the form of selenite in moist and acidic soils, and tends to form relatively insoluble complexes and compounds with half oxides of iron, manganese and aluminum (Fe_2O_3 , MnO_2 , Al_2O_3) or be trapped by metal hydroxides (especially $\text{Fe}(\text{OH})_3$). Therefore, Se is easily enriched in iron-rich, manganese and aluminum-rich environments.

Relevant determinants influencing the bioavailability of soil Se

To explore the impact of soil properties on the bioavailability of Se (Fig. 7), we utilized PLSPM to assess the relationships between independent variables (e.g., pH, SOM, heavy metals) and dependent variables (e.g., rice grain Se and soil Se). We distinguished their effects as direct and indirect, with arrow values indicating the strength and direction (positive or negative) of these influences.

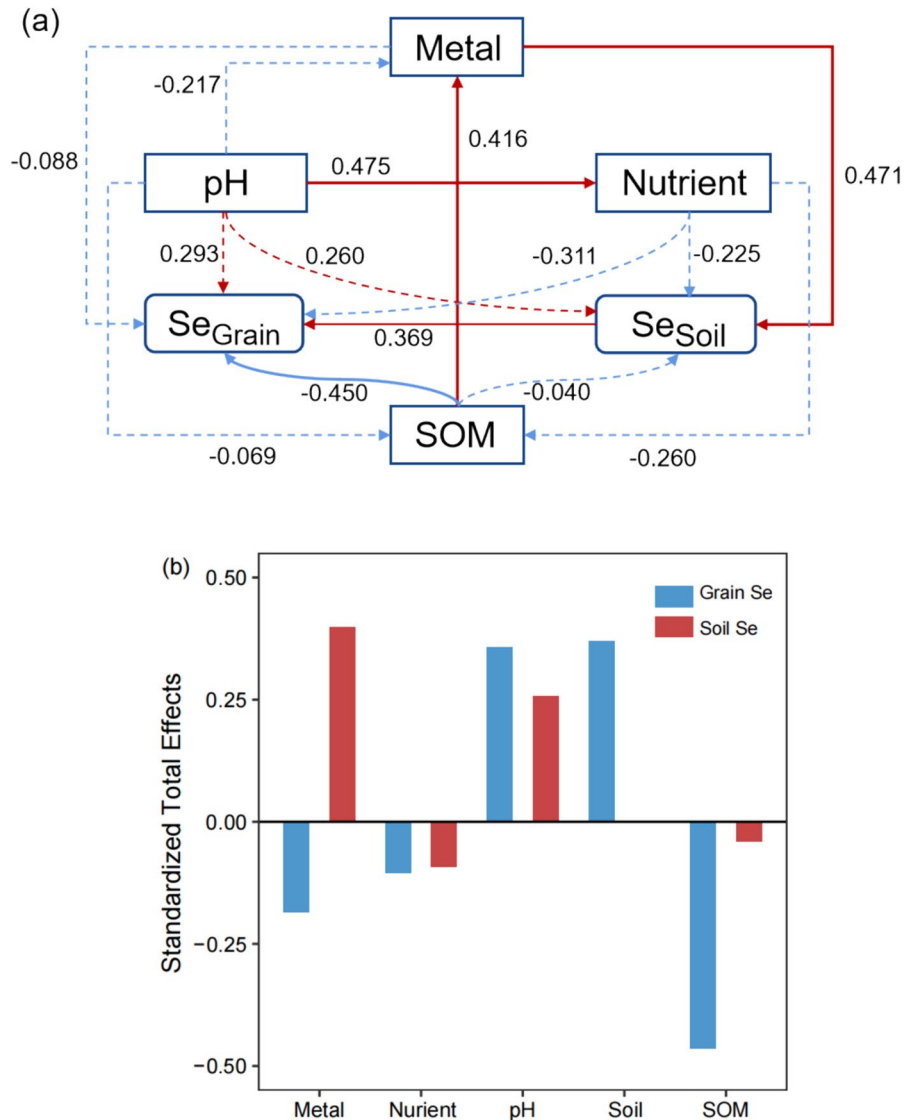
As illustrated in Fig. 7, heavy metals exhibited a positive influence on soil Se, while nutrients and SOM exerted a negative impact on soil Se, with heavy metals demonstrating the most substantial effect (path coefficient: 0.471). Furthermore, SOM displayed a significantly positive effect on rice grain Se, with a path coefficient of -0.450. In contrast, soil Se content positively affected rice grain Se, with a path coefficient of 0.369. Notably, it became evident that rice grain Se content increased with higher levels of soil Se. Consequently, SOM and heavy metals had a more pronounced influence on rice grain Se content compared to other soil physicochemical properties, affirming the outcomes of Pearson correlation analysis.

Conclusions and future perspectives

Se has dual effects, presenting both potential benefits and risks to humans, animals, and plants. The concentration of Se in soil plays a significant role in its uptake by plants, subsequently affecting human Se levels. Furthermore, the bioavailability of soil Se is a critical determinant of Se deficiency in humans. This review investigates the current spatial distribution of grain and soil Se in China, with a specific emphasis on parent materials and their impact on Se bioavailability. The following sections highlight key points for consideration:

- (1) China exhibits significant regional variations in soil Se levels. Despite analysis method differences, we found that the results of most studies were consistent in overall trends. This suggests that significant variability in Se levels in soil and plants may reflect environmental and geographic differences more than differences

Fig. 7 Major influencing factors and regulatory pathways of soil and grain Se contents. Blue and red arrow lines represent positive and negative path coefficients, respectively, with line width indicating the strength of the corresponding path coefficient. Solid lines indicate significant path coefficients, while dashed lines signify non-significant ones (a), along with standardized total effects (b)



in experimental methods. Se-deficient regions are concentrated along a geographical belt from southwest to northeast China, with an average Se concentration of 0.1 mg/kg. Some Se-rich areas are sporadically found, primarily in Guangxi and Guizhou Province. Additionally, there are reports of Se-toxic areas, such as Ziyang in Shaanxi and Enshi in Hubei. However, certain provinces, including Tibet, Xinjiang, and Qinghai, lack sufficient study cases, limiting our understanding of Se geochemical behavior in these regions. Therefore, further research is warranted to enhance our

knowledge of Se dynamics in the environment of China.

- (2) In most regions, soil Se concentrations are primarily influenced by the geological parent rock materials. Igneous rock serves as the primary source of the Se cycle, with high Se contents also observed in siliceous rock and medium-deep metamorphic rock. In sedimentary rock environments, such as Mesozoic black shale and coal, Se is the main source. Nevertheless, parent rock materials play a pivotal role in determining soil Se concentrations, although other fac-

tors like weathering and organic matter can also exert influence. Se-rich areas can be categorized into various scenarios based on their parent rock materials.

- (3) While the total Se concentration in soil is an important criterion for assessing soil Se richness, numerous studies have indicated that plant Se uptake is not solely determined by the total Se concentration in soil. It is also closely correlated with the soil Se bioavailability. Key soil physicochemical properties, including organic matter content, iron/aluminum oxide content, pH, and mineral composition, significantly impact soil Se bioavailability.
- (4) The process of Se transport from crops to humans is impacted by various factors, and the actual Se content in the human body may not be as high as previously assumed. Further studies should advance our understanding of Se speciation and concentration in the human-food chain, with a focus on assessing Se status in humans.
- (5) Establishing precise criteria for categorizing Se in soil and cereals is crucial for effective biofortification programs. Comprehensive research is required to thoroughly assess Se bioavailability in Chinese soil, including an analysis of contributing factors.

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Data availability Data is provided within the manuscript or supplementary information files.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors declare no competing interests.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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