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Review

Advances in selenium-enriched foods: From the farm to the fork

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ABSTRACT

Background: Selenium(Se) is an element found in the soil, which is also an essential micronutrient for human body. In fact, Se content of most of foods is very low, the Se requirement of the body can be satisfied with dietary supplements, Se-enriched foods is a good choice to deliver Se.

Scope and approach: In modern society, the suitable agronomic-based and processing-based strategies can be utilized by farmers and producers to produce Se-enriched food products with high quality. We can also use some methods to optimize the Se content and bioaccessibility of Se-enriched foods.

Key findings and conclusions: Agricultural stragety biofortification is an efficient way to produce Se-enriched local original products. But some processing methods may decrease the Se content of processed food. In addition, different Se forms have different bioaccessibility to living organisms.

1. Introduction

Selenium(Se) belongs to group XVI in the periodic table of the elements, is an essential element required for several functional Se-dependent proteins in most living organisms(Arteel & Sies, 2001). Prior to 1950s, the toxicity of selenium was the major research interest and was reported elsewhere(Schrauzer, 2000; Schwarz & Foltz, 1957). After that period, it uses as a kind of nutritive supplementation in cases of regional selenium deficiency or as a pharmacologic supplementation to prevent cancer diseases have received recent attention(Ganther, 1999; Rayman, 2000).

Previous studies shows that a narrow margin between nutritionally optimal and potentially toxic concentrations exists in Se, it is an essential nutrient, but can become toxic at only slightly higher concentration optimum(Porcella, Bowie, Sanders, & Cutter, 1991; Presser & Luoma, 2010). The Committee on the Medical Aspects of Food Policy (COMA) proposed a Reference Nutrient Intake (RNI) of 60 and 75 μg/day for females and males, respectively, based on a requirement of 1 μg Se/kg body weight/day (Broadley, 2011). However, the criterion of maximization of plasma selenoproteins has been chosen by different countries to give the reference nutrient intake that has been recommended by the WHO as 40 μg/day for men and 30 μg/day for woman(Frias et al., 2009).

As an essential micronutrient, Se requires for metabolic activities in humans and animals including thyroid hormone metabolism, antioxidant defense, and immune function(Suhajda, Hegoczki, Janzso, Pais, & Vereczkey, 2000), for example, the antioxidant glutathione peroxidases are likely to protect neutrophils from oxygen-derived radicals that are produced to kill ingested foreign organisms(Arthur, McKenzie, & Beckett, 2003). As such, its deficiency can cause a number of degenerative diseases including endemic Kashin-Beck diseases(KBD), which also known as "Big Bone Disease", is a disorder affecting the bones and joints of the hands (including fingers), elbows, knees, and ankles of children and adolescents(Diowksz, Kordialik-Bogacka, & Ambroziak, 2014; Guo & Wang, 2011).

Until now, Se is found in varying quantities in the rocks and soils of different regions around the world. In these areas, the feature of Se-enriched reflected on forage crops to animals and locally foods for humans(Arthur et al., 2003). Based on the previous studies, diet is the dominant route of Se exposure for living organisms(Presser & Luoma, 2010). Furthermore, Se-enriched foods have the potential functions which are beneficial to our health. Flohe(FLOHÉ, 1985) reported that plants accumulate Se as analogues of methylcysteine, γ-glutamylcysteine, cystatonine, and adenozylomethionine, some of which may exhibit free radical scavenging activity. The higher antioxidant capacity was found in Se-enriched lupin sprouts, it may be related to the biotransformation of inorganic Se forms in compounds able to scavenge ABTS$^{\cdot+}$ cation radicals, because selenate cannot be oxidized during the scavenging reaction of ABTS$^{\cdot+}$ (Frias et al., 2009).

For plants and animals, the Se-enriched fertilizer and fodder is an

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effective way to increase the content of Se; and for human, in order to ensure adequate Se balance in the human body, people need to deliver it through Se-enriched foods. From dietary sources, the bioavailable forms of Se include both inorganic (e.g. selenate, selenite) and organic (e.g. selenomethionine and selenocysteine) forms (Arteel & Sies, 2001). So people need to find ways to increase the bioavailable forms in plants and animals, meanwhile, use some efficient technologies to decrease the Se content in the products.

1.1. Agronomic-based methods in selenium enrichment

Se can be originated from natural sources like volcanic eruptions, weathering of soils and rocks, wildfires, and volatilization from waterbodies and plants(Eisler, 1985; Floor & Román-Ross, 2012; Lantzy & Mackenzie, 1979). The content of Se in some areas soil is high, and the Se content of plant and animal products is corresponding higher than other areas. For example, Brazil is a country where there is significant variety in the food products rich in Se, including vegetables and animal origin foods, which are commonly exported abroad(dos Santos, da Silva Júnior, & Muccillo-Baisch, 2017). But Se deficiency is more prevalent in regions where the soil Se content is low such as northeastern/western United States, northeastern China, Russia, and Finland(Frias et al., 2009).

Agricultural strategies such as biofortification seems to play a major role controlling Se concentrations, and because of the plant-animal-human food chain, we can use the suitable agricultural methods to increase the content and bioaccessibility of Se, in order to reach the highest values in agricultural products for humans who consume them, and may help reduce dietary deficiencies of Se occurring throughout susceptible regions of the world.

The influence of agronomic methods on the selenium content and bioaccessibility is presented in Table 1.

1.2. Plants

Plants tend to contain low concentrations of Se, depending on the place of cultivation(Broadley, 2011). Se enters the food chain through plants, and the Se concentration of plants varies according to available soil Se concentration, its bioavailability for uptake into plant roots, and plant species(Haug, Graham, Christophersen, & Lyons, 2007).

Fertilization is an usual way to deliver Se to plants. If Se fertilizers are to be adopted for cereal crops, it is important to quantify the likely transfer of Se into final food products. For example, in test bakes with UK-grown wheat, 77% and 90% of the Se in the grain was retained in white and wholemeal breads, respectively(Hart et al., 2011); flour derived from Spanish Se-enriched wheat, retained 72% of the initial Se in the grain(Poblaciones, Santamaría, García-White, & Rodrigo, 2014).

Foliar application is an agronomic-based strategy utilized by farmers, the foliar exposure route application ensures a high efficiency of Se assimilation by the plant since it does not depend on root-to-shoot translocation(Fontanella et al., 2017). Fontanella et al. found that, compared with untreated group, the treated grapes in the pre-flowering period with sodium selenate (100 mg Se L^{-1}) had a higher amount of Se in the treated leaves at harvest, the treated ones had a content of Se of 0.800 ± 0.08 mg/kg dry weight(dw), while that untreated ones was 0.065 ± 0.025 mg/kg dw(Fontanella et al., 2017).

Sprouting seeds regard to be a good Se-enriched media, some applications of Se-rich germinated seeds may be considered to be mixed into various food products(Frias et al., 2009). Sprouts, known as selenium accumulators(Lintschinger, Fuchs, Moser, Kuehnelt, & Goessler, 2000), can accumulate selenium from different inorganic sources (e.g., selenite, selenate). During the growth of sprouts, Se is incorporated in the newly synthesized proteins. Rye grain treated with selenite during germination has been shown to accumulate 55 mg/kg Se, which was all converted to organic forms, mostly Se-Met, and the Se-rich rye was then blended with ordinary rye to make bread with a final Se concentration of 4 mg/kg(Bryszewska et al., 2005).

Make the choice of the enrichment solutions to promote a balanced distribution of different chemical forms may favour the plants to accumulate of organic forms(Businelli, D'Amato, Onofri, Tedeschini, & Tei, 2015; Fontanella et al., 2017). The results were observed by Ximenez-Embun et al.(Ximenez-Embur, Alonso, Madrid-Albarra´n, & Ca'mara, 2004)in Indian mustard, sunflower, and lupin showed that selenate is more readily taken up by plants than Selenite. A similar result presented in the work of Pedrero et al.(Pedrero, Madrid, & Ca'mara, 2006), they observed the Se-enriched broccoli obtained by hydroponic culture and exposed to selenite solutions for up to 40 days showed an increase in the total Se content in the plant and was higher in roots than in stems.

In addition, plant species may vary widely in Se uptake and accumulation. Se enrichment of lupin sprouts in the present work was lower than in other sprouts reported in the reasearch(Frias et al., 2009). Rye grain treated with selenite during germination has been shown to accumulate 55 μg of Se/g of dw(Bryszewska et al., 2005). Wheat and alfalfa germination enriched Se up to concentrations of 100 and 150 μg/g of dw, respectively(Lintschinger et al., 2000).

It is also important to know not only the total amount of Se in foods but also the chemical forms in which Se is presented, to obtain precise information about the Se benefits. Actually the most dietary Se is adsorbed efficiently but the organic forms is more retrained for further bioactivity (e.g protein incorporation) than that of inorganic Se forms (Fairweather-Tait, Collings, & Hurst, 2010; Thiry, Ruttens, De Temmerman, Schneider, & Pussemier, 2012). Plants convert Se mainly into selenomethionine (Se-Met) and incorporate it into protein instead of methionine(Frias et al., 2009). Se-Met is the major selenocompound in cereal grains, grassland legumes, and soybeans, whereas selenomethylcysteine (SeMCys) is the major selenocompound in Se-enriched plants such as garlic, onions, sprouts, and wild leeks(Haug et al., 2007).

1.3. Animals

In our daily life, the most important dietary source is meat. Se-enriched meat is potentially a unique source of dietary Se. The Se concentration in meat is directly related to the Se concentration of the crops on which the animals graze. Based on the previous researches, fish and beef are the main research objectives.

Red meat such as pork and beef can accumulate high amounts of Se when the animal is fed a Se-rich diet. The results demonstrated that cattle fed diets high in Se from agricultural products will accumulate substantial amounts of Se in the beef without developing signs of Se toxicity and that prior Se status regulates Se accumulation in some organs(Hintze, Lardy, Marchello, & Finley, 2002). Moreover, Se from meat has been shown to be highly bioavailable for protein-synthesis (Dumont, Vanhaecke, & Cornelis, 2006).

Table 1
The influence of agronomic methods on the selenium content and bioaccessibility.

Agronomic methods	Materials	Products	Se content	Se bioaccessibility	References
germination	lupin seeds	lupin sprouts	> 10 μg/g of dw	antioxidant activity (up to 117.8 and 103.5 μmol of Trolox/g of dw)	(Frias et al., 2009)
germination	garden cress seeds	garden cress sprouts	> 30 μg/g of dm		(Frias et al., 2010)
foliar application	rice	rice	35.9%		(Chen et al., 2002)