Emir. J. Food Agric. 2015. 27 (3): 231-241
doi: 10.9755/ejfa.v27i3.19285
http://www.ejfa.info/

REVIEW ARTICLE

Selenium Biofortification in Rice - A pragmatic perspective

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Abstract

Selenium is an antioxidant trace mineral with important biochemical functions related to the enzymatic activity of selenoproteins. Due to a wide variation in the content of selenium from different plant sources, there is a high risk of deficiency of this nutrient in human nutrition, and particularly in the early childhood. Thus, the use of biofortified staple foods, namely selenium rice flour can be understood as an important trait, namely for food production for infants. This study aims to evaluate the importance of selenium biofortified rice flour, further considering baby foods.

Key words: Baby food, Biofortification, Rice flour, Selenium

Introduction

The World Health Organization (WHO) has shown that micronutrient deficiency is a problem, not only in developing countries, but also in underdeveloped (Nutti et al., 2009). In this context, natural fortification of plant products have the potential to provide continuous benefits in developing countries, while presenting a lower recurring cost than supplementation and postharvest fortification (Bouis et al., 2009). Biofortification provides feasible means of reaching malnourished populations who may have limited access to diverse diets, supplements, and commercially fortified foods (Saltzman et al., 2013). This strategy may benefit populations with limited access to markets and health systems (Bouis et al., 2011). Once the investment is made in the development of nutritionally improve varieties, the seeds obtained will be adapted to the growing conditions of many countries

Selenium deficiency affects approximately 15% people worldwide (White and Broadley, 2009), being infants further reported to be at risk of a poor selenium status, due to the low levels of this nutrient in human milk and infant formula, which are their sole or major food source during early life (Litov and Combs, 1991). In this context, biofortification is one of the safest ways to alleviate selenium deficiency, as it can be assimilated by plants under organic forms bioavailable to humans (Helina, 2005). Considering that rice (*Oryza sativa* L.) is a predominant food in more than 30 countries (Lucca et al., 2006), further being the second largest cereal crop in the world, surpassed only by corn, this crop biofortification in selenium has an enormous potential for reducing this nutrient deficiency in the world population (Hu et al., 2002). Additionally, this plant species it also has a strategic role for promoting the economic and social levels of many countries (FAOSTAT, 2011).

This study aims to summarize the importance of the use of biofortified rice flour in selenium, as

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Received 05 June 2014; Revised 21 July 2014; Accepted 01 August 2014; Published Online 01 March 2015

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well as its characteristics and potential in the human diet.

About selenium biofortification

Biofortification of plant species can be carried out through agronomic biofortification, to achieve higher nutrients uptake (Cakmak, 2008; Velu et al., 2013). In this context, agronomic biofortification in selenium, basically increases this nutrient concentration in agricultural crops through fertilization, eventually using different chemical forms (Gupta and Gupta, 2002; Carvalho et al., 2003; Graham et al., 2007; Pyrzynska, 2009).

The content of micronutrients in the food products of vegetable origin is partly determined by the level and availability in the soils in which crops are obtained (Nub and Voortman, 2006). The mineral composition of cereal grains, according to Anglani (1998), might vary with genotype, growing season, soil conditions and practices of fertilization. Therefore, in developing countries, it is suggested that biofortification strategies should focus on the dominant staple food in population’s diets (Bouis, 2000; Pfeiffer and McClafferty, 2007). According to Bouis et al. (2000) and Graham et al. (2007), if the concentrations of mineral elements in staple foods can be augmented, then the supply of mineral elements in vulnerable populations can be increased, following a consumption proportion of these foods to the diet.

The target foods include biofortification of rice, wheat (which fall into the category of staples foods for more than half the world's population), corn (the most consumed crop in most of Africa and Central America) and beans (with a relevant consumption in Africa and Latin America). Yet, selenium content in soils varies geographically between and within countries, which affects his nutrient contents in the food products, as well as the estimates of the dietary intake of selenium in each country (Pappa et al., 2006; Smrkolj et al., 2005). Nevertheless, often, the edible parts have low concentrations of minerals because crops grow in soils lacking mineral elements for plants, whereas fertilization mostly increases the mineral concentration in leaves and improves their performance (Welch and Graham, 2002).

In a global survey, selenium content in rice is usually low, which limits the nutritional requirements of populations depending on rice consumption for their dietary selenium intake (Williams et al., 2009). Indeed, approximately, 50% of the human population is reliant upon paddy rice for sustenance (Harvest Plus, 2014), since not only can rice contribute up to approximately 80% of energy intake in some regions, but it can further account for a significant proportion of their daily dose of protein and micronutrients (Hels et al., 2003). Thus, there is considerable interest in obtaining crops that are efficient in the exploitation of minerals, produce high yields and accumulate minerals in infertile soils. This strategy has the potential to become sustainable, profitable and reach remote rural populations (Bouis et al., 2003).

Selenium, besides being an essential trace element for humans and animals, also has anticancer and antioxidant properties, which determines its use in food biofortification programs (Rios et al., 2010). The interest in selenium has evolved due to their presence in the enzyme glutathione peroxidase. Glutathione peroxidase is an antioxidant enzyme that removes hydrogen peroxide or other oxidizing organic hydroperoxide glutathione (Figure 1), which may then be reduced by glutathione reductase (Ji et al., 1998).

The role of this element in plants is still controversial (Zhu et al., 2009; Pilon-Smits and Quinn, 2010), yet some studies seem to indicate that selenium maintain plants physiologically active for longer life periods, which in some cases determines an increasing crop production (Hartikainen et al., 2000; Lyons et al., 2009; Ramos et al., 2011). Nevertheless, is worth emphasizing that, in biofortification programs the form of selenium applied must be taken into account (Zhang and Sparks, 1990), since plant species not have different uptake capacities, but also the accumulation of selenium forms (selenite, selenite and organic forms of selenium) in the soil can vary (Kabata-Pendias, 1999 cf. Hawrylak and Szymanska, 2004). In a study conducted by Wang et al. (2013), rice sprayed with 10.5g and 21 g of selenite/hectare produced more tillers per plant, more grains per panicle, bigger grains and higher yields. Additionally, this treatment also shortened the number of days to heading, leading to an earlier maturity of rice. Hu et al. (2002) have also showed that foliar application of selenite alone was as efficient as selenium-enriched blended fertilizers, in terms of yield, selenium, protein and lipid content, and crude ash. Besides, several authors (Chen et al., 2002; Ríos et al., 2008; Broadley et al., 2010) found that selenium content in crops might increase with additional fertilization, being therefore a useful technique to augment selenium intake of human populations.

In rice Chen et al. (2002) also found that selenium content increased with fertilization, whereas Combs (2001) stated that an adequate level of selenium in a population is highly correlated with its content in food. Accordingly, increasing the content of selenium in foods of vegetable origin seems to be a strategy to decrease human deficiency of this element (White and Broadley, 2009; Ramos et al., 2010). In a study by Hu et al. (2014), with application of selenium (0.5 mg kg^{-1}), it was found that its amount significantly increased in rice tissues, in particular its translocation from roots. Moreover, earlier studies also reported beneficial effects of selenium, because it increases the antioxidant activity in plants, leading to a yield (Hartikainen et al., 2000; Lyons et al., 2009). Hu et al. (2002) further reported a 10 fold increase in selenium content of mature polished rice grain, following a single foliar spray application of 14–18 g ha^{-1} at the heading stage. Fang et al. (2009) showed that foliar applications of 100 g ha^{-1} of selenite might led to 55 fold increase in the selenium content of rice grain (from 0.032 to 1.79 mg kg^{-1}). Lyons et al. (2004) further reported that the application of selenium is probably the most successful example of agronomic intervention by mineral fertilization, because selenate is highly mobile in many soil types, being easily absorbed by plants and accumulated in the grains in a bioavailable form (i.e., methionine and cysteine).

About selenium bioavailability

Bioavailability is defined as the proportion of an ingested nutrient that is used for normal physiological functions and storage (Tapiero et al., 2003). Absorption in the intestinal mucosa and retention of the nutrient in the human body are also taken as indirect measures of bioavailability (Sneddon, 2012). The World Health Organization recommends a daily selenium dose of 30 - 40 µg for adults (Bitterli et al., 2010; Pérez-Corona et al., 2011) and also emphasizes that a selenium daily dose of 400 µg is harmless. Moreover, the Food and Nutrition Board of the National Academy of Science states that the daily selenium requirement according to age varies in men (40–70 µg), in women (45–55 µg) and children (15-20 µg) (El-Bayoumy, 2001).

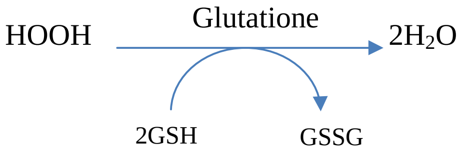

Figure 1. Enzymatic reaction catalyzed by selenoenzima glutotiona peroxidase.

There are several classes and selenium compounds, but its bioavailability depends on the composition of food and its occurrence (Kieliszek and Blazejak, 2013). Among the various forms of selenium, we can find two categories: inorganic (selenito - SeO_3, selenate - SeO4) and organic (and amino acids, methylated forms, SE-proteins) (Pedrero et al., 2006; Pedrero and Madrid, 2009). The form of selenium with improved rates of assimilation for humans is organic forms, since they can be absorbed more easily and with a lower excretion rate (Daniels, 1996). Indeed, estimates of total elements content of a particular food are not reliable, as bioavailability of the nutrient is related with the fraction that is absorbed and transformed into a biologically available form (Cabrera et al., 1996; Cabañero et al., 2007). Indeed, estimates of total elements content of a particular food are not reliable, as bioavailability of the nutrient is related with the fraction that is absorbed and transformed into a biologically available form (Cabrera et al., 1996; Cabañero et al., 2007).

The proportion of the nutrient absorbed from the gastrointestinal tract is a major determinant of bioavailability, but is not the only factor that influences bioavailability (King, 2001). The bioavailability of micronutrients in plant foods to humans is pervaded with numerous complexities, and is influenced by endogenous and exogenous factors.

Accordingly, to study selenium bioavailability, experiments can be conducted in vitro on cultivated intestinal cells, in vivo on laboratory animals or directly on persons. On persons, bioavailability can be estimated by measuring selenium levels in blood and in body tissues. The bioactive part of selenium is converted into biologically active selenometabolites (Thiry et al., 2012). Additionally, according to Ruby et al. (1999), the bioaccessible fraction of an element is the fraction that is soluble in the intestine and that is therefore available for subsequent processes of absorption through the intestinal mucosa (Figure 2).

The absorption of selenium compounds in the intestinal mucosa varies according to their chemical form (about 90% for selenomethionine and 80% for selenite). Selenium is mainly absorbed in the duodenum by enterocytes (through aminoacid transport systems) and catabolized into elemental selenium that therefore gets incorporated into glutathioneperoxidase (Rayman, 2008; Fairweather-Tait et al., 2011). These selenoproteins are transported into the liver, being converted into selenoprotein P and distributed in the organs

(Fairweather-Tait et al., 2011), namely brain, kidney, heart, spleen, muscles and gonads (Kumar and Priyadarsini, 2014). In this context, Wang et al. (2013) found that selenium bioavailability in biofortified rice about 80% of this nutrient remained in the organic form, and that the main species of seleno-bound protein were Se-methionine and Se-cysteine. Additionally, the concentration of the water soluble Se-cysteine was below the detection limit (4.6 g / L). These authors have concluded that the foliar applied selenite was first converted into selenoamino acids in rice grains, which are easily absorbed by humans and other animals. Also, Poblaciones et al. (2014), to increase the intake of selenium in the human population, used two foliar fertilizers (sodium selenate and selenite) and applied four doses (0,1,2 and 40 g ha^{-1}) in durum wheat. These authors found that 10 g of sodium selenate (applied as a foliar spray and at the end of tillering) was enough to increase selenium concentrations in the grain (close to recommended values for human food products) and also improved the proportion of Se-Met, a very bioavailable form of selenium humans. In rice plants grown in a Se-rich environment, Sun et al. (2010) further reported that Se concentrations in rice decreased according to the following order rice straw > bran > whole grain > polished rice > husk and that, within the grain, that nutrient mostly accumulated in the bran layer, with concentrations almost twice those of the polished grain. They also found that in the mature grain selenium was primarily present in organic forms, chiefly Se-methionine. This pattern of selenium speciation was also found by Li et al. (2008). Accordingly, all these studies indicate that Se-methionine is the major selenium species found in selenium enriched rice metabolized from inorganic selenium after foliar application. Therefore, selenium enriched rice can be used as a food supplement in addition to its use as a food staple in selenium deficient geographical areas (Fang et al., 2009).

About the reduction of selenium malnutrition using biofortified rice

Micronutrient malnutrition is widespread especially in the most vulnerable populations the globe, reducing productivity of adults and leading to premature death in severe cases, particularly among women and children. Dozens of nutrients are essential to meet the metabolic needs of humans, and deficiencies of various minerals and vitamins are often treated together as "hidden hunger", which is considered one of the most serious global challenges facing humanity (Hirschi, 2009; White and Broadley, 2009). From the 1960s and 1970s, there has been a shift: agriculture must now not only produce more calories to reduce hunger but also more nutrient-rich food to reduce hidden hunger. One in three people in the world suffer from hidden hunger, caused by a lack of minerals and vitamins in their diets, which leads to negative health consequences (Kennedy et al., 2003). Micronutrient deficiencies in humans exist in both developing and developed countries (Genc et al. 2005; Thompson, 2011).

Those who suffer from hunger due to insufficient energy intake are easily recognizable because it causes wasting and stunting, however, lack of nutrients, may not be visible, but may have serious health consequences (Stein, 2014). Serious health consequences have been reported in low selenium areas of China and Eastern Siberia, where selenium deficiency causes endemic Keshan disease in the Keshan region of China. This pathology is an endemic juvenile cardiomiopathy with myocardial insufficiency that primarily affects children aged 2 to 10 years old, and to some extent women of child-bearing age (Hartikainen, 2005).

The identification and propagation of agricultural methods that enhance the yield, and biological value, of micronutrient-rich foods was considered the one of the research priorities by FAO (2012), in order to facilitate the implementation of food-based approaches in the prevention of micronutrient deficiencies. Micronutrient-efficient genotypes could provide a number of benefits such as the reduction in the use of fertilizers, improvements in seedling vigor, and resistance to abiotic and biotic stresses (Teklić et al., 2013). Accordingly, in countries where rice is used as staple food, the per capita consumption of this “global grain” (Sharma et al., 2013) is very high, ranging between 62 - 190 kg year (Lu et al., 2008). In developing countries, a large percentage of the population has no access to meat in their diet; the daily food intake is mostly cereal-based and does not support the microelement and vitamin needs of the population, as well as the biochemical diversity of food needed for a healthy life (Mayer et al., 2008).

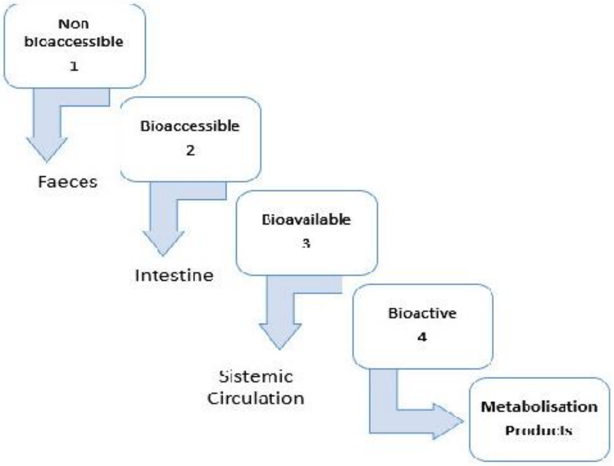

Figure 2. Destination ways of the ingested selenium (modified from Thiry et al., 2012).

In populations with low purchasing power, there is a shortage of food, which is often less than the daily needs, resulting in an inadequate supply of macro and micronutrients (Nubé and Voortman, 2006). The selenium might enter in the food chain through plant food materials, yet its availability directly depends on the content of this element in soils (Dhillon and Dhillon, 2003). Selenium deficiency, due to low intake of plant foods with substantial amounts of this element, affect various parts of the world, namely Australia, Africa, Eastern Europe, United Kingdom, and China (Chen et al., 2002; Lyons et al., 2004). This is mostly due to the low availability of this element in the soil (Smkolji et al, 2005; Pedrero et al., 2006). Because of the low levels of selenium in soils, in countries like Finland selenium is annually applied as fertilizer (Eurola, 2003). In this context, according to Chen et al. (2002), Hawkesford and Zhao (2007), Lyons et al. (2004) and Ramos et al. (2010), selenium content in rice, wheat and lettuce significantly increased with fertilization usage, which therefore favors selenium intake by human populations. Rice was found to be particularly interesting in this context, because it is a staple food in, at least, 33 countries and provides about 80% of daily caloric intake to 3 billion people (Lucca et al., 2006; Meng et al., 2005). Indeed, biofortification provides a viable mean of reaching malnourished rural populations, who may have limited access to various diets, supplements and fortified foods commercially middle. Varieties bred for a country also can be judged by the performance and adapted to other geographies, multiplying the benefits of the initial investment (Saltzman et al., 2013).

Is not expected that biofortification might address micronutrient deficiencies or eliminate them in all population groups, however, biofortification can complement existing micronutrient interventions to alleviate the most vulnerable people at relatively low cost (Nestel et al., 2006; Qaim et al., 2007; Meenakshi et al., 2010).

About biofortified rice flour: A healthy alternative to baby foods

During childhood breast milk is the main source of nutrients for newborns (Ikem et al., 2002). Although the World Health Organization recommends breastfeeding, as the best feeding option (WHO, 2009), infant formulas are an alternative and often play an important role in the infant's diet (Pandelova et al., 2012). Complementary, commercially prepared foods have become an important part of the diet of many infants and children (Davies and O'Hare, 2004; Melo et al., 2008), and that includes sufficient amounts of vitamins and minerals to meet the requirements of specific group targets. The supplementary feeding for children refers to timely introduction of safe and nutritionally rich foods, besides breast feeding at about 6 months of age and usually provided from 6 to 23 months of age (WHO, 2002). Infant feeding from birth until the first years of life can influence the whole future life of an individual (Monte and Giugliani, 2004). Low intake or reduced bioavailability of minerals can lead to deficiencies, which cause a decrease in body functions (Schlenker and Williams, 2003). In childhood, the high rate of growth and development of organ systems requires a balanced diet rich in nutrients. Minerals are involved in many important functions in the human body, for example, enzymatic reactions, bone mineralization and protection of cells and lipids in biological membranes, among others.

Rice flour is present, in a greater or lesser extent, as an auxiliary ingredient, consists mainly of starch and small amounts of proteins, lipids, fiber and minerals, whose levels vary mainly depending on the type of processing (Champagne, 2004; Walter et al., 2008). Starch contributes greatly to the texture properties of many foods (Fitzgerald, 2004), and is widely used in food and industrial applications such as thickening agent, stabilizer, gelling agent, bulking agent, and water retention (Yeh, 2004). Because industrially produced foods are an important part of the diet of many infants and small children, it is very important that these foods contain sufficient quantities of minerals (Melo et al., 2008). The limited number of foods in the diet of children might correspond to low supply of selenium, which is available only in human milk and/or commercially infant formulas (Lockitch et al., 1989; Litov and Combs, 1991).

More practical, healthy and fast food, prepared according to the needs of babies, are fundamental requirements for revenge in the competitive market of baby food. According to Deobald (1972), despite the lower cost, rice flour lacks significant production volume by not showing competitive application in relation to wheat. However, its special characteristics should be further explored. For example, it contains low sodium levels and high proportion of easily digestible starches (Torres et al., 1999). It is not allergenic, and varieties present a wide range of amylose content (which allows selection according to the purpose). It is not toxic to patients with celiac disease (it can be used as substitute for wheat in developing gluten-free products), and the small size of starch granules with cooking results in extremely smooth texture and bland flavor (Polanco et al., 1995).

Besides the rheological and sensory properties that rice flour can provide, it is also necessary that the same offers security, since the codex standards establish safety criteria in the international food trade. As a consequence, raw materials intended for baby food production have to be chosen carefully. In this context, grains especially from rice, the staple food in many countries, is a major intake source of cadmium. For example, the rice was estimated to represent 36-50% of the total oral intake of cadmium for the Japanese population over 1998-2001 (Kikuchi et al., 2008). Cadmium is one of the most harmful and widespread pollutants in agricultural soils, and expresses a direct contact risk to both human and ecological receptors, due to its relatively high toxicity and plant readily uptake (Wu et al., 2007; Chen et al., 2007). Nevertheless, selenium is an essential element for humans and animals, being its biochemical roles widely studied. The positive effect of selenium on heavy metal stress was observed in different biological systems, namely relatively to cadmium and silver (Nehru and Bansal, 1997; Drasch et al., 2005). Indeed, the alleviating effects of selenium on heavy metal toxicity to plants by decreasing uptake of arsenic and mercury have been reported (Ebbs and Leonard, 2001; Nehru and Bansal, 1997). He et al. (2004) also studied the antagonistic effects of supplementation of selenium to the soil on vegetables and found that the content of lead and cadmium in the two vegetables have been markedly reduced, while the healthy content of some elements (such as magnesium and manganese) increased. In this context, being rice flour a promising ingredient, there is an increasing need to develop differentiated products that add value to the product. In this sense, the use of biofortified rice flour emerges as an alternative to the development of new products, namely healthier products for a specific niche market as is the case of infants.

Conclusion

Selenium biofortification of rice varieties can be used to increase the concentration of this mineral in food products and improve its supply to humans, namely children. Increasingly rice biofortification stands out, not only as a major food, but also as a food with nutritional quality, which can assist in maintaining health. However, for the development of new products to a niche specific market (namely baby food), processing technologies must attain the needs of quality control to ensure safety and avoid undesirable effects on human health.

Author contributions

All authors contributed to the writing of the paper. K. O. was involved in the overall planning and writing of the paper. F. C. L. was responsible for the supervision and I. M. P., M. P. M., C. S., J. P., J. C. R., A. E. L., I. P., P. S. C., F. H. R. and M. F. P. were mostly involved in revision.

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