Concentrations and Soil-To-Plant Transfer Factor of Selenium in Soil and Plant Species from an Arid Area

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Abstract. The concentration of selenium in 97 plants related to seven different species and the associated soil samples was considered in an arid area in the central part of Iran. The mean of Se in the soil samples varied from 0.17 to 0.43 mgkg⁻¹ which is within the worldwide range. There was a highly significant correlation (r=0.688, p<0.01) between selenium concentration in the two soil depths (e.g. 0-5 cm and 5-25 cm) indicating that the selenium in deeper parts of the soil (5-25 cm) has most probably originated from the surface part (0-5 cm). The highest accumulation of Se was recorded in the chives with the average value of 0.35 mgkg⁻¹. Except for apricot, the concentrations of selenium in top parts of the plants (e.g. leaf, grain, fruit) were higher than stem/stalk implying the facile translocation of this element in the considered plant species. The higher than one bio concentration factors (BCFs) of selenium for the chives, spindle tree and wheat is indicative of high phytoremediation potential for these plants.

1. Introduction
Selenium is an essential element however it is harmful in higher than normal levels, so the bioaccumulation of this element has received attention in recent years [1]. There are four oxidation states for selenium in the environment including selenide (-2), elemental selenium (0), thioselenate (+2), selenite (+4), and selenate (+6) [2]. In aerobic and neutral to alkaline environments, selenate is the dominant species whereas in anaerobic environments selenide and elemental selenium are the prevalent forms [3]. All in all, organic forms of Se are more plant available than inorganic forms. However, among different forms, selenate is more easily translocated in plant species thus it is more likely to be transported to above-ground parts than selenite or organic forms [4]. Due to the low values of selenium in atmospheric deposition, the soil is the main contributing factor for the concentrations of Se in plant species [5]. Thus, the bioavailability of Se in soil is the main contributing factor to the accumulation of selenium in plants. In some earlier studies, a linear correlation has been found between the selenium in plant tissues and the contents in soils. For instance, Van Dorst and Peterson [6] reported a close positive correlation between the Se content of plants and the selenite ion concentration in the soil solution. In addition, because of the easier translocation of selenate, the accumulation of this species in plant leaves is much higher than that of selenite and organic form of selenium [3]. Regarding the accumulation capabilities of different plants, garlic and other Allium
species are known to have a great potential for bioaccumulation of selenium [5, 7]. In this field, the values of Se in garlic grown on seleniferous soils was as high as 7 mgkg\(^{-1}\) [7]. As a result of the previously described researches, the main objectives of this study were (i) to consider the accumulation of selenium in the plant and the associated soil groups in an arid area (ii) to study the soil-to-plant transfer factor of selenium in the plant species (iii) to investigate the possible impacts of agricultural practices (fertilizer application and tillage in this case) on the fate of selenium in the soil.

2. Materials and Methods

Plants species (including white mulberry, apricot, spindle, pistachio, wheat, barley, chives) were collected from 97 different locations in the study area. The associated soil samples from the surface part of the soil (0-5 cm) were also taken at the same locations that the plant species were collected. To study the possible impacts of tillage on Se levels, soil samples were taken at two soil depths (e.g. 0-5 cm and 5-20 cm) in thirteen sampling locations in the agricultural fields. In the laboratory, plant samples were thoroughly rinsed first with tap water and then with deionized water to remove dust and soil particles. For the case of soil samples, the collected soils were air-dried and sieved through a 2-mm stainless steel mesh to remove stones and plant roots. Following the digestion of soil samples with nitric acid (HNO\(_3\)) and hydrochloric acid (HCl) in a ratio of 3:1 (HNO\(_3\): HCl), the total heavy metal concentrations of Se were analysed by inductively coupled plasma (ICP) optical emission spectroscopy (ICP-OES). Dried plant samples were ground using a stainless steel grinder (<0.25 mm) and the total content of the Se and S were detected by ICP-OES. The detection limits of Se in the soil and plant samples were 0.1 and 0.05 mg/kg and that of S was 50 mg/kg for both plant and soil samples, respectively. The comparison between the levels of Se in different plant species and the associated soil samples was implemented by an analysis of variance (ANOVA) test. A paired sample t-test along with Spearman Correlation were applied to consider the possible impacts of tillage on the selenium values in the surface soils (e.g. 0-5 cm and 5-20 cm) in 13 agricultural soil samples in the study area. The Spearman correlation coefficient was performed between the concentrations of Se and S in the considered plant species. The normality of data was tested through Shapiro-Wilk test of normality and the data transformation was implemented for those data that did not fulfill the normality requirement. In addition, Mann-Whitney U test was applied to test the significance of variation between different plant's parts for each plant species.

3. Results and Discussions

The results of analysis of variance for different soil samples associated with each plant species have been illustrated in Figure 1. The soil groups are related to 1. white mulberry, 2. apricot, 3. chives, 4. spindle tree, 5. wheat, 6. barley, 7. pistachio. There were no significant differences between the soil groups in this regard. The mean values of Se in soil samples varied from 0.17 to 0.43 mgkg\(^{-1}\).

![Figure 1](image-url) Concentration of selenium in the soil groups associated with each plant species. Each soil group number is related to a plant species which are 1. white mulberry, 2. apricot, 3. chives, 4. spindle tree, 5. wheat, 6. barley, 7. pistachio, respectively.
The concentration of selenium in the worldwide soils fluctuates between 0.005 and 3.5 mg kg\(^{-1}\) with the average level of 0.33 mg kg\(^{-1}\) [8]. The values detected in this study are within the worldwide range. The study area is an arid region located in the central part of Iran. The amount of precipitation in the region had been below the long-term annual average of 152 mm [9]. The soil is mainly oxidizing with high salinity (e.g. because of high evaporation rate) and high pH levels which are common in arid and semi-arid regions [10]. In oxidizing environments selenate is the dominant form of selenium, while selenite is the favoured species in reducing environments [8]. In alkaline well-aerated soils of arid and semi-arid area, selenate (SeO\(_4^{2-}\)) is weakly sorbed to the soil particles resulting in its higher phytoavailability [8]. Moreover, among environmental factors, temperature is the most important factor influencing Se uptake by plants in which the rate of uptake is higher at >20°C than <15°C [4]. Therefore, it is expected that the rate of selenium accumulation be higher in these climate conditions than other environments.

In the study of Nazemi et al [11] the mean concentration of Se in the soils of north, south and central area of Iran were 0.156, 0.260, and 0.284 mg kg\(^{-1}\) in which the values of central part were significantly higher than that of other parts. The highest amount was recorded in the arid area of Yazd (having the same climate condition as that of the current study area) with the value of 0.45 mg kg\(^{-1}\) implying the higher levels of selenium in arid regions compared with that of wet climate regions. The mean values of Se in this study were lower than samples from United Kingdom (UK) (0.1 - 4 mg kg\(^{-1}\)) [12], Scandinavia (0.42-0.57 mg kg\(^{-1}\)) [13] and Mediterranean area of Spain (0.06-1.51 mg kg\(^{-1}\)) [14], but roughly in the same range as that of Belgian soils (0.14-0.70 mg kg\(^{-1}\)) [5]. There was a highly significant correlation coefficient (r = 0.688, p < 0.01) between selenium concentration in the two soil depths (e.g. 0-5 cm and 5-25 cm) indicating that selenium in the deeper parts of the soil (5-25 cm) has most probably originated from the surface part (0-5 cm). The main factor controlling the retention of Se in surface soil is organic matter [15]. Because of the fact that about 73 % of soil samples are located in agricultural fields so, it is most likely that the tillage has influenced the vertical movement of selenium in the surface soil through the vertical transfer of soil organic carbon between soil depths [16]. Eich-Greatorex et al [17] discussed the role of soil organic matter on the selenium availability in the surface soils for wheat, barley and oats. In this field, Johnson et al [18] proved that the organic content of soil is the main contributing factor influencing the availability of selenium in the soils of Keshan disease area in China. That is to say, the higher the organic content of the soil, the lower the bioavailability of the selenium will be and vice versa. Fernandez-Martinez and Charlet [19] also emphasized the role of soil organic carbon on the maintenance of selenium in surface soils of arid environments through avoiding precipitation of this species to deeper soil layers as well. The ANOVA test showed significant difference among various plant species (Figure 2). The mean concentration of selenium in the chives was 0.35 mg kg\(^{-1}\) significantly higher than that of the other plant species. In addition, there was also a significant difference between the levels of selenium in pistachio (mean=0.11) and apricot (mean=0.12) compared with that of the other plant types.

![Figure 2](image1.png)  
**Figure 2.** The variation of selenium in the different plant species

![Figure 3](image2.png)  
**Figure 3.** Concentrations of sulphur in the considered plant species
As there was no significant difference between the associated soil groups, this difference most likely emanated from the accumulation strategy of these plants. In this field, Di Gregorgio [20] presented a broad review of the Se metabolism in plants and concluded that regardless of the common traits of these processes, different plant capacities to extract and accumulate this element is evidently related to their different metabolic strategies. On the other hand, the average values of Se in different parts of plant species are shown in Table 1. According to this table, except for apricot, although the concentrations of selenium in top parts of the plants (e.g. leaf, grain, fruit) were higher than stem/stalk however, these differences were not significant based on the results of Mann-Whitney U test which may be because of the low number of samples and high variations (high standard deviations relative the average value) that preclude statistical significant difference among plant parts. In the previous studies, there have been higher selenium concentrations in the leaves of plants compared with other parts (e.g. root) (e.g. [5]).

Table 1. The variation among selenium in different parts of the plant species

| Plant species           | Number of Samples | Standard deviation | Plant tissue       |
|-------------------------|-------------------|--------------------|--------------------|
|                         |                   |                    | stem/stalk leaf    |
| Morus alba              | 13                | 0.18               | 0.19               |
| Prunus armeniaca        | 15                | 0.08               | 0.20               |
| Allium ampeloprasum     | 4                 | 0.12               | 0.40               |
| persicum                |                   |                    |                    |
| Euonymus europaeus      | 9                 | 0.09               | 0.25               |
| Triticum monococcum     | 21                | 0.13               | 0.19               |
| Hordeum vulgare         | 12                | 0.10               | 0.17               |
| Pistacia vera           | 19                | 0.06               | 0.11               |
|                         |                   |                    | fruit grain        |

There was nearly the same level of selenium in grains of wheat and barley in this study. As a whole, as stated by Kabata-Pendias and Mukherjee [8] through a literature review in various countries, mean value of selenium in arid regions is higher than similar samples from humid climates. The overall mean values of selenium found in the vegetables and fruits from Greece were 6.5 µgkg⁻¹ and 3.4 µgkg⁻¹, respectively [21], lower than that found in our study area while the levels in the vegetables and fruits from Saudi Arabia were 0.001 and 0.067 mgkg⁻¹ [22].

As the solubility of selenium in soils is low so, the levels in plant samples from the majority of agricultural area are low, accordingly [4]. The highest levels of selenium have been found in seleniferous soils and also in calcareous soils and soils of arid area [8]. The wheat samples collected from different parts of Iran contained selenium in the range of 0.34 to 1.44 mgkg⁻¹ with the average level of 0.74 mgkg⁻¹ [11], which is higher than that found in this research. In the study of De Temmerman et al [5], among field crops, the highest accumulation of Se was recorded in wheat although the values were half of that found in leafy vegetables which is in agreement with that found in the current study. On the other hand, among the nuts, pistachio (due to the higher levels of protein) was the richest sources of selenium [23]. The values of Se in pistachio fluctuated between 0.32 and 0.46 mgkg⁻¹ with the average value of 0.40 mgkg⁻¹ in the study of Nazemi et al [11]. With respect to different plant species, the highest value of Se was found in chives. Despite the fact that most of the fresh vegetables have low levels of selenium [24], garlic, chives and onions tend to have a greater fraction of sulphur containing amino acids and their derivatives, in addition to other sulphur compounds like glycosinolates or sulfoxides [25]. Substitution of sulphur with selenium will result in higher Se concentrations in these plants [26]. In agricultural fields of the study area, black and white fertilizers are used locally and include phosphate-rich and nitrate-rich types of compounds [27].
For instance, in Mojjen and Tash townships, the application rate of fertilizers have been over twofold and threefold of the government recommended values, respectively [27]. One of the possible consequences of phosphorus fertilizer application in agricultural soils is the substitution of phosphate with selenites attached to soil particles leading to increase of Se mobility and its phytoavailability in soils [8]. In this regard, phosphorus fertilizer has been known to increase selenium accumulation in wheat and barley in Japan although soil-to-plant transfer factor of Se is not affected by fertilizer application [1]. Other than P-fertilizer application, the ligand-exchangeable Se desorption from the soil as a result of P input is another mechanism that contributes to the accumulation of Se in plants [1].

On the contrary, there is a high similarity between chemical properties of selenium and sulphur, so the uptake and absorption of these elements from soil is possibly the same as well [28]. Sulphate transporter in the root plasma membrane is responsible for the uptake of selenate and sulphur in plant species leading to the competition between these two elements for absorption by plant's root system [3]. There is no significant correlation between the plant's levels of S and Se in this research. No correlation coefficient was also found between selenium and sulphur values in grain samples collected from UK in the study conducted by Adams et al [29] which is consistent with the results found in the current study. Although there have been some antagonistic effects between these elements in some earlier studies (e.g. [30]), similar trend for selenium and sulphur in different plant species was observed (Figure 2 and Figure 3) in the current study.

Moreover, no statistically significant correlation was found between the soil and plant contents of selenium. In this respect, the influence of S from fertilizers, which compete with Se for uptake to plants along with atmospheric deposition, may obscure the relationships between soil and plant levels of selenium.

Öborn et al. [31] did not find any correlation between the selenium levels of soil with that of wheat which is in agreement with the findings of this study. Plant ability to take up chemical elements from growth media is evaluated by a ratio of element concentration in plants to element concentration in soils and is called bioconcentration factor (BCF) or transfer factor (TF) [4]. Plants with BCF lower than one are not suitable for phytoextraction [32]. The soil-to-plant transfer factors for selenium in the considered plant species have been given in Figure 4. The highest values of bioconcentration factors have been recorded for chives followed by spindle tree and wheat which are all higher than 1. On the contrary, the lowest level was established for pistachio which was equal to 0.17.

![Figure 4. Bioconcentration factor of selenium in the different plant species](image)

TF values in soils containing native Se (uncontaminated soils) are generally below 1, [33]. On the other hand, the transfer factor of selenium ranged from 0.032 to 0.046 for barley, and 0.050 to 0.054 for wheat in the study conducted by Altansuvud et al [1] which are lower than the findings of this study. There was low level of transfer factors (TF) for Se (varying from <0.001 to 0.146) in the study of Száková et al [34] as well.
4. Conclusions
Selenium biofortification (e.g. mineral fertilization or plant breeding) is usually implemented in some countries to increase selenium concentrations in edible crops. Plants with high capability for selenium accumulation can be used as mineral supplements in the area with deficiency of selenium. In this study, three plant species including chives followed by spindle tree and wheat were proved to be hyperaccumulators of selenium. The oxidizing environment of the soil, high temperature of arid environment and application of phosphorus fertilizers in agricultural fields are some of the possible contributing factors for the high accumulation of selenium in the plant species.

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