A global survey of effects of genotype and environment on selenium concentration in lentils (Lens culinaris L.): Implications for nutritional fortification strategies

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Lentils (Lens culinaris L.) are an important protein and carbohydrate food, rich in essential dietary components and trace elements. Selenium (Se) is an essential micronutrient for human health. For adults, 55 μg of daily Se intake is recommended for better health and cancer prevention. Millions of people around the world have Se-deficient diets and biofortification may be an effective solution. The total Se concentration of lentils grown in six major lentil-producing countries were analysed to determine the potential for Se biofortification in these regions. The highest Se concentrations based on location means were found in lentils from Nepal (180 μg/kg) and southern Australia (148 μg/kg) while the lowest were those from Syria (22 μg/kg), Morocco (28 μg/kg), northwestern USA (26 μg/kg), and Turkey (47 μg/kg). Significant location effects within a country were observed for Nepal and Australia. All values were lower than previous published data for Saskatchewan grown lentils (425–672 μg/kg). Lentils originating from Australia, Nepal, or Canada could be considered good sources of Se, as consumption of 50 g would provide 13–61% of the recommended dietary allowance (RDA). Our findings indicate lentil may be appropriate as a target crop for Se biofortification and investigated as a food-based solution for populations with Se deficiencies.

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1. Introduction

The impact of Se on human health is an increasingly important topic of interest in global public health systems. Although first discovered by the Swedish chemist Berzelius in 1817, selenium’s biological importance remained unknown until 1957 when Schwarz and Foltz found necrotic liver degeneration occurred in rats with insufficient Se intake (Moghadaszadeh & Beggs, 2006). Se was later recognised as an essential component of mammalian enzymes, such as glutathione peroxidases (Flohe, Guenzler, & Schock, 1973). Since then, Se-containing compounds have been recognised as key components of enzymes, antioxidant compounds, and hormones (Rayman, 2002). Health benefits conferred through Se intake are associated with the prevention of cancer, cardiomyopathy, free radical induced diseases, and protection against HIV and heavy metal poisoning (Combs & Lu, 2001; Gailer, Madden, Burke, Denton, & Aposhian, 2000; Moghadaszadeh & Beggs, 2006; Rayman, 2002).

The recommended dietary allowance (RDA) of 55 μg of Se day−1 for adults is considered essential for healthy living (National Academy of Sciences, 2004). Daily intake of less than 55 μg can have serious health implications. For example, daily dietary intake of less than 25 μg of Se day−1 has resulted in juvenile cardiomyopathy (Keshan disease) in regions of China and arsenicosis in Bangladesh (Combs, 2001; Spallholz, Boylan, & Rhaman, 2004). Dietary intake of 55–200 μg of Se day−1 is recommended as safe and adequate to reduce the risk of bladder and prostate cancer (Combs & Lu, 2001; Rayman, 2002; Reid et al., 2008). Several clinical trials suggest high Se intake and Se supplementation may increase the risk of developing Type 2 diabetes (Bleys, Navas-Acien, & Guallar,
In contrast, a recent study has suggested that Se may be essential in reducing the risk of developing abnormal blood sugar metabolism (Akbaraly et al., 2010). Globally, an estimated 30 to 100 million people intake less Se than the daily requirements (Ellis & Salt, 2003; Spallholz et al., 2004), which is attributed to low concentrations of Se in commonly eaten foods.

In general, the micronutrient profile of lentils depends on the geographical location of production due to the influence of soil factors, temperature, photoperiod, and other growing season conditions (Thavarajah, Thavarajah, See, & Vandenberg, 2010). Soil Se concentration may have the most significant influence on Se concentration in lentil seed. Soils that are low in Se generally lead to production of grain crops with low Se concentrations. Soils in New Zealand, Australia, Denmark, Finland, central Siberia, north-east to south central China, Turkey, parts of India, Nepal, and Bangladesh are deficient in Se (Giray & Hincal, 2004; Lyons, Ortiz-Monasterio, Stangoulis, & Graham, 2005; Spallholz et al., 2008b; Spallholz et al., 2004). Soils of the Great Plains of the USA and Canada, the Enshi region in China, Ireland, Colombia, and Venezuela are naturally rich in Se (Combs, 2001).

Lentil (Lens culinaris L.) is a traditional minor pulse crop mostly grown in low rainfall dryland cropping systems in rotation with temperate cereals. Most lentil production occurs in Mediterranean winter conditions (Middle East, Mediterranean region, Australia), in the dry season of the north Indian sub-tropical savannah, and in temperate summer climates in North America. More than 85% of the annual global production occurs in four specific regions: the eastern half of the Indo-Gangetic plain of south Asia including India, Nepal, and Bangladesh (32%); the Dark Brown and Brown soil zone of western Canada (29%); the greater Euphrates river valley region of south-eastern Anatolia in Turkey and northern Syria (18%); and the southeastern area of Australia, comprised of western Victoria and eastern southern Australia (4%) (FAO/STAT, 2008). Over the past 25 years, production of lentils for export has shifted in response to increased global demand and to changes in cropping patterns related to agricultural policies. Recent studies indicate lentils grown in Canada are naturally high in Se concentration (Thavarajah, Ruszkowski, & Vandenberg 2008). Since Canada is one of the major global exporters of lentils (along with Turkey, Syria and Australia), high-Se lentils are available to many people in countries with relative low Se intakes.

By knowing the baseline of Se concentrations of Canadian-grown lentils and factors contributing to the changes in total Se in lentil seeds, this study was initiated to assess lentil supplies from key global production regions as sources of daily dietary Se. The specific objectives of this study were to (1) determine the total Se concentrations in lentil genotypes grown in six key lentil growing regions of the world, (2) determine the effect of genotype and environmental influence on Se uptake in these regions, and (3) assess the Se biofortification potential to develop Se-rich lentils in the context of providing a potential whole food solution for regions with Se-deficient populations.

2. Materials and methods

2.1. Materials

Standards and chemicals used for Se analysis were purchased from VWR International (Canada) and Alfa Aesar, A Johnson Matthey Company (Ward Hill, MA, USA). Lentil seed samples were obtained from lentil variety trials harvested at appropriate harvest times in Syria (Tel Hadya), Nepal (Rampur, Itahari, Nawalpur, Surket and Parawanipur), Morocco (Annaceur and Sidi El Aidi), northwestern USA (Pullman), Australia (Melton and Horsham), and Turkey (Diyarbakir and Sanliufa) in 2007–2009. Genotypes in each trial were advanced breeding lines and check cultivars well adapted to the geographical area of production (Table 1). Sub-samples of between 20 and 25 g of dry lentil seeds (14% moisture) from each plot in each trial were shipped to the Crop Development Centre, University of Saskatchewan, and stored at −20°C until further analysis.

2.2. Se concentration

Each sample of lentil seeds was finely ground prior to HNO₃–H₂O₂ digestion as described previously (Thavarajah, Vandenberg, George, & Pickering, 2007). Measurements of Se concentrations in lentil seeds and digestion method were validated using NIST standard reference material 1573a (tomato leaves; [Se] = 0.054 ± 0.003 mg kg⁻¹). Astragalus bisulcatus leaves ([Se] = 45 mg kg⁻¹) and red lentil cultivar CDC Redberry ([Se] = 300 μg kg⁻¹) were used as internal laboratory reference material (LRM). Additionally, the digestion method was validated with randomly selected samples with pressure digestion with a HNO₃–H₂O₂ mixture, yielding identical results within the acceptable errors. Independent ICP-MS and HG-AAS analysis of the same biological samples (NIST standard reference and LRM) at two different laboratories in Canada and USA was used as external validation process. Se concentration in the lentil seeds was measured by AAS (AJ ANOVA 300) equipped with a flow–injection hydride generator (Lab Synergy, Goshen, NY, USA). The limit of detection of this method is 100 ng/kg.

2.3. Statistical analysis

Lentils from all regions had been grown in randomised complete block designs with 2–3 replicates per genotype (Table 1). Data for lentils grown in trials in Syria and Turkey were analysed separately for each year. Data for lentils from Nepal, Australia, and Morocco were analysed separately for each location. Data from five small trials at the same location in the USA were consolidated and analysed as a single trial using a randomised block design with three replicates of all 72 lentil genotypes. Analysis of variance was performed for all trials in each country using the General Linear Model procedure (PROC GLM) of SAS version 9.2 (SAS User’s Guide: Statistics, 2009). Means were separated by Fisher’s protected least significant difference (LSD) at p < 0.05.

3. Results

3.1. Se concentration in lentil seeds

Se concentrations in lentil seeds for six different lentil growing regions of the world ranged from 15 to 180 μg/kg (Table 2). The Se concentrations of lentils ranged as follows: Syria, 16–44 μg/kg; Morocco, 6–65 μg/kg; northwestern USA, 9–28 μg/kg; Turkey, 30–67 μg/kg; Nepal, 147–254 μg/kg; Australia, 110–174 μg/kg. The Se concentrations of lentils grown in Nepal and Australia were significantly greater (p < 0.05) than those of lentils produced in the other areas. Significant genotypic effects on Se concentration were evident in lentils grown in Syria, Turkey, Morocco, and the USA (Table 2). In 2008, lentils from line 35126–4 grown in Syria had significantly higher Se concentrations than line 35151–4 (24 vs. 16 μg/kg). In 2009, lentil line ILL7012 had significantly higher Se than lentil line ILL7978 (44 vs. 16 μg/kg). Different genotypes were grown in Turkey in each year; these years were analysed separately and no significant effect of year on Se concentration was found. However, lentil genotype Firat-87 had a significantly higher Se concentration compared to Altintoprak (65 vs. 35 μg/kg) in 2008; Seyran-96 had
a significantly higher concentration of Se compared to F2002–32L (67 vs. 30 μg/kg) in 2009. Variation in Se concentration in lentil seeds grown in Morocco and USA was similar to results observed in each country.

Se concentration of lentils grown in yield trials for six key lentil-producing countries, Table 2. A high Se concentration of 17 lentil genotypes grown at 5 locations in Nepal and 9 genotypes grown at 2 locations in Australia, 2007.

Table 3

Se concentration in lentils clearly varies significantly between countries. Canadian lentils provide the most Se/50 g serving (61% RDA), followed by lentils grown in parts of Nepal and Australia (13–16% RDA); those from the northwestern USA, Syria, Morocco, and Turkey provide only 2–4% of the RDA for Se.

4. Discussion

Se concentration in lentils varies significantly between and within different production regions. Although the soil Se concentrations at each location was not analysed, previous studies have shown soil Se significantly affects Se concentrations in other food crops (Lyons et al., 2005; Lyons, Stangoulis, & Graham, 2003; Broadley et al., 2006).
Spallholz et al., 2008a). The data indicated that the production regions bordering the Euphrates River (south-eastern Anatolia and northern Syria), Morocco, and the Pacific northwestern USA produce lentil seeds with low Se concentrations which are likely due to Se-deficient soils. Regions such as the Indo-Gangetic plain and southeastern Australia have regional variability, with 5- to 10-fold differences in lentil Se concentrations across regions, again most likely due to varying Se in the soils. Our previous studies show lentils produced in the Dark Brown and Brown soil zones of western Canada have relatively high Se concentrations, 425–672 µg/kg (Thavarajah et al., 2008). Regions such as the northern Great Plains states of the USA, which are adjacent to the southern Canadian prairies and share similar soils, are likely to produce lentils with similar Se concentrations.

Turkey produces 15% of the world lentil supply. However, Turkish soils are deficient in Se (Giray & Hincal, 2004) and thus Turkish lentils contain low concentrations of Se. Assuming no other dietary Se sources, a serving of 50 g of Turkish lentils would only provide 2–3 µg of Se day \(^{-1}\), much lower than the country-specific Se RDA values of 55–70 µg day \(^{-1}\) (Aras, Nazli, Zhang, & Chatt, 2001; Giray & Hincal, 2004). Low levels of Se intake cause significant health problems in Turkey including iodine-deficient goitres and oxidative DNA damage among children living in rural areas (Giray & Hincal, 2004). Thus, unless fortified with Se, Turkish lentils may not be a good source of Se for deficient populations. On the other hand, consumption of lentils produced in Canada (a 50 g serving providing 37–61% RDA) and specific regions of Australia and Nepal (13–16% RDA) will result in significantly higher Se intake. Canada, Australia, and Nepal produce 38% of the world’s lentils (FAOSTAT, 2008), and identity-preserved lentil production based on Se concentrations could have nutritional significance for delivering Se to target populations.

In regions producing lentils with low Se concentrations (northwestern USA, Turkey, Morocco, or Syria), increasing Se concentration may be possible via agronomic fortification using Se fertilizers. Although genotypic differences were noted in these countries, the potential for genetic biofortification is limited by extremely low mean levels of Se uptake. A significant location effect was observed in Nepal and Australia, the two production countries where lentils could on average provide more than 10% of RDA values. Therefore, selection of production regions known to have Se-rich soils or application of Se fertilizer to Se-deficient soils would be required to produce lentils with elevated Se in these countries. Increasing Se concentration through a combination of genetic improvement and soil amendments may be possible. Significant location effects were also evident in Canadian-grown lentils (Thavarajah et al., 2008), although the concentrations in all growing regions were generally higher than those reported for any other key production regions considered here.

Selenium is essential to human health for disease prevention and as a component of some 25 human enzymes. While 55 µg of daily Se intake is recommended for adults in North America and Asia (65 µg day \(^{-1}\) in Europe), millions of people do not achieve these levels. Efforts to increase Se supply through commonly eaten foods may be the most effective solution to provide the RDA to populations deficient in this micronutrient. Therefore, it is necessary to consider other food sources rich in this essential element to combat Se deficiency around the world. Total Se concentration in major food classes occur within the following ranges: 100–600 µg/kg (fish); 50–300 µg/kg (red meat); 2–8 µg/kg (fruits and vegetables); 75–98 µg/kg (rice, regular cooked); 270–300 µg/kg (bread); 225–342 µg/kg (eggs) (Lyons et al., 2003; USDA, 2010). Overall, intake of diversified diets with range of food richer in Se would be an important solution for Se-deficient population.

Despite the fact that legumes provide nutritional benefits through amino acid complementation of proteins when consumed with cereal grains, and contribute environmental benefits through nitrogen fixation, per capital global production of pulses is declining (Vandenberg, 2009). Among the sixty or so pulse crops consumed by humans, lentil may be unique in that consumption is increasing three to four times faster than human population growth, likely due to the convenience factors of reduced preparation time and savings of cooking fuel costs associated with their quick-cooking characteristics. This makes lentil an ideal candidate crop to promote improved nutrition through whole food consumption on a global scale.

This is the first comprehensive study reporting Se concentration in lentils on a global scale using a large and diverse number of genetic materials and samples from all major lentil-producing countries. The results build on our previous work demonstrating soil Se level at the origin of production is the critical factor to enrich Se levels in lentils. Moreover, the results have implications for international efforts to promote lentil consumption on the basis of Se concentration. This could be especially beneficial for high consumption regions such as Bangladesh, where improving Se intake could have significant nutritional benefits. All lentil producing regions should further investigate the regional distribution of Se concentration in their lentil production, especially India and Bangladesh which represent large proportions of the world’s lentil production and may have the most to gain from a nutritional improvement perspective. At present, identity preservation of Canadian, Nepalese, and Australian lentils could enhance the ability to deliver Se-rich lentils to importing countries with diets containing inadequate Se. Lentil could be used as a model crop with which to develop a biofortification strategy for providing food-based solutions to Se deficiencies. On a global scale, the potential nutritional and environmental benefits of increased lentil consumption are significant.

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