Selenium in wheat from farming to food

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Abstract

Selenium (Se) plays an important role in human health. Approximately 80% of the world's population does not consume the recommended Se levels. Wheat is an important staple food and Se source for most people in the world. This article summarizes literatures about Se from 1936 to 2020 to investigate Se in wheat farming soil, wheat, and its derived foods. Selenium fortification and the recommended Se level in wheat were also discussed. Results showed that Se contents in wheat farming soil, grain, and its derived foods were 3.8–552 (mean, 220.99), 0–8,270 (mean, 347.30), and 15–2,372 (mean, 211.86) $\mu g \cdot kg^{-1}$, respectively. Selenium content could be increased by leaf Se fertilizer application, and the contents in grain, flour, and its derived foods could be improved from 93.94 to 1,181.92, 73.06 to 1,007.75, and 86.90 to 587.61 $\mu g \cdot kg^{-1}$ in average. Both Se content in farming soil and grain, foliar Se fertilizer concentration rate and grain Se increased rate showed significant linear relationship. The recommended Se fortification level of wheat in different countries was calculated in China, India, and Spain, with recorded values of 18.53–23.96, 2.65–3.37, and 3.93–9.88 $g \cdot hm^{-2}$, respectively. Thus, suitable Se fortification in farming effectively improved Se content in wheat grain and its derived foods. Appropriate milling processing and food type are also important factors to be considered to meet people's Se requirement by wheat.

INTRODUCTION

Selenium (Se) is a metalloid element of group VI A in the fourth period of the periodic table of the elements. It was first discovered by Swedish scientist Berzelius JJ in 1817 and named it after the Selene, the goddess moon(1). However, researchers discovered in 1934 that the "alkaline soil disease" and "stumble" of animals were caused by excessive intake of Se. Since then, research on Se has mainly been based on its toxicity(2). In 1860s, Se was determined as an essential element in animals and human bodies and has gradually gained widespread attention worldwide(3). Selenium is among the 14 essential trace elements in human body. It is also an important component of Se-containing proteins and enzymes in galacturids(4). Selenium is closely related to the health, but its total amount in the human body is only 14–20 mg(5). Selenium deficiency can cause more than 40 kinds of diseases, such as Keshan disease, large bone nodule disease, anemia, infertility, and muscular dystrophy(6). Moreover, excessive Se intake can cause hair and nail loss, skin ulceration, nerve damage and other toxic symptoms(7). Therefore, a safe and suitable daily Se intake should be maintained. The range of Se intake recommended by World Health Organization (WHO) is 50–400 μg/day(8). More than 40 countries in the world lack Se, and approximately 80% people do not

consume the recommended Se intake(9). In addition, Se bioavailability in human body is not high with values ranging from 10% to 85%(10), and Se can only be ingested through diet. Therefore, an important and long-term task is to improve the Se deficiency situation of people through safe Se-rich diet.

Wheat is the second largest food crop in population consumption(11), and it provides nearly 50% daily calorie intake in most developing countries and more than 70% calorie intake in rural areas(12). Especially, wheat has a strong ability to enrich Se. It can produce organic Se by absorbing Se in soil or foliage and store them in grains(13). Selenium is mainly combined with protein in wheat grain and more evenly distributed throughout the whole grain than other minerals(14). Therefore, a large amount of Se can be stored during grain grinding. Hence, human Se demand can be met through the Se fortification of wheat.

Selenium fortification by wheat is a comprehensive and multi-objective process. Generally, the Se fortification of wheat can be significantly affected by three processes, including grain Se enriching in the field, grain grinding, and wheat-derived food processing. This article summarizes reports related to the Se fortification of wheat to investigate the Se content in farming soil, wheat grain and different wheat derived foods, the effects of field cultivation factors on grain Se content, and food processing on food Se loss. The results provide valuable reference for the suitable amount of leaf fertilizer application rate in field.

MATERIALS AND METHODS

2.1 Data collection

The papers relation to Se of wheat grain, flour and wheat derived foods published between 1936 and 2020 were used to set up the database by a literature search using Wiley, ACS, Science Direct, Springer Link and China National Knowledge Infrastructure (CNKI). Search keywords included different combinations, “wheat” or “Selenium” and “flour” or “Selenium” and “food” or “Selenium”. Selection criteria included: a) Field experiment: report wheat harvest time, wheat type and fertilization type, including soil pH and Se content; b) wheat milling: report Se fertilizer type and Se content in different components after milling; and c) Food processing: report the source of wheat flour, food type, and Se content in food.

2.2 Data Classification

In selected reports, we summarized these data from soil to grain, milling, then to food under different conditions. A total of 66 research papers and 1066 paired observations were obtained (Figure 1); Grain Se content in different countries came from 41 references (Table S1); Selenium content of different wheat milling components were also obtained under different peeling and flour milling processing were got in 20 papers (Table S2); Selenium content of six kinds of different foods under different flour processing were obtained from 26 reports (Table S3). Total of 117 paired observations for the effects of soil Se on wheat grain from 21 articles, and 188 paired data for the effects of different Se fertilizer on wheat grain from 21 articles were extracted.

2.3 Data management

The database was established using Excel 2019 software. OriginPro 8.5 and PowerPoint 2019 software were used to draw graphics. All statistical analyses were performed using SPSS 18.0 software.

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RESULTS

3.1 Grain Se content in wheat grain

Selenium content in wheat grain had large variance, which ranged from 0 μg·kg^{-1} to 1,500 μg·kg^{-1} (110.98 μg·kg^{-1} in average) in the world(8, 15-50). The average Se content was lower than that suggested by the reference of Se rich grains (200–300 μg·kg^{-1}(39)). The large variance of Se content in wheat grain was mainly attributed the difference of wheat varieties, area, basic properties of soil, and Se biological strengthening measures in the field.

3.1.1 Variance of Se content among different wheat varieties

Generally, the old and new varieties might have different potentials to accumulate Se in grain. According to our data, grain Se content in wheat reported in 1936–2000 could reach 198.76 μg·kg^{-1} in average, and this value was significantly higher than that in 2001–2020 (Figure 1a). Different wheat varieties own different ability to accumulate Se under the same soil environment. For example, black grain wheat Se content was 177.34 μg·kg^{-1}, which was significantly higher than that in white grain (70.29 μg·kg^{-1})(33).

3.1.2 Grain Se content of wheat in different continents and countries

No significant difference was observed among the average grain Se contents of wheat in Asia(8, 15-20, 22-25, 27-29, 31, 33-40, 43) (63.36 μg·kg^{-1}), Africa(20, 22, 32, 50) (64.15 μg·kg^{-1}), and Europe(20, 22, 26, 29, 30, 41, 42, 44, 46, 48, 50) (85.98 μg·kg^{-1}), and these values which were all lower than the normal level (100 μg·kg^{-1}(39)). A significant difference was observed among the grain Se content in South America(22, 50), North America(20, 22, 47, 49, 50), and Oceania(22, 45, 50) with values of 600.00, 286.23, and 194.80 μg·kg^{-1}, respectively (Figure 2). These values were significantly higher than that in Asia, Africa, and Europe. Grain Se content in different countries on the same continent varied greatly. For Europe, the grain Se content in Spain, Slovakia, Portugal, and Norway varied from 26.75 μg·kg^{-1} to 93.90 μg·kg^{-1}, but that in Italy was 133.44 μg·kg^{-1}.

3.1.3 Basic properties of soil affecting grain Se content of wheat

Soil Se content and pH are the basic properties of soil, and these properties can significantly affect Se content in wheat grain. The total soil Se content varied greatly among different regions. Se-deficient, Se-sufficient, Se-rich, and Se-high soil were considered at soil Se contents of 0–175, 175–450, 450–2,000, and 2,000–3,000 μg·kg^{-1}, respectively(28). The soil in most parts of the world is Se-deficient. For instance, soil Se contents in Italy, China, India, and South Africa were 130, 21.21 12.60, and 6.14 μg·kg^{-1}, respectively. Globally, soil Se content in farming system range from 10 μg·kg^{-1} to 2,000 μg·kg^{-1} (300 μg·kg^{-1} in average)(51), while that in wheat farming soil is 3.80–552.00 μg·kg^{-1}. Soil Se content had a significant positive correlation with grain Se content (Figure 3). Grain Se content in the soil with Se content of 0–200 μg·kg^{-1} was significantly lower than that in 200–400 and 400-600 μg·kg^{-1}, but no significant difference was observed between that in the soil with Se contents of 200–400 and 400–600 μg·kg^{-1} (Figure 1a).

Soil pH also significantly affects grain Se content in wheat, and a significant difference was observed in wheat grain Se content among neutral soil (pH 6.5-7.5), alkaline soil (pH>7.5), and acid soil (pH<6.5). The grain Se content of wheat planted in neutral soil (pH 6.5–7.5) was the highest (229.42 μg·kg^{-1}), whereas that in acid soil (pH<6.5) was the lowest (55.50 μg·kg^{-1}) (Figure 1a).

However, acid soil occupies approximately 30% of the world's ice-free land area and occur mainly in tropical and subtropical regions, and this soil is more likely to be Se-deficient(52).

Therefore, Se-rich soil is an important factor to obtain Se-rich grain. However, most of the soil in the world is Se-deficient, and grain Se content can be effectively improved by artificial fertilization enhancement.

3.1.4 Effects of different Se fertilization on grain Se content in wheat

Se fertilization during wheat planting can significantly increase grain Se content compared with the treatment without Se fertilization. The process of improving grain Se by fertilizer in the field is the most important part in Se fortification. The grain Se contents in wheat around the world since 1936 are summarized in Table S1. The grain Se content of wheat planted in natural soil without Se fertilization treatment ranges from 0 to 1,500.00 $\mu g \cdot kg^{-1}$ (110.98 $\mu g \cdot kg^{-1}$ in average)(8, 15-50), and that with Se fertilization treatment ranges from 58.00 $\mu g \cdot kg^{-1}$ to 8,270.00 $\mu g \cdot kg^{-1}$ (677.21 $\mu g \cdot kg^{-1}$ in average). However, significant differences were observed in the effect of different Se fertilizer treatments. Grain Se content with soil Se fertilization treatment ranged from 190.00 $\mu g \cdot kg^{-1}$ to 6,090.00 $\mu g \cdot kg^{-1}$ (528.87 $\mu g \cdot kg^{-1}$ in average)(19, 28, 29, 38, 42, 48, 53), that with foliar Se fertilization treatment ranged from 58.00 $\mu g \cdot kg^{-1}$ to 8,270.00 $\mu g \cdot kg^{-1}$ (729.69 $\mu g \cdot kg^{-1}$ in average)(8, 13, 15, 16, 18-20, 23-31, 35-38, 51, 53), and that with seed Se soaking treatment ranged from 64.80 $\mu g \cdot kg^{-1}$ to 300.00 $\mu g \cdot kg^{-1}$ (128.67 $\mu g \cdot kg^{-1}$ in average)(39, 54).

Foliar Se fertilization treatment might be the most effective way to improve grain Se content. Grain Se content with foliar Se fertilization treatment was significantly higher than that of soil Se fertilization treatment and CK (Figure 1a). A positive correlation was observed between foliar Se fertilizer application amount and grain Se content growth rate, and this correlation can be expressed with the equation Y=22.20587 x (Figure 4a). The use of foliar Se fertilizer might be more environmentally safe than direct application in soil because of its low concentration in solution, effective absorption, and more accurate control of total Se application. The foliar Se fertilizer is the most popular method in Se fortification. Moreover, Na_2SeO_3 is the most common form of foliar Se fertilizer because of its low toxicity than Na_2SeO_4.

The grain Se content in different countries increased significantly after Se fortification in the field (Figure 4 b), and this value increased from 93.94 $\mu g \cdot kg^{-1}$ to 1181.92 $\mu g \cdot kg^{-1}$ after Se fortification. A large variance in effectiveness was observed in different countries. For example, the grain Se content increased in Pakistan, India, Turkey, Spain, South Africa, Norway, Portugal, Slovakia, China, and Italy by 2.16–25.98 times. The grain Se content in Pakistan and Italy increased by 2.16 and 25.98 times, respectively. The differences of fortification effect in these countries might be ascribed to the different Se fertilizer application amount. For example, the wheat Se fertilizer application amount in Italy and China were mostly 120 and 60 $g \cdot hm^{-2}$, respectively, while that in India, Pakistan, Turkey, and South Africa was only 1 $g \cdot hm^{-2}$.

All the reports for Se fertilization indicated that foliar Se fertilization is an effective way to improve the Se content of wheat grain. The most important factor that can affect the effectiveness of Se fertilization for one wheat variety is the Se concentration of the solution. Hence, the determination of the appropriate application amount of foliar fertilizer is the key to the effect of Se nutrient enhancement.

3.2 Selenium in flour and its influencing factors

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The proportion of selenium in wheat grains that can be directly ingested by the human body is also a key link for human Se supplementation. Most of the wheat will be ground into flour, which is then made into different foods. Wheat grain is generally divided into bran, embryo, and endosperm, accounting for 14%–16%, 2%–3%, and 81%–84% of the grain weight, respectively(39, 54). During milling, wheat grains are peeled off. Subsequently, the seed coat, aleurone layer, and embryo are stripped off. Although Se distribution in wheat grain is much more uniform than that of other elements, Se content in bran is approximately three times higher than that in flour after grinding(19, 26, 45). Bran Se content ranged from 15.00 $\mu g \cdot kg^{-1}$ to 520.00 $\mu g \cdot kg^{-1}$ (149.48 $\mu g \cdot kg^{-1}$ in average)(13, 19, 26, 28, 45), which was significantly higher than that in flour (101.02 $\mu g \cdot kg^{-1}$ in average)(13, 19, 26, 28, 30, 41, 45, 55-66). Hence, the milling process can result in a part of Se loss.

Different wheat milling methods remarkably affect flour Se content (Figure 1 b). Flour can mainly be divided into two types, namely, whole wheat flour and flour, according to the milling method. Se content in flour was significantly lower than that in whole wheat flour. According to our results (Table S2), flour Se content ranged from 13.00 $\mu g \cdot kg^{-1}$ to 500.00 $\mu g \cdot kg^{-1}$ (101.02 $\mu g \cdot kg^{-1}$ in average)(13, 19, 26, 28, 30, 41, 45, 55-66), and the whole wheat flour Se content ranged from 35.60 $\mu g \cdot kg^{-1}$ to 650.00 $\mu g \cdot kg^{-1}$ (227.58 $\mu g \cdot kg^{-1}$ in average)(26, 56, 61, 63, 65, 67). Flour road during flour milling can be divided into six flour parts (i.e., three “Broken [B]” and three “Reduced [R]” milling parts) and two kinds of bran parts (i.e., bran and shorts). A significant difference was observed among the ingredients in different flour roads. The flour collected by B1, R1, B2, R2, B3, and R3 was standard flour, the flour collected by B1, R1, B2, and B3 was bread flour, and the flour from B1 and R1 was refined flour(45). Flour road schematic diagram of Bühlermlu-202 mill and Se content of flour in each flour road is shown in Figure 5. The Se content in different components after wheat milling can be arranged as follows: Bran> B flour >R flour. The Se contents of flour from R1, R2, R3, B1, B2, and B3 were 66.42, 65.73, 68.98, 71.59, 81.52, and 77.94 $\mu g \cdot kg^{-1}$ in average, respectively. The Se content of flour in common flour roads was B3>B2>R3>R1>R2>B1. The rate of Se concentration loss and Se content loss in wheat milling were 17.19% and 46.40%, respectively. Most of the published literature used Se concentration loss, and a few studies have focused on Se content loss. The peeling rate of 4%–5% can effectively increase flour Se content. When the peeling rate was greater than 9%, no significant difference was observed in the Se content between flour and unpeeled flour(19).

Field biofortifications can significantly increase Se content in flour and have significant effects on Se content in each flour road. After Se fortification, Se content increased from 227.58 $\mu g \cdot kg^{-1}$ to 1,110.03 $\mu g \cdot kg^{-1}$ in whole wheat flour and from 101.02 $\mu g \cdot kg^{-1}$ to 714.90 $\mu g \cdot kg^{-1}$ in flour, respectively. Se contents in foliar fortified whole wheat flour and foliar fortified flour were significantly higher than those in whole wheat, soil fortified, and unfortified flour (Figure 1b). The Se content in flour roads after field biofortifying can be arranged as B2>R3>B1>R2>R1, which was quite different with that of common flour. The average rates of Se concentration and content loss in wheat milling were 15.04% and 38.56%, respectively, after Se fortification.

Therefore, milling methods might affect flour Se content.

3.3 Selenium in wheat derived foods

Flour is generally used for the preparation of foods, such as bread, noodles, and biscuits. These staple foods play an important role in people’s diet. For example, wheat-related traditional foods account for 75% of the total wheat consumption in China(34). Se content in most wheat-derived foods is in normal range according to the data over the past 50 years. Se content in foods ranged from 3.60

μg·kg^{-1} to 1130.00 μg·kg^{-1} with an average of 191.87 μg·kg^{-1}(13, 30, 41, 45, 46, 56, 58-61, 63-66, 68-79). Se content in different wheat-derived foods were significantly different (Figure 6), and Se content in cooking foods was 382.83 μg·kg^{-1}, which was significantly higher than that in baked foods (244.98 μg·kg^{-1}). The average Se contents in pasta, noodles, biscuits, and bread were 325.45, 251.53, 181.65, and 137.51 μg·kg^{-1}, respectively.

High temperature can result in the volatilization of Se. Hence, Se loss in food processing is mainly lost during heating. Especially, Se loss is high under the dual effect of dissolution and heat volatilization when cooking, steaming, and frying the same food(80, 81).

Hence, boiling, baking, or other food processing methods will lead to Se loss in food. Moreover, soaking steps in food fermentation will reduce food Se content, but it is easily affected by foods species, such as Se content in mung bean and millet decreased in soaking(80). The change of Se content after wheat food fermentation has not been study, but its possibility is not excluded.

In addition, field Se fortification can significantly increase Se content in wheat-derived foods (Figure 1c). For example, Se content in pasta increased from 22.4 μg·kg^{-1} to 424.43 μg·kg^{-1} (17.94 times) and that in bread increased from 119.15 μg·kg^{-1} to 644.69 μg·kg^{-1} (4.41 times). Se content in food is also related to the amount of Se fertilizer. Hart et al(56). found that foliar Se application rate is positively correlated with bread Se content, and it can be expressed using the formula Y=19.2262 X+95.95332.

Food processing is an important factor that affects Se content in food. Moreover, field Se fortification is an effective way to increase Se content in wheat-derived foods.

3.4 Selenium bioavailability

Not all the Se content obtained from foods can be used by the human body. The ratio of body absorbed Se to total intake Se is called bioavailability(10). The Se from food can be effectively used by the human body only absorbed in blood circulation or tissues and transformed into active substances. A large difference was observed for the bioavailability of different Se types. Selenium types in foods include inorganic Se (i.e., selenite) and organic Se (i.e., SeMet). Selenium mainly exists in the form of SeMet in wheat grain, flour, and food, and it accounts for 70%-90%(14, 82), 59%-82%(43, 76, 83, 84), and 42%-83%(43, 56, 83) of total Se, respectively.

Different Se types are digested and absorbed in different ways, causing difference in bioavailability. Organic Se is mainly actively absorbed by human small intestine, in which bioavailability generally fluctuates between 70%–90%(10, 73). Inorganic Se absorption modes occur via simple absorption (selenite) and passive diffusion (selenite), in which bioavailability is generally less than 50%. Moreover, the long-term consumption of inorganic Se might result in toxic and side effects(10). The molecular of H_2Se is the key to human body's Se metabolism. The role of H_2Se mainly includes two aspects(85, 86): 1) H_2Se first transforms to selenite and SeMet form, and then synthesizes selenoprotein in liver and 2) SeMet and SeMeCys catalyze H_2Se to form different Se ions forms under continuous methylation, which are discharged through respiration, urine, and sweat.

Se bioavailability in the human body can be predicted via *in vitro* simulated gastrointestinal digestion model(87), Caco-2 based cell model(88), animal models(89), and human Se bioavailability detection(90). Selenium bioavailability in wheat was 83% in rat feeding trials, while those in mushroom, tuna, and beef kidneys were 5%, 57%, and 97%, respectively(89). Selenium

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bioavailability in wheat flour was also very high, with values ranging from 75.4% to 91.8%. The consecutive consumption of Se-enriched wheat for six weeks could significantly increase human serum Se content, but Se-enriched fish had no obvious effect(90). Generally, SeMet can be effectively absorbed by the human body, in which bioavailability may exceed 90%. By using *in vitro* gastrointestinal digestion method to simulate bread digestion, soluble Se content after gastric and gastrointestinal digestion accounted for 75% and 89% of total Se content in bread, respectively, in which SeMet content accounted for 95% and 96.8% of soluble Se(91).

Selenium bioavailability in foods ranged from 10% to 85%(10). These differences in bioavailability might be ascribed to the following factors: 1) selenium type in food - different Se types showed different bioavailability, for instance, SeMet and SeMeCys have a bioavailable of up to 90%, while selenates and selenite have a bioavailability of up to 50%(89). 2) food type - a high-fat diet can hinder Se absorption, resulting in low Se bioavailability(87). 3) food processing - heat treatment not only affects total Se content but also reduced Se antagonist content. However, proper heat treatment might improve Se bioavailability(89). 4) antagonism with other minerals - Ca intake in the human body would reduce Se bioavailability. Meanwhile, Vc could transform selenates into insoluble Se compounds in a short time, thus reducing Se bioavailability(92). 5) digestion and absorption capacity of human body - for instance, gastrointestinal diseases will reduce Se bioavailability.

Despite the numerous influencing factors, Se can be supplemented to the human body through wheat-related foods, because Se bioavailability in wheat is relatively high (75.4%–91.8%).

3.5 Suitable level of Se in wheat grain and in fertilizer applied in the field

Considering that both insufficient and excessive Se intake will have adverse effects on human health, a suitable and safe amount of Se intake should be maintained. The range of Se intake recommended by WHO is 50–400 μg/day. Inorganic Se has a strong potential toxicity to the human body. Hence, the supplement of organic Se in food is the first choice. Se-rich wheat might be an ideal popular food to improve Se in the human body because of its relatively stable intake, high ability to accumulate Se, and high Se bioavailability. Field Se fortification can effectively improve grain Se content in wheat and then obtain the Se-rich wheat-derived foods.

Dietary pattern, which refers to the combination of various forms of food ingredients used in people's actual life, should also be considered(93, 94). The representative dietary patterns are divided into Western, Oriental, and Mediterranean dietary patterns. Western dietary patterns are mainly characterized by the intake of large amounts of red meat, processed meat products, refined cereals, desserts, French fries, and high-fat dairy products. Oriental dietary patterns are mainly characterized by the intake of a large number of fruits, vegetables, legumes, whole wheat, an appropriate amount of fish, and poultry. Mediterranean dietary patterns are mainly characterized by the intake of monounsaturated fatty acids rich in olive and olive oil, whole grains, fruits, vegetables and dairy products, weekly intake of fish, poultry, nuts, and legumes. The distribution law of food Se content is as follows(61): fish > meat > egg > cereal > fruits and vegetables. Hence, the actual Se intake per capita in western dietary patterns countries could reach the recommended level. The actual Se intake per capita in some Mediterranean dietary pattern countries could reach the recommended level such as Italy, but some countries such as Spain cannot not reach the recommended level. Interestingly, the actual Se intake per capita in Oriental dietary patterns countries, such as China and India, did not reach the recommended level.

With wheat as Se source, the level of Se needed in wheat grains and the amount of Se to be applied in the field should be determined.

According to the recommended daily Se intake per capita, actual Se intake per capita, total Se loss rate, the proportion of Se in cereals in daily Se intake and flour Se content, daily insufficient Se intake, and suitable Se fortification level by wheat could be calculated to determine whether Se is deficient in the region and to calculate the appropriate Se fertilizer amount for biofortification.

$$\text{Daily insufficient Se intake} = \text{Recommended Se intake per capita} - \text{Actual Se intake per capita}$$

$$\text{Total Se loss rate} = \frac{\text{Unit weight of grain} \times \text{Grain Se content} - \text{Unit weight of grain} \times \text{Flour extraction} \times \text{Flour Se content}}{\text{Unit weight of grain} \times \text{Grain Se content}} \times 100\%$$

$$\text{Recommended grain intake per capita} = \frac{\text{Recommended flour intake per capita}}{\text{Flour extraction}}$$

$$\text{Suitable Se fortification Level in grain} = \frac{\text{Daily insufficient Se intake} + \text{Actual Se intake per capita} + \text{Proportion of Se intake by grain (daily Se intake)}}{\text{Recommended grain intake per capita} \times (1 - \text{Total Se loss rate})}$$

In China, according to the national nutrition and health guidelines, the recommended Se intake per capita is 60–400 μg·day-1, the recommended Se in grain is 150 g (assuming all for wheat), the actual Se intake is 43.90 μg·kg-1, and grain daily Se intake accounts for approximately 22.6%. The upper limit of Se content in wheat grain is 300 μg·kg-1 in China, and the scope of Se content in wheat grain is 242.74–300.00 μg·kg-1. According to the formula and the parameters, the amount of Se fortification by foliar Se fertilizer in China should be 18.53–23.96 g·hm-2 to meet people's daily need. Thus, the amount of Se fortification should be 2.65–3.37 and 3.93–9.88 g·hm-2 in India and Spain, respectively (Figure 7, Table 1(8, 92, 95-100)).

Table 1 Recommended amount of wheat selenium fertilizer in different countries

Dietary pattern	Country	Recommended daily Se intake per capita (μg·d^{-1})	Wheat grain Se content (μg·kg^{-1})	Actual Se intake per capita (μg·d^{-1})	Recommended wheat grain Se content (μg·kg^{-1})	Recommended Se fertilizer applying amount (g·hm^{-2})
Oriental dietary patterns	China	60.00 (100)	47.46	43.90 (97)	242.74-300.00	18.53-23.96
	India	50.00 (8)	171.70	48.00 (98)	272.76-300.00	2.65-3.37
Mediterranean dietary patterns	Spain	50.00 (8)	93.90	49.24 (95)	175.84-300.00	3.93-9.88
	Italy	50.00 (8)	133.44	66.53 (96)	No need to fortification	No need to fortification
Western dietary patterns	Australia	55.00 (92)	191.83	57.0 (99)	No need to fortification	No need to fortification
	America	55.00 (92)	304.95	80.00 (98)	No need to fortification	No need to fortification

FUTURE TRENDS

The enhancement of Se nutrition to human body by wheat involves many processes, such as acquisition of Se-rich wheat grains, reduction of Se loss in the process of flour milling and food processing, and improvement of Se bioavailability in food.

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Wheat varieties and their corresponding Se fortification cultivation measures are both important to obtain Se-rich grain. The development of wheat variety with high potential ability to accumulate Se in grain is needed. Variety with potential high Se accumulation can save limited Se fertilizer resources and obtain an ideal Se enrichment effect. Conventional wheat breeding and modern biotechnology methods should be used to breed Se-rich wheat variety. The detection and use of Se-rich gene existing in wheat and its relatives should also be considered. Other nutrient influence on Se utilization needs to be detected. This field should be further studied. Se enhancement measures in the field also need to be updated according to the change of cultivars and cultivation environment, and further investigation is required.

For the reduction of Se loss during flour milling and food processing, the mechanism of the effects on Se loss in different food processing methods should be focused on. The improvement of Se bioavailability in food is a very complicated task.

If the metabolism of different forms of Se in body and the interaction mechanism with other substances are well understood, the addition of food additives to improve Se bioavailability or Se products with high bioavailability to directly increase Se content in food can be considered. This process should also be considered in the food industry.

Selenium deficiency is a worldwide problem, and its fortification should strengthen international cooperation through international schemes such as Harvest Plus. Moreover, we should raise public awareness of the dangers of Se deficiency to obtain as much support as possible, such as sustained funding from local government.

In summary, suitable Se fortification, appropriate processing, reasonable food type, international collaboration, and government support are all important to meet people's Se requirements through wheat.

CONFILCT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

MW, SL and ZWS collected and analysed data. MW, FMK and XCZ wrote this paper. XCZ, FMK and BQL conceived and modified this paper.

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FIGURES

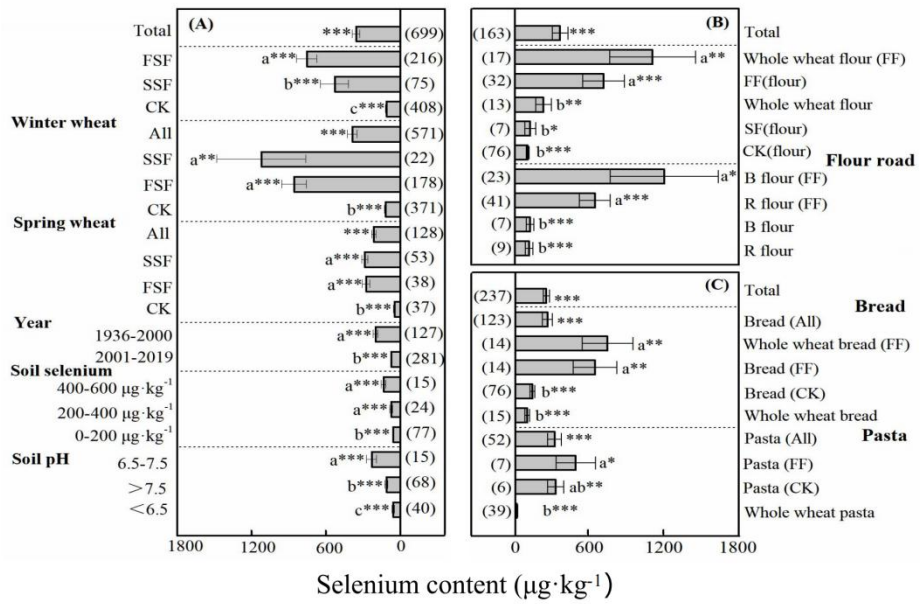

Figure 1 Comparison of Se content in wheat grain (A), flour (B) and food (C)

Note: Data originated from 66 studies; FSF: foliar Se fertilizer treatment, SSF: Soil Se fertilizer treatment; CK: unfortified Se treatment; The year is based on the harvest year of wheat; Data are presented as mean ± 95% CIs, with n in parentheses. Asterisks indicate significant differences (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$); Different letters indicate significant differences between mean effect size for groups within each category.

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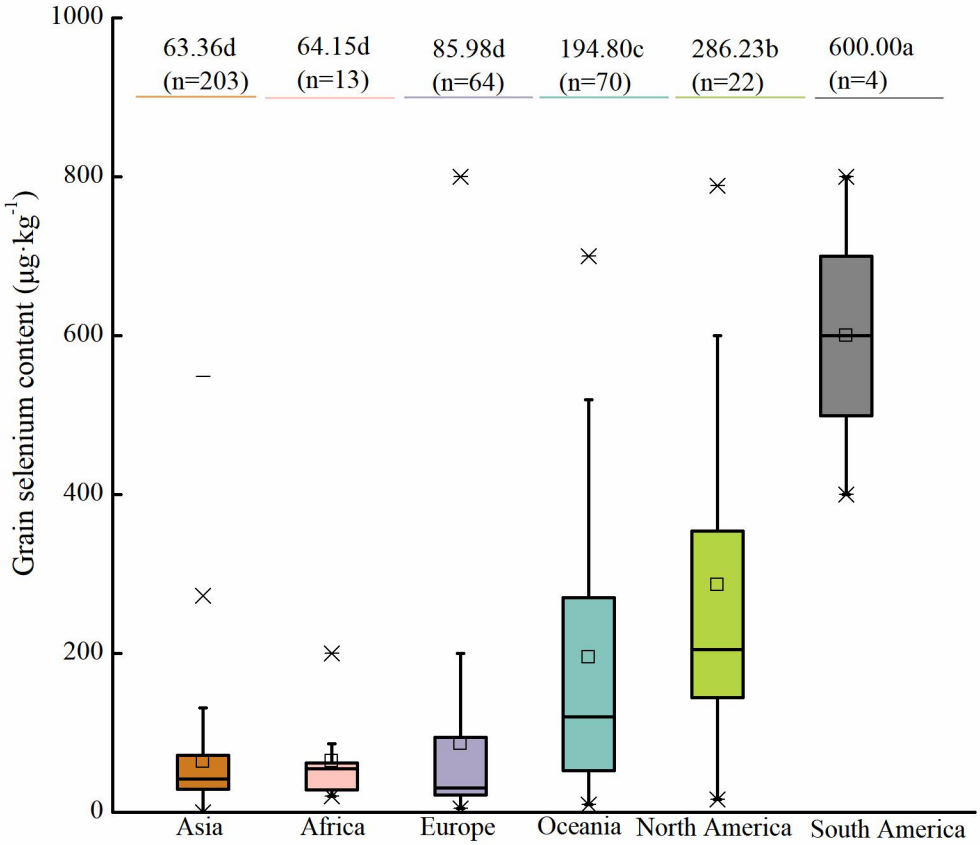

Figure 2 Selenium content of wheat among different continents

Note: Data originated from 42 studies; The letters a, b, c and d indicate a significant difference at the level of $P < 0.05$; n is the total number of samples.

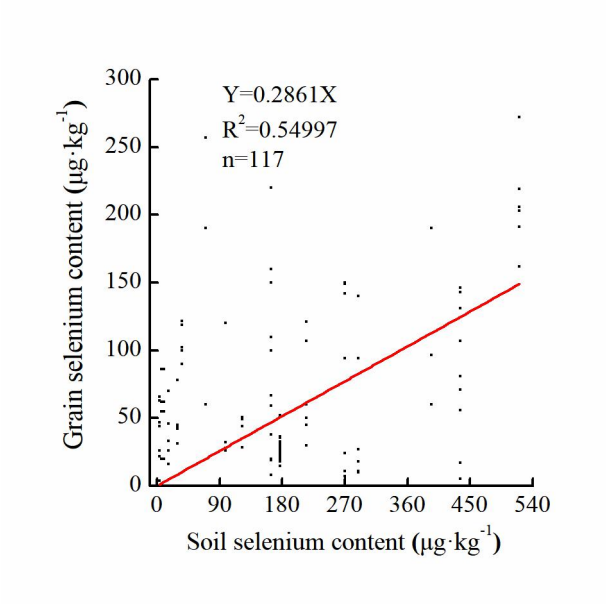

Figure 3 Relationship between soil selenium content and grain selenium content

Note: Data originated from 21 studies; n is the total number of samples.

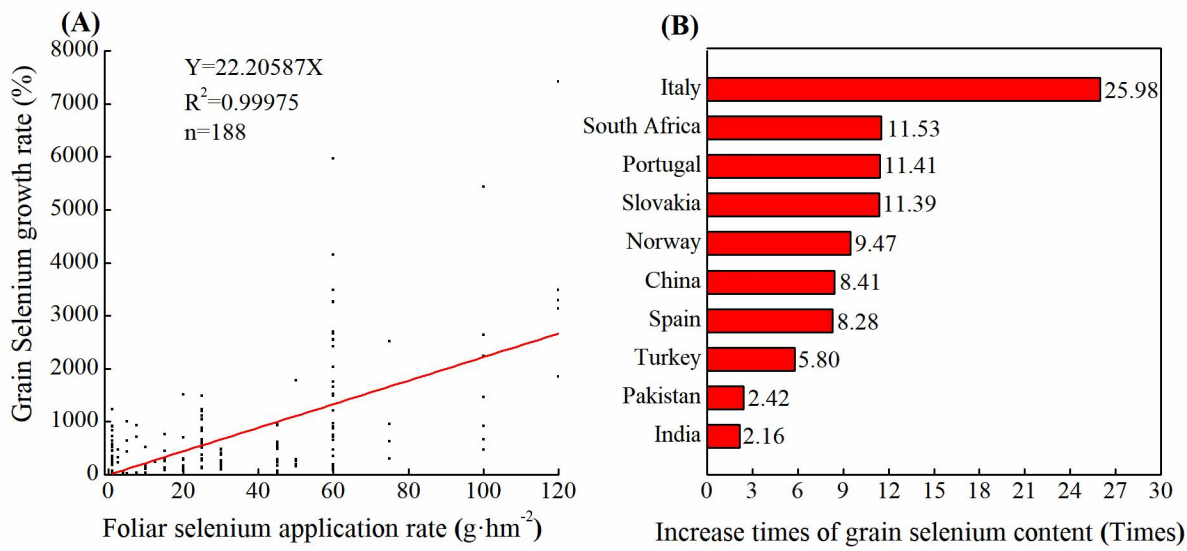

Figure 4 Relationship between foliar fertilization application rate and grain selenium content (A) and increase times of grain selenium content after fortification in different countries (B)

Note: (A) Data originated from 21 studies; Selenium was added in the form of Na2SO3 solution; n is the total number of samples; (B) Data originated from 42 studies.

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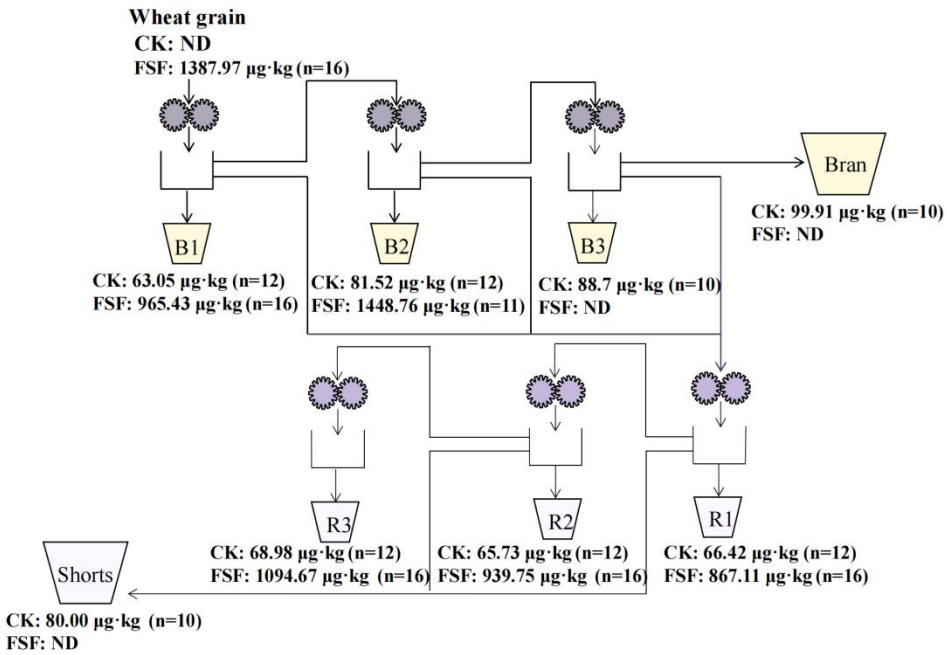

Figure 5 Schematic diagram of Selenium content in the flour road

Note: Data originated from 2 studies; B1, B2 and B3 refer to three Broken [B] milling parts; R1, R2 and R3 refer to three Reduced [R] milling parts; FSF: foliar Se fertilizer treatment, CK: unfortified Se treatment, ND: relevant information is not mentioned in the literature; The letters a, b, c and d indicate a significant difference at the level of $P < 0.05$; n is the total number of samples.

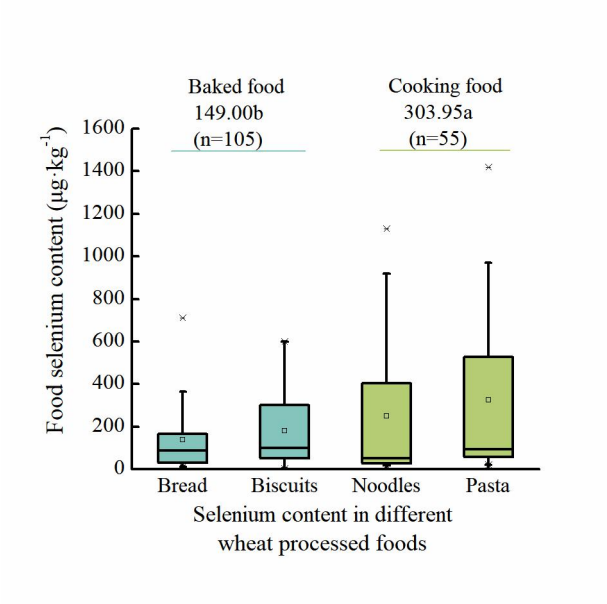

Figure 6 Selenium content in different wheat derived foods

Note: Data originated from 26 studies; The letters a and b indicate a significant difference at the level of $P < 0.05$; n is the total number of samples.

Note: The letters a and b indicate a significant difference at the level of $P < 0.05$; n is the total number of samples.

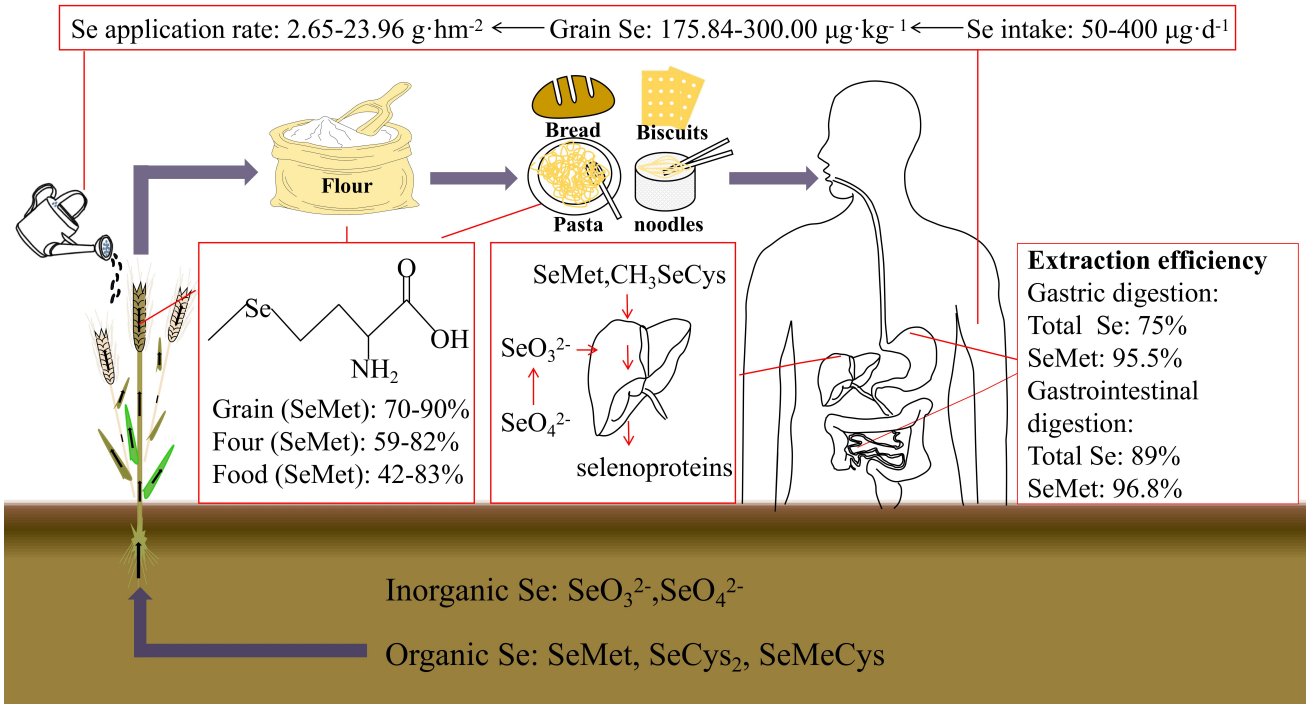

Figure 7 The change of selenium from grain to human body and the appropriate level of selenium fortification

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SUPPLEMENTARY TABLE

666 **Table S1** Selenium content in wheat grains around the world

Serial number	Country	Fertilizing method	Fertilizing amount	Number of samples	Grain Seleniumc content		References
					mean	range	
1	Australia	ND	ND	7	442.86	100.00-700.00	Robinson, 1936 (51)
	Argentina	ND	ND	4	600.00	400.00-800.00	Robinson, 1936 (51)
	Canada	ND	ND	1	1900.00	ND	Robinson, 1936 (51)
	Mexico	ND	ND	1	600.00	ND	Robinson, 1936 (51)
	South Africa	ND	ND	2	850.00	200.00-1500.00	Robinson, 1936 (51)
	Spain	ND	ND	4	500.00	200.00-800.00	Robinson, 1936 (51)
	America	ND	ND	6	183.33	100.00-300.00	Robinson, 1936 (51)
	New Zealand	ND	ND	1	400.00	ND	Robinson, 1936 (51)
	Hungary	ND	ND	2	350.00	300.00-400.00	Robinson, 1936 (51)
2	America	ND	ND	190	401.80	144.00-789.00	Harn et al.,1981 (50)
3	Norway	Soil fertilization	5.82/6.45/12.9 g·hm^{-2} Se	47	249.19	25.00-497.00	Tveitnes et al.,1995 (49)
	Norway	ND	ND	16	26.75	5.00-94.00	Tveitnes et al.,1995 (49)
4	Spain	ND	ND	2	35.50	31.70-39.40	Diaz-Alarcon et al., 1996 (47)
5	Mexico	ND	ND	9	190	140.00-210.00	Wyatt et al., 1996 (48)
6	Australia	ND	ND	2	460	410.00-510.00	Lyons et al., 2005 (46)
	Australia	ND	ND	151	147.59	15.00-520.00	Lyons et al., 2005 (46)
7	Italy	ND	ND	749	123.5	7.00-245.00	Spadoni et al., 2007 (45)
8	India	ND	ND	17	165.76	107.00-272.00	Yadav et al., 2008 (44)
9	Italy	ND	ND	3	109.17	95.20-122.50	Cubadda et al., 2009 (42)
10	Slovakia	ND	ND	4	46.25	30.00-60.00	Ducsay et al., 2009 (43)
	Slovakia	Soil fertilization	150/300/500 g·hm^{-2} Se	6	526.83	140.00-818.00	Ducsay et al., 2009 (43)
11	China	ND	ND	1	38.10	ND	Tang et al.,2010 (40)
	China	Soaking seeds	0.1/0.5/1.0/2.5 mg·L^{-1} Se	1	70.50	64.80-77.60	Tang et al.,2010 (40)
12	China	ND	ND	62	35.47	16.00-72.00	Lu et al.,2010 (41)
13	China	ND	ND	1	78.34	90.00-100.00	Tang et al., 2011 (39)
	China	Soil fertilization	0.1/0.25/0.5/1.0/2.0/3.0/5.0 kg·hm^{-2} $Na_2SeO_3 \cdot 5H_2O$	8	2447.50	210.00-6090.00	Tang et al., 2011 (39)
	China	Foliar fertilization	15/30/45/60/75 g·hm^{-2} Se	10	37.84	180.00-1060.00	Tang et al., 2011 (39)
14	China	Foliar fertilization	57.95 g·hm^{-2} Se	1	288.94	ND	Zhang et al., 2012 (37)
	China	ND	ND	3	114.16	102.16-121.49	Zhang et al., 2012 (37)

Continued Table S1 Selenium content in wheat grains around the world

Serial number	Country	Fertilizing method	Fertilizing amount	Number of samples	Grain Seleniumc content		References
					mean	range	
15	Portugal	Foliar fertilization	4/20/100 g·hm^{-2} Se	12	466.67	75.00-2100.000	Galinha et al., 2012 (53)
16	China	ND	ND	1	12.50	8.60-17.10	Zhang et al., 2012 (36)
	China	Foliar fertilization	57.95 g·hm^{-2} Se	1	755.90	ND	Zhang et al., 2012 (36)
17	China	ND	ND	4	97.50	71.00-131.00	Zhang et al., 2012 (35)
	China	Foliar fertilization	3.626 g·hm^{-2} Se	2	141.50	129.00-154.00	Zhang et al., 2012 (35)
18	China	ND	ND	3	7.67	5.00-12.00	Wang，2012 (34)
	China	Foliar fertilization	3/15/19/30/38/46/57/61/76 g·hm^{-2} Se	8	484.13	38.00-1006.00	Wang，2012 (34)
	China	Soil fertilization	150/300/450/600 g·hm^{-2} Se	4	166.25	84.00-339.00	Wang，2012 (34)
19	Algeria	ND	ND	8	52.00	21.99-153.00	Beladel et al., 2013 (33)
20	China	ND	ND	1	177.34	ND	Pei et al., 2013 (33)
21	Brazil	Soaking seeds	10 μM Na_2SeO_4	20	245.00	190.00-300.00	Souza et al., 2014 (56)
22	China	Foliar fertilization	57.95 g·hm^{-2} Se	2	330.07	192.69-467.45	Meng，2014 (32)
	China	ND	ND	6	58.15	30.63-96.76	Meng，2014 (32)
23	Spain	ND	ND	1	66.60	ND	Poblaciones et al., 2014 (31)
	Spain	Foliar fertilization	10/20/40 g·hm^{-2} Se	1	551.47	153.60-1383.20	Poblaciones et al., 2014 (31)
24	China	ND	ND	3	101.33	31.00-144.00	Zhang et al., 2015 (28)
	China	Foliar fertilization	0.0089 g·hm^{-2} Se	3	1248.00	803.00-1694.00	Zhang et al., 2015 (28)
25	China	ND	ND	3	29.00	19.00-38.00	Yu,2015 (29)
	China	Foliar fertilization	18/45 g·hm^{-2} Se	6	139.17	26.00-397.00	Yu,2015 (29)
	China	Soil fertilization	15/700 g·hm^{-2} Se	6	166.83	23.00-256.00	Yu,2015 (29)
26	Portugal	ND	ND	9	85.00	60.00-150.00	Galinha et al., 2015 (30)
	Portugal	Foliar fertilization	100 g·hm^{-2} Se	7	1331.67	610.00-2700.00	Galinha et al., 2015 (30)
	Portugal	Soil fertilization	100 g·hm^{-2} Se	7	1111.33	760.00-1510.00	Galinha et al., 20155 (30)
27	China	Foliar fertilization	120 g·hm^{-2} Se	1	1640.00	ND	Wang et al., 20165 (14)
28	China	ND	ND	31	31.0	0.00-117.00	Liu et al., 20165 (8)
	China	Foliar fertilization	57.95 g·hm^{-2} Se	31	647.8	152.6-1796.5	Liu et al., 2016 (8)
29	Italy	ND	ND	5	148.75	100.00-220.00	De Vita et al., 2017 (8)
	Italy	Foliar fertilization	1/5/10/15/20/25/50/80/100/120 g·hm^{-1} Se	4	3864.00	330.00-8270.00	De Vita et al., 2017 (27)
30	China	Foliar fertilization	30/60 g·hm^{-2} Se	1	225.00	70.00-380.00	Wang et al.,2017 (57)
31	China	ND	ND	7	52.57	27.00-143.00	Wang et al., 2018 (24)

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669 **Continued Table S1** Selenium content in wheat grains around the world

Serial number	Country	Fertilizing method	Fertilizing amount	Number of samples	Grain Seleniumc content		References
					mean	range	
31	China	Foliar fertilization	22.49 g·hm^{-2} Se	7	315.86	58.00-608.00	Wang et al., 2018 (24)
32	Israel	ND	ND	1	128.22	ND	Ji et al., 2018 (23)
	Russia	ND	ND	1	125.48	ND	Ji et al., 2018 (23)
	Canada	ND	ND	13	97.81	30.86-144.77	Ji et al., 2018 (23)
	Portugal	ND	ND	1	120.37	ND	Ji et al., 2018 (23)
	Australia	ND	ND	1	141.27	ND	Ji et al., 2018 (23)
	Ukraine	ND	ND	1	164.02	ND	Ji et al., 2018 (23)
	South	ND	ND	1	148.34	ND	Ji et al., 2018 (23)
	America	ND	ND	3	115.61	100.98-123.45	Ji et al., 2018 (23)
	Argentina	ND	ND	1	121.12	ND	Ji et al., 2018 (23)
	Spain	ND	ND	2	82.385	58.36-106.41	Ji et al., 2018 (23)
	Cypress	ND	ND	1	55.06	ND	Ji et al., 2018 (23)
	Italy	ND	ND	1	30.86	ND	Ji et al., 2018 (23)
	Syria	ND	ND	1	144.77	ND	Ji et al., 2018 (23)
	Iraq	ND	ND	1	97.17	ND	Ji et al., 2018 (23)
	India	ND	ND	1	61.06	ND	Ji et al., 2018 (23)
33	China	ND	ND	3	47.99	44.04-50.75	Feng et al., 2018 (25)
	China	Foliar fertilization	15/30/45/60 g·hm^{-2} Se	12	288.80	177.19-428.21	Feng et al., 2018 (25)
34	China	ND	ND	6	53.83	26.00-72.00	Jin et al., 2018 (26)
	China	Foliar fertilization	2.5/5/7.5/10/12.5 g·hm^{-2} Se	24	199.42	87.00-443.00	Jin et al., 2018 (26)
35	China	Foliar fertilization	57.95 g·hm^{-2} Se	4	2081.10	1810.40-2515.50	Zhang et al., 2019 (17)
	China	ND	ND	4	67.75	58.00-75.00	Zhang et al., 2019 (17)
36	China	ND	ND	5	307.20	214.00-396.00	Qin et al., 2019 (18)
37	China	ND	ND	1	28.56	ND	Dong et al., 2019 (19)
38	China	ND	ND	1	225.88	ND	Chen, 2019 (20)
	China	Soil fertilization	425 g·hm^{-2} Se	1	375.04	ND	Chen, 2019 (20)
	China	Foliar fertilization	45 g·hm^{-2} Se	1	748.47	736.21-1621.73	Chen, 2019 (20)
39	China	ND	ND	2	39.00	26.00-45.00	Zou et al., 2019 (21)
	China	Foliar fertilization	1 g·hm^{-2} Se	2	197.00	144.00-297.00	Zou et al., 2019 (21)
	India	ND	ND	2	188.17	26.00-549.00	Zou et al., 2019 (21)
	India	Foliar fertilization	1 g·hm^{-2} Se	2	406.17	178.00-725.00	Zou et al., 2019 (21)

Continued Table S1 Selenium content in wheat grains around the world

Serial number	Country	Fertilizing method	Fertilizing amount	Number of samples	Grain Seleniumc content		References
					mean	range	
39	Mexico	ND	ND	2	24.50	16.00-33.00	Zou et al., 2019 (21)
	Mexico	Foliar fertilization	1 g·hm^{-2} Se	2	199.00	185.00-213.00	Zou et al., 2019 (21)
	turkey	ND	ND	1	41.00	4.00-66.00	Zou et al., 2019 (21)
	turkey	Foliar fertilization	1 g·hm^{-2} Se	1	238.00	155.00-244.00	Zou et al., 2019 (21)
	Pakistan	ND	ND	1	125.20	31.00-257.00	Zou et al., 2019 (21)
	Pakistan	Foliar fertilization	1 g·hm^{-2} Se	1	302.80	222.00-446.00	Zou et al., 2019 (21)
	South	ND	ND	2	55.75	20.00-86.00	Zou et al., 2019 (21)
	South	Foliar fertilization	1 g·hm^{-2} Se	2	643.00	558.0-711.00	Zou et al., 2019 (21)
40	Spain	ND	ND	ND	27.96	14.68-51.84	López-Bellido et al., 2019 (22)
41	China	Foliar fertilization	20/100 g·hm^{-2} Se	4	3442.50	610.00-68200.00	Wang et al., 2020 (16)
	China	ND	ND	ND	120	ND	Wang et al., 2020 (16)
-	Mean	-	-	-	411.38	0.00-68200.00	-

Note: ND indicates that relevant information is not mentioned in the literature.

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Table S2 Selenium content in different components of wheat

Serial number	Country	Peeling rate (%)	Flour extraction rate (%)	Number of samples	Selenium content in wheat		Selenium content in wheat		References
					Mean	range	Mean	range	
1	Canada	ND	ND	3	280.00	260.00-280.00	ND	ND	Arthur, 1972 (67)
	Canada	ND	100%	3	610.00	560.00-650.00	ND	ND	Arthur, 1972 (67)
2	Germany	ND	ND	2	24.00	23.00-25.00	ND	ND	Oster et al., 1989 (66)
	New Zealand	ND	ND	2	18.00	14.00-22.00	ND	ND	Oster et al., 1989 (66)
	Greece	ND	ND	2	189.00	38.00-340.00	ND	ND	Oster et al., 1989 (66)
	America	ND	ND	1	190.00	ND	ND	ND	Oster et al., 1989 (66)
3	Britain	ND	100%	23	59.00	23.00-110.00	ND	ND	Barclay et al., 1995 (65)
	Britain	ND	ND	47	38.00	17.00-85.00	ND	ND	Barclay et al., 1995 (65)
4	Spain	ND	ND	1	32.20	ND	ND	ND	Diaz-Alarcon et al., 1996 (64)
5	Slovakia	ND	ND	11	25.10	15.00-32.30	ND	ND	Kadrabova et al., 1997 (68)
6	Ireland	ND	ND	ND	64.00	13.00-99.00	ND	ND	Murphy, 2001 (63)
	Ireland	ND	100%	3	130.00	128.00-132.00	ND	ND	Murphy, 2001 (63)
7	Croatia	ND	ND	2	57.55	56.30-58.80	ND	ND	Klapec et al., 2004 (62)
8	Australia	ND	60%	2	170.50	41.00-300.00	235.00	60.00-410.00	Lyons et al., 2005 (46)
9	Libya	ND	ND	1	45.00	ND	ND	ND	Alamin et al., 2006 (61)
10	China	ND	ND	3	67.33	14.00-120.00	ND	ND	Wang et al., 2008 (60)
11	Italy	ND	66%	3	91.27	83.50-97.30	ND	ND	Cubadda et al., 2009 (42)
12	Spain	ND	ND	3	55.67	50.00-67.00	ND	ND	Matos-Reyes et al., 2010 (59)
13	Britain	ND	ND	2	553.46	30.30-2008.20	ND	ND	Hart et al., 2011 (58)
	Britain	ND	100%	2	640.31	41.60-2259.10	ND	ND	Hart et al., 2011 (58)
14	Spain	ND	ND	1	391.60	44.00-1235.60	ND	ND	Poblaciones et al., 2014 (31)
15	China	ND	100%	6	102.35	64.30-118.00	ND	ND	Gao et al., 2015 (69)
16	China	ND	89%	15	68.27	19.00-288.00	119.93	15.00-520.00	Yu,2015 (29)
17	China	ND	73.22%	1	1420.00	ND	1910	ND	Wang et al., 2016 (14)
18	China	0-15.2%	ND	2	204.21	20-580	ND	ND	Li et al., 2017 (10)
	China	0-14.8%	ND	1	411.00	110.00-850.00	ND	ND	Li et al., 2017 (10)
19	Italy	ND	100%	1	2640.00	150.00-5380.00	ND	ND	De Vita et al., 2017 (27)
	Italy	ND	66%	1	2343.33	120.00-4690.00	3113.33	230.00-6360.00	De Vita et al., 2017 (27)
20	China	ND	ND	1	795.96	242.01-1433.81	932.03	236.61-1715.52	Chen, 2019 (20)
-	Mean	-	-	-	404.04	13.00-5380.00	1547.59	60-6360	-

Note: ND indicates that relevant information is not mentioned in the literature

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Table S3 Selenium content in different wheat processed foods

Name	Number of samples	Selenium content (μg·kg^{-1})		References	Remark
		Mean	Range		
Bread	3	676.67	650.00-710.00	Arthur, 1972 (67)	Whole wheat
	3	536.67	420.00-670.00	Arthur, 1972 (67)	White bread
	8	19.00	13.00-25.00	Oster et al., 1989 (66)	White bread
	16	220	140.00-270.00	Eurola et al., 1991 (78)	
	1	203.00	ND	Aro et al., 1994 (77)	
	5	180.20	87.00-337.00	Aro et al., 1994 (77)	
	25	92.00	26.00-200.00	Barclay et al., 1995 (65)	Whole wheat
	24	44.00	18.00-35.00	Barclay et al., 1995 (65)	
	5	42.12	25.50-77.90	Diaz-Alarcon et al., 1996 (64)	
	3	23.63	19.50-26.70	Finley et al., 1996 (76)	
	3	27.97	22.70-32.60	Finley et al., 1996 (76)	Whole wheat
	6	17.60	14.30-21.50	Kadrabova et al.,1997 (68)	
	4	127.10	63.99-274.00	Hussein et al., 1999 (81)	
	1	364.29	ND	Holben et al., 1999 (75)	Whole wheat
	1	284.00	ND	Holben et al., 1999 (75)	White bread
	26	129.00	84.00-158.00	Murphyt et al., 2001 (63)	Whole wheat
	18	66.00	55.00-95.00	Murphyt et al., 2001 (63)	White bread
	20	118.00	94.00-146.00	Murphyt et al., 2001 (63)	Adding bran
	2	57.55	45.70-47.70	Klapec et al., 2004 (62)	
	1	171.33	167.00-177.00	Lyons et al., 2005 (46)	White bread
	1	172.33	170.00-177.00	Lyons et al., 2005 (46)	Whole wheat
	ND	91.90	70-131.8	Pappa et al., 2006 (74)	
	1	40	ND	Bryszewska et al., 2007 (73)	
	16	578.99	34.40-2090.50	Hart et al., 2011 (58)	Soil fertilization
	16	669.44	39.60-2372.20	Hart et al., 2011 (58)	Whole wheat+Soil fertilization
Pasta	6	821.67	650.00-1420.00	Arthur, 1972 (67)	
	7	390.00	ND	Olson et al., 1984 (79)	
	1	870.00	ND	Olson et al., 1984 (79)	Whole wheat
	10	55.00	35.00-88.00	Barclay et al., 1995 (65)	Whole wheat
	12	48.00	37.00-58.00	Barclay et al., 1995 (65)	
	2	24.40	22.30-26.80	Diaz-Alarcon et al., 1996 (64)	

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Continued Table S3 Selenium content in different wheat processed foods

Name	Number of samples	Selenium content (μg·kg^{-1})		References	Remark
		Mean	Range		
Pasta	1	32.70	ND	Finley et al., 1996 (76)	
	1	212.86	ND	Holben et al., 1999 (75)	
	20	66.00	49.00-78.00	Murphyt et al., 2001 (63)	Fresh + whole wheat
	6	221.17	48.00-526.00	Alamin et al., 2006 (61)	
	3	71.00	20.00-130.00	Wang et al., 2008 (60)	
	3	91.10	83.50-97.30	Cubadda et al., 2009 (42)	
	3	88.37	80.30-92.80	Cubadda et al., 2009 (42)	
	12	154.00	84.00-227.00	Cubadda et al., 2009 (42)	
	7	367.00	22.40-1190.40	Poblaciones et al., 2014 (31)	
	1	23.92	ND	Wang et al., 2015 (72)	
	1	492.10	ND	Wang et al., 2015 (72)	Adding selenium-rich yeast
Steamed buns	1	770.00	ND	Wang et al., 2016 (14)	Foliar fertilization
Noodle	3	936.67	760.00-1130.00	Arthur, 1972 (67)	
	2	430.00	ND	Olson et al., 1984 (79)	Whole wheat
	5	590.00	ND	Olson et al., 1984 (79)	Adding eggs
	1	48	ND	Oster et al., 1989 (66)	
	2	29.50	27.00-32.10	Diaz-Alarcon et al., 1996 (64)	
	1	23.40	ND	Finley et al., 1996 (76)	
	3	56.80	53.00-59.00	Kadrabova et al., 1997 (68)	
	1	216.88	ND	Holben et al., 1999 (75)	Adding eggs
	4	43.80	ND	Klapec et al., 2004 (62)	
	4	118.25	15.00-220.00	Wang et al., 2008 (60)	
Wheat groats	3	40.00	30.00-50.00	Arthur, 1972 (67)	
	2	46	43.00-49.00	Ferretti et al, 1974 (80)	
	5	51.00	ND	Olson et al., 1984 (79)	
	28	31.00	28.00-34.00	Murphyt et al., 2001 (63)	
Biscuits	14	60.00	ND	Olson et al., 1984 (79)	
	15	242.00	90.00-600.00	Arthur, 1972 (67)	
	4	60	50.00-60.00	Eurola et al., 1991 (78)	
	3	28.20	8.20-44.90	Diaz-Alarcon et al., 1996 (64)	
	2	4.50	3.60-5.40	Finley et al., 1996 (76)	

693 **Continued Table S3** Selenium content in different wheat processed foods

Name	Number of samples	Selenium content (μg·kg^{-1})		References	Remark
		Mean	Range		
Biscuits	2	34.20	ND	Klapec et al., 2004 (62)	2
	1	420.00	ND	Zhai et al., 2018 (71)	1
	1	500.00	ND	He, 2019 (70)	1
-	Mean	211.86	15.00-2372.20	-	-

694 Note: ND indicates that relevant information is not mentioned in the literature

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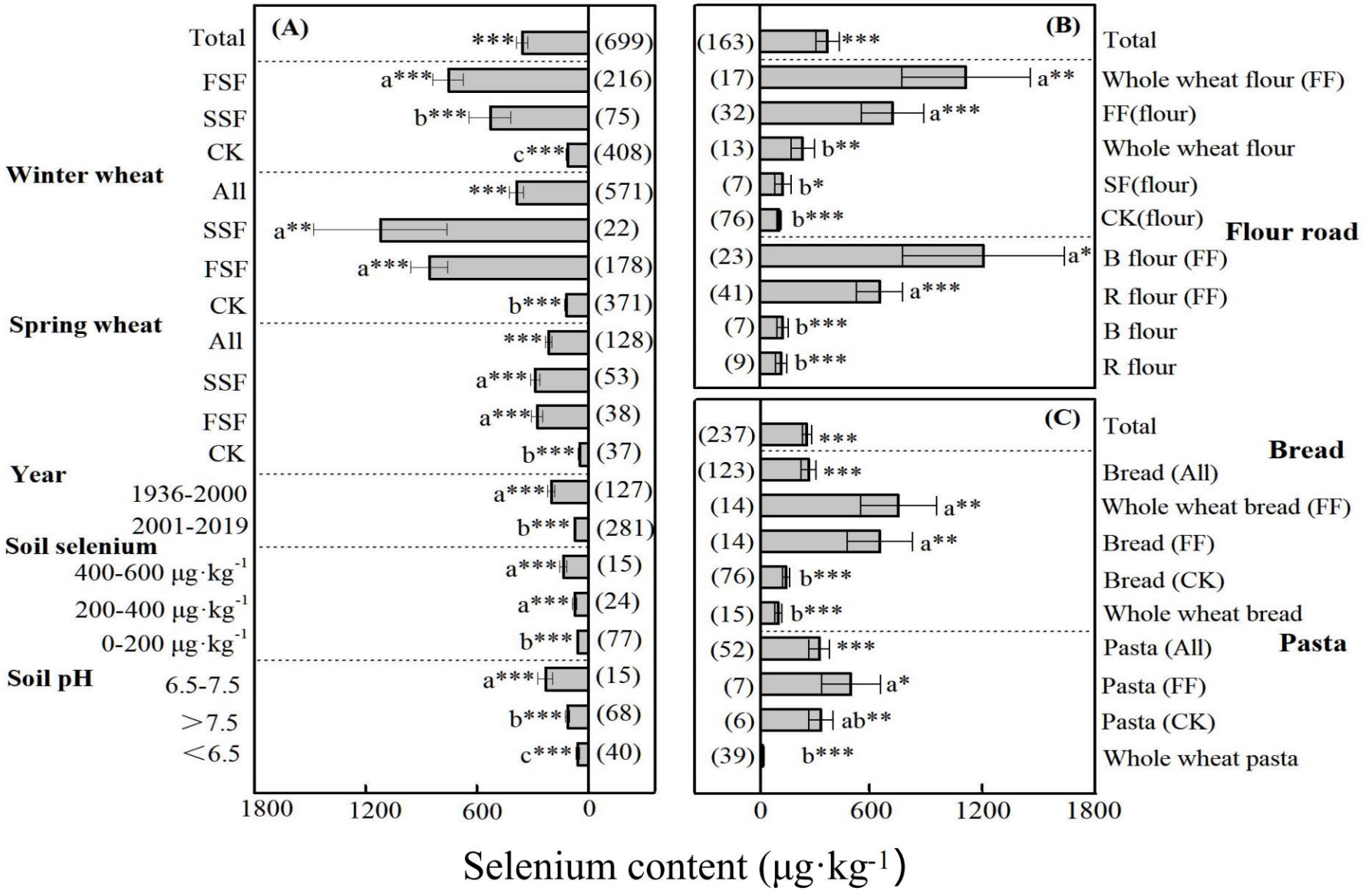
(A)
Total
FSF
SSF
CK
Winter wheat
All
SSF
FSF
CK
Spring wheat
All
SSF
FSF
CK
Year
1936-2000
2001-2019
Soil selenium
400-600 μg·kg-1
200-400 μg·kg-1
0-200 μg·kg-1
Soil pH
6.5-7.5
>7.5
<6.5
***
a***
b***
c***
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a**
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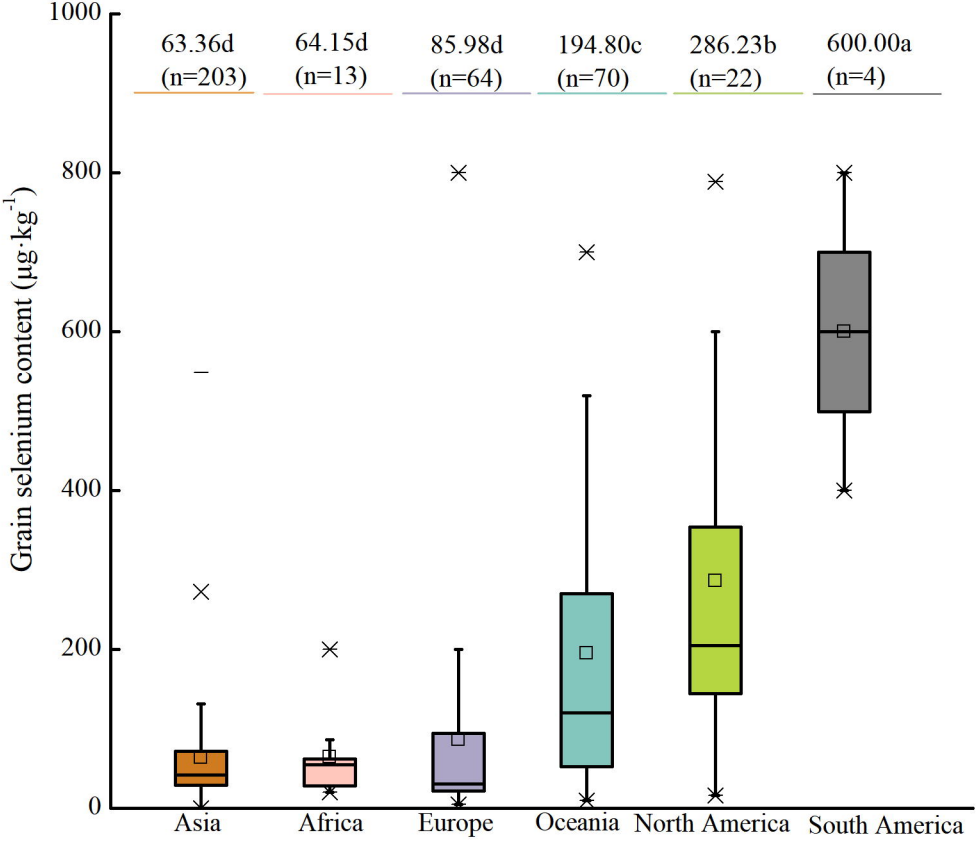
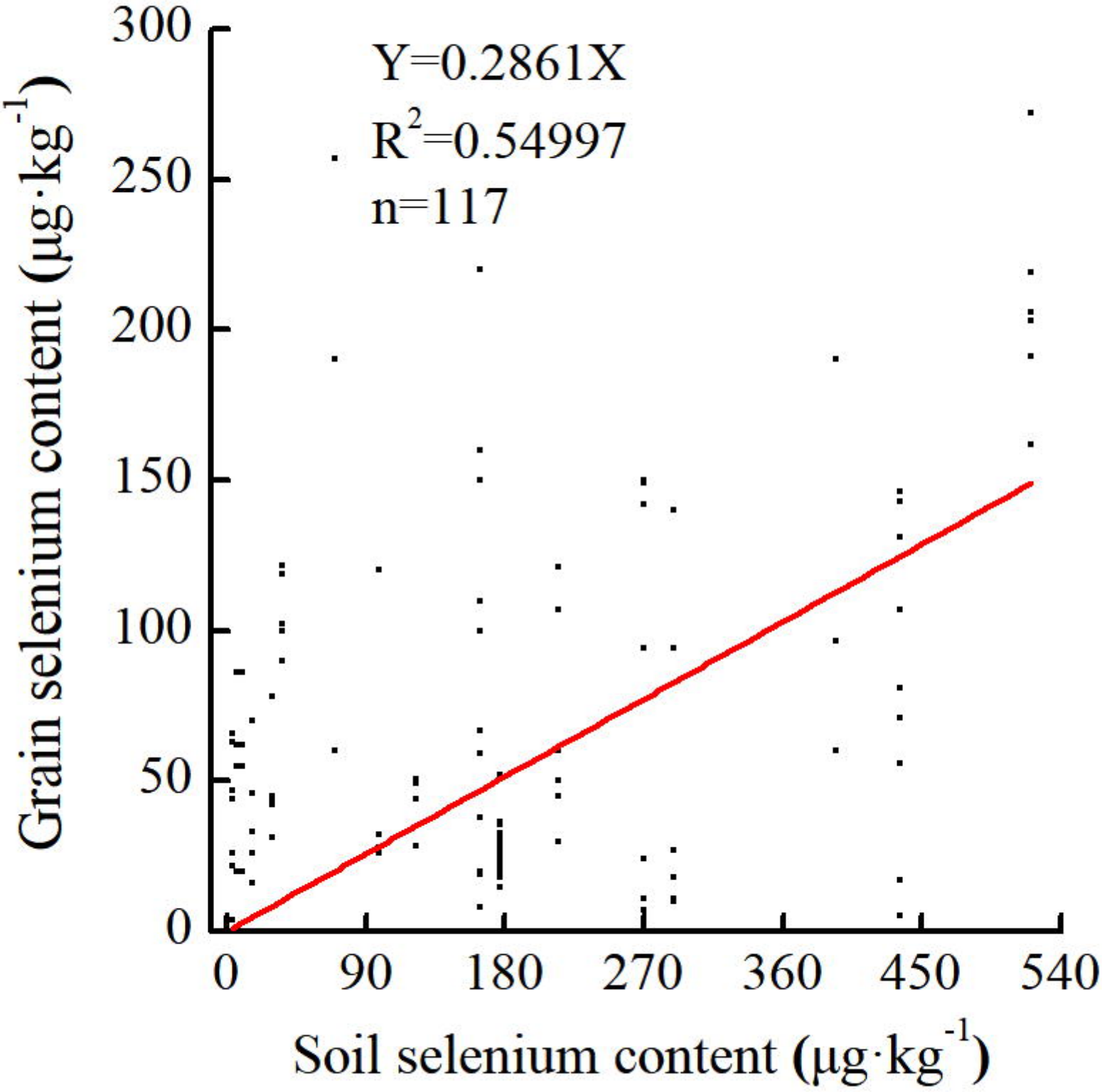
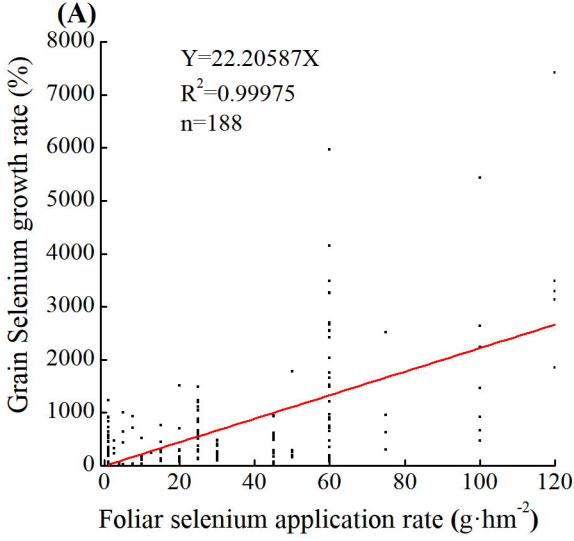
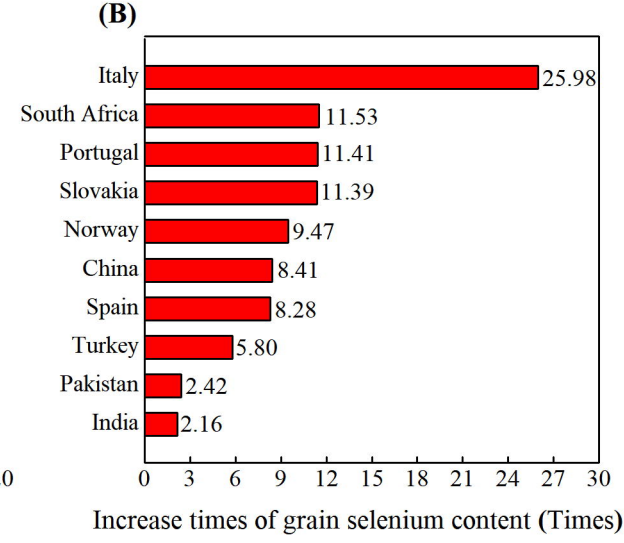
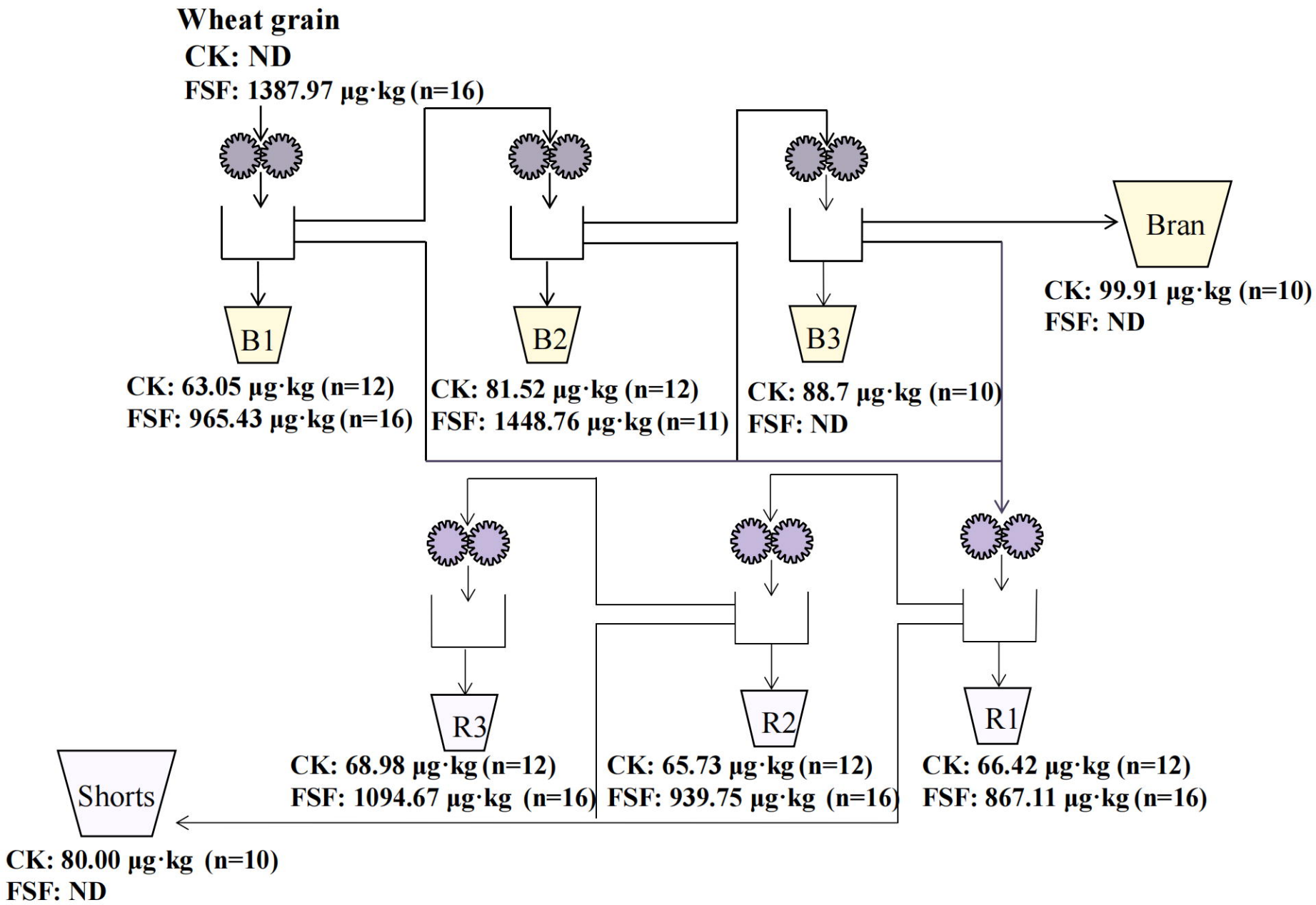
c***
(699)
(216)
(75)
(408)
(571)
(22)
(178)
(371)
(128)
(53)
(38)
(37)
(127)
(281)
(15)
(24)
(77)
(15)
(68)
(40)
1800
1200
600
0
(B)
Total
Whole wheat flour (FF)
FF(flour)
Whole wheat flour
SF(flour)
CK(flour)
Flour road
B flour (FF)
R flour (FF)
B flour
R flour
(163)
(17)
(32)
(13)
(7)
(76)
(23)
(41)
(7)
(9)
***
a**
a***
b**
b*
b***
a*
a***
b***
b***
(C)
Total
Bread
Bread (All)
Whole wheat bread (FF)
Bread (FF)
Bread (CK)
Whole wheat bread
Pasta
Pasta (All)
Pasta (FF)
Pasta (CK)
Whole wheat pasta
(237)
(123)
(14)
(14)
(76)
(15)
(52)
(7)
(6)
(39)
***
***
a**
a**
b***
b***
***
a*
ab**
b***
0
600
1200
1800
Selenium content (μg·kg-1)

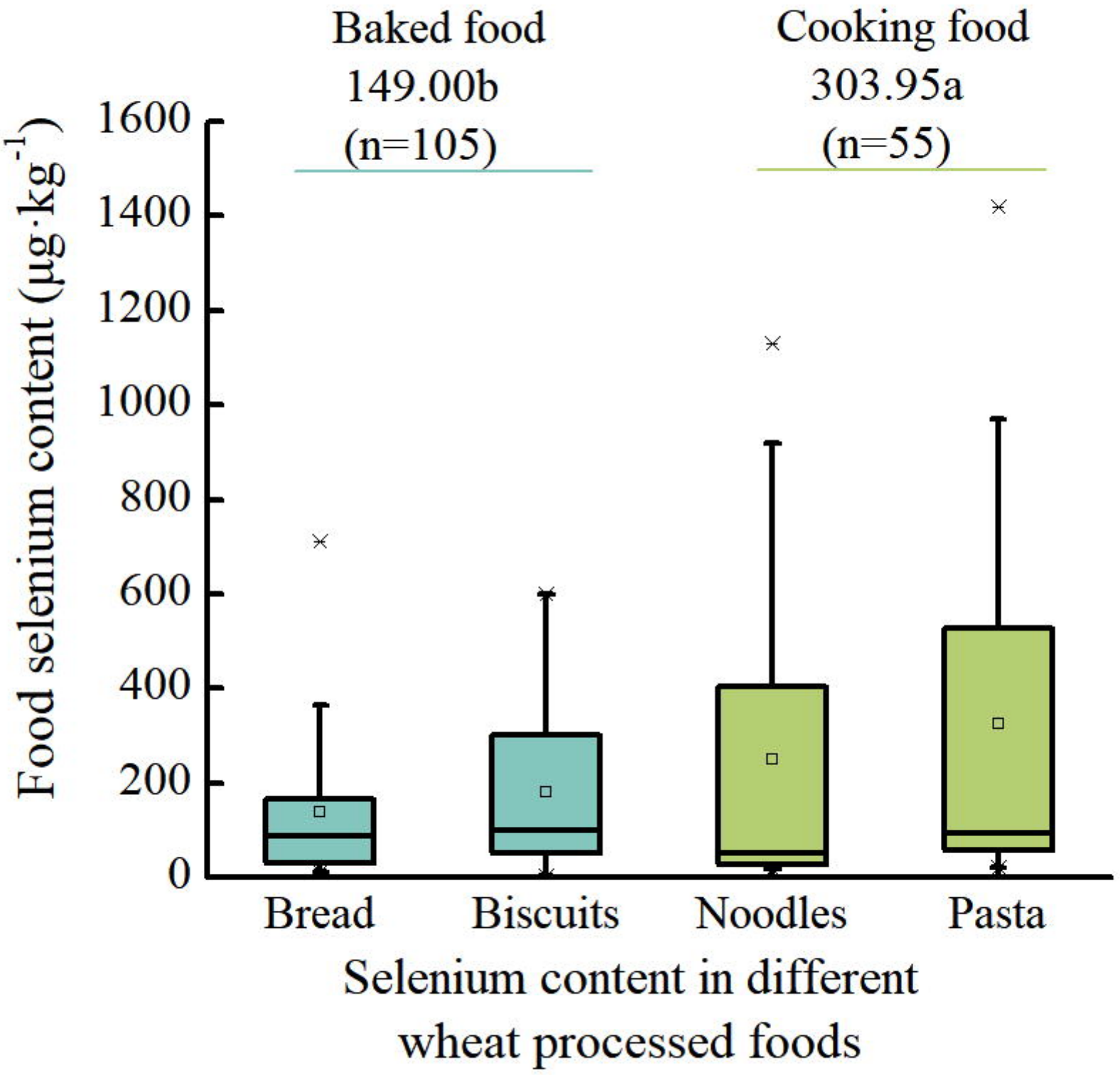

63.36d
(n=203)
64.15d
(n=13)
85.98d
(n=64)
194.80c
(n=70)
286.23b
(n=22)
600.00a
(n=4)
Grain selenium content (μg·kg-1)
1000
800
600
400
200
0
Asia
Africa
Europe
Oceania
North America
South America

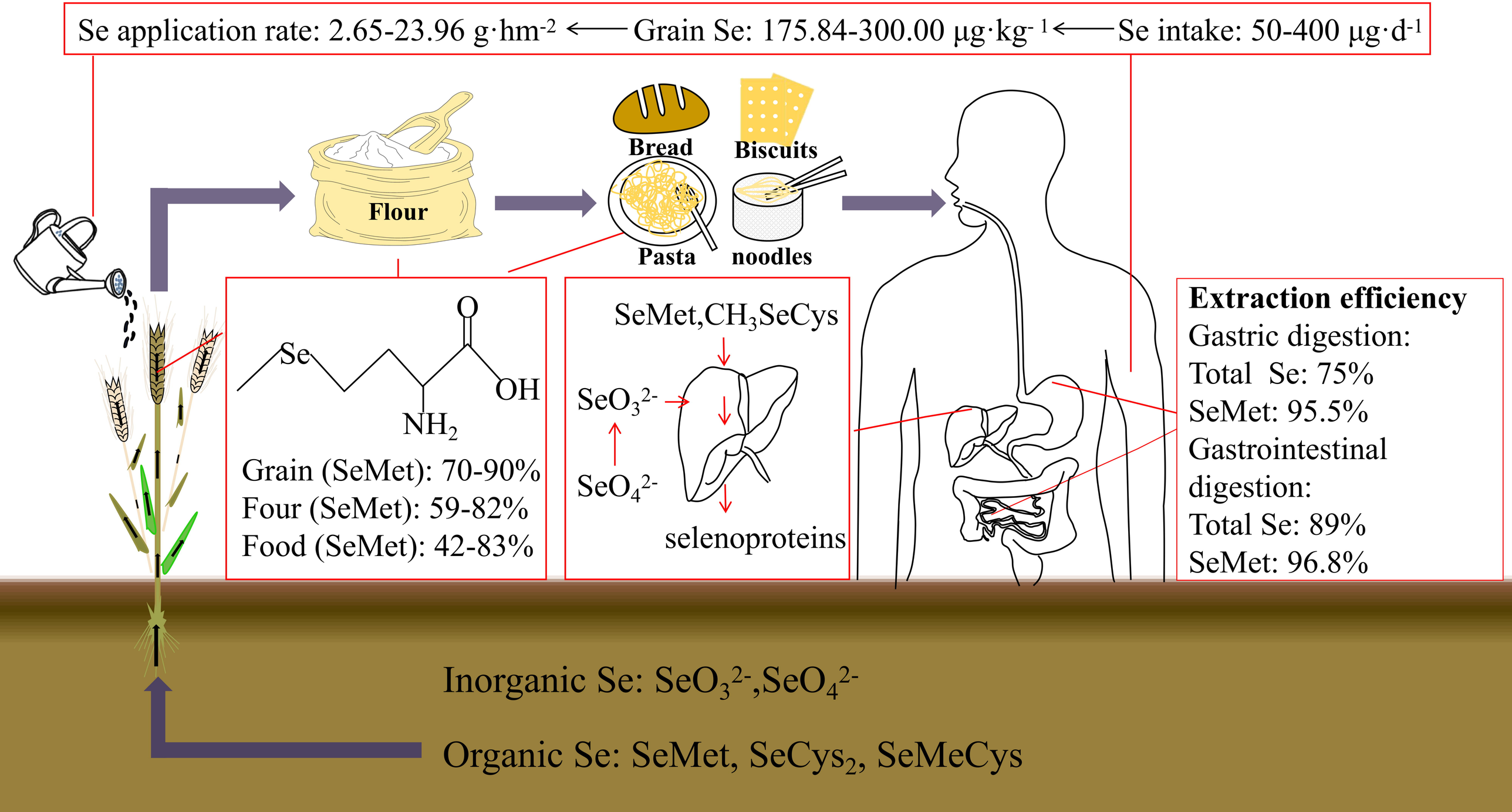

Y=0.2861X
R2=0.54997
n=117
Grain selenium content (μg·kg-1)
Soil selenium content (μg·kg-1)
0
50
100
150
200
250
300
0
90
180
270
360
450
540


(A)
Y=22.20587X
R2=0.99975
n=188
Grain Selenium growth rate (%)
Foliar selenium application rate (g·hm-2)
0
1000
2000
3000
4000
5000
6000
7000
8000
0
20
40
60
80
100
120


(B)
Italy 25.98
South Africa 11.53
Portugal 11.41
Slovakia 11.39
Norway 9.47
China 8.41
Spain 8.28
Turkey 5.80
Pakistan 2.42
India 2.16
0
3
6
9
12
15
18
21
24
27
30
Increase times of grain selenium content (Times)


Wheat grain
CK: ND
FSF: 1387.97 μg·kg (n=16)
B1
CK: 63.05 μg·kg (n=12)
FSF: 965.43 μg·kg (n=16)
B2
CK: 81.52 μg·kg (n=12)
FSF: 1448.76 μg·kg (n=11)
B3
CK: 88.7 μg·kg (n=10)
FSF: ND
Bran
CK: 99.91 μg·kg (n=10)
FSF: ND
R3
CK: 68.98 μg·kg (n=12)
FSF: 1094.67 μg·kg (n=16)
R2
CK: 65.73 μg·kg (n=12)
FSF: 939.75 μg·kg (n=16)
R1
CK: 66.42 μg·kg (n=12)
FSF: 867.11 μg·kg (n=16)
Shorts
CK: 80.00 μg·kg (n=10)
FSF: ND


Baked food
149.00b
(n=105)
Cooking food
303.95a
(n=55)
Food selenium content (μg·kg-1)
1600
1400
1200
1000
800
600
400
200
0
Bread
Biscuits
Noodles
Pasta
Selenium content in different
wheat processed foods


Se application rate: 2.65-23.96 g·hm-2
Grain Se: 175.84-300.00 μg·kg-1
Se intake: 50-400 μg·d-1
Flour
Bread
Biscuits
Pasta
noodles
Se
O
OH
NH2
Grain (SeMet): 70-90%
Four (SeMet): 59-82%
Food (SeMet): 42-83%
SeMet,CH3SeCys
SeO32-
SeO42-
selenoproteins
Extraction efficiency
Gastric digestion:
Total Se: 75%
SeMet: 95.5%
Gastrointestinal digestion:
Total Se: 89%
SeMet: 96.8%
Inorganic Se: SeO32-,SeO42-
Organic Se: SeMet, SeCys2, SeMeCys