

Relationship between the Absorption Behavior of Iron and Silicon by Plant and the Macronutrients Affected by Some Sandy Soil Additives

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

Original Research Article

ABSTRACT

Aims: A field experiment was carried out to study the relationship between the plant content of iron (Fe) and/or silicon (Si) and the macronutrients under the sandy soil conditions in presence of soil additives different in their effect on the nutrient availability.

Place and Duration of Study: A field experiment for two successive seasons (Sesame in summer season 2015 and wheat in winter season 2016) in sandy soil of the Ismailia Agricultural Research Station - Egypt.

Methodology: Separate single rates of 1190.48 kg/ha for rice straw, cellulose, silica were mixed with the soil surface before cultivation and then covered with a thin layer of soil. Sesame seeds and/or wheat grains were hand sown and planted as recommended. At harvest, the seeds and grains were analyzed for N, P, K, Si and Fe, as well as the soil available N, P, K after harvesting each crop.

Study Design: Single levels of rice straw, cellulose, silica, and K-humate were applied in a completely randomized design.

Results: Treatments decreased the Fe content in seeds in the order Control > silica > rice straw > K-humate > cellulose. The content of Fe in grains was enhanced by treatments compared to the control in the direction: K-humate > silica > rice straw > cellulose > control.

Si content in sesame seeds was inhibited affected by the treatments compared to the control in the order: Control > rice straw > K-humate > silica > cellulose.

Conclusion: Positive correlation coefficient (r) exists between Fe and/or Si content and the total NPK in the sesame seeds but an irregular trend was observed for wheat grains. Also, positive correlation exists between Fe and Si percents in both sesame and wheat during the successive seasons with higher for wheat than sesame.

The correlation with the available NPK was positive (r) for the seeds' Fe content but negative for the Si content while an irregular trend was observed for wheat grains.

Keywords: Iron; nutrients' content; silicon; sandy soil; soil additives.

1. INTRODUCTION

Deficiencies in micronutrients of some crops produce deficient diets of a large proportion of the world's population especially for Fe and Zn,

which affects the human health. Little is known about the relation between Si and micronutrient (Fe, Zn and Mn) deficiencies in some types of plants [1].

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All plants grown in soil contain Si from 0.1% to 10% by weight of plants in their tissues. Silicon uptake by plants varies greatly between species and cultivars, i.e., gramineous vs leguminous plants, and plants are classified as high-, intermediate-, and non-Si-accumulators. Si concentration in plant tissues depends upon the characteristics of Si uptake and transport, variability between species and genotypes within a species. Plant roots take up Si in the form of un-dissociated H_4SiO_4 and Si uptake mechanisms differ between plant species. Transporters responsible for Si uptake by roots have been identified in different plant species such as rice, barley, maize, wheat, and cucumber [2, 3].

Silicon nutrition increased the accumulation of both organic acids and phenolic compounds in cucumber tissues which was exclusively related to Fe nutrition but without affecting the mobility and tissue distribution of Zn or Mn. The biological importance of Fe is a result of its reversible changes of oxidation state over a wide range of redox potentials. Iron (Fe) is a component of a number of enzymes involved in various biological processes, including respiration and photosynthesis [1].

Studies on the Fe hyper-accumulator plants such as *Imperata cylindrica* have been indicated that the metabolism in plants is much more complex than has been reported. Jarosite ($\text{KFe}_3(\text{OH})_6(\text{SO}_4)_2$) and ferrihydrite-ferritin, accumulate in the different tissues like roots and rhizomes while in the leaves most of the Fe^{3+} is stored in ferritin as the main Fe managing structure of the plant [1]. Ferritins are a class of ubiquitous Fe storage proteins, found in all living kingdoms and their presence is related to the beneficial effect of Fe on seed production. *Zea mays* treatment by Fe induced ferritin protein accumulation in the roots and leaves [4-6].

Cucumber, pumpkin, and soybean demonstrate Si-induced increase of the apoplastic Fe pool, with the enhanced expression of genes involved in biosynthesis of Fe-mobilizing compounds in roots of Fe-deficient cucumber. A probable mechanism might involve the chelation of Fe by Si-induced biosynthesis of chelating compounds [1]. For soybean, presence of Si in the Fe deficient nutrient solution, prevented the chlorophyll degradation, delayed the Fe chlorosis symptoms appearance, slowed down the growth decrease due to the Fe deficiency, and maintained the Fe content in leaves. In cucumber, Si addition delayed the decrease of

stem dry weight, stem length, node number, and Fe content in stems and roots, but no effect was observed in chlorosis symptoms alleviation in leaves. The effect of Si in plants grown under Fe deficiency was plant-specific and different responses were observed for soybean and cucumber [5].

Si mediates the heavy metal toxicity by the accumulation of As, Cr, Cd and Fe^{+2} in *Lycopersicon esculentum*, *Brassica chinensis*, *Avicennia marina*, and *O. sativa* respectively [6-9]. Addition of Si along with Fe^{+2} in the solution significantly ameliorated the toxicity of Fe^{+2} to root cells of rice plants [2, 3].

Silicon applications significantly increased Fe concentrations in Fe plaque of different genotypes. The oxygenation of plant roots by radial oxygen loss ROL and rhizosphere oxygenation by microbial activities convert Fe^{+2} to Fe^{+3} , leading to the formation of Fe-plaque around roots. Root radial oxygen loss (ROL) rates are considered as the key biotic factor controlling Fe plaque formation. The plaque mainly comprises of ferric hydroxides (63%), goethite (32%) and minor concentrations of siderite (5%), whose structure is characterized as amorphous or crystalline Fe (oxyhydr) oxides. Due to adsorption or co-precipitation mechanisms, Fe plaque can sequester metals, metalloids (e.g. As) and anions such as carbonate and silicate on rice roots [4].

Many factors influence the formation of Fe plaque such as ROL, genotype, pH, Eh and presence of microorganisms. Iron oxides are able to combine with silicate to form Fe silicate and deposit on root surfaces. Silicon application can significantly increase Fe plaque formation. Silicon acid limited the adsorption of As(III) and As(V) on ferrihydrite by occupying the absorption sites [4].

The oxidation of Fe^{2+} resulted in the co-precipitation of Si with Fe. Dissolved Si is adsorbed preferentially to poorly crystalline Fe rather than crystalline Fe, and a part of the poorly crystalline Fe is reducible in a flooded soil. When the soil Eh decreases to a sufficient level to permit Fe-reducing bacteria to be active, its associated Si becomes available to rice plants. The oxidation of Fe^{2+} following the drainage of floodwater may induce the co precipitation of Si in soil solution [10-12].

The growth and water status were reduced by K-deficient stress, but Si application significantly

alleviated these decreases and alleviated the plant hydraulic conductance. Si mediates K⁺ accumulation in xylem, which ultimately alleviates the plant-water status under the K-deficient condition [13]. Some properties of Fe particles could stimulate the soil bacterial community structure that facilitates C and N cycling in soil [12]. Magnetic processes may affect salt movement and solubility of nutrients [14].

The present study aims to evaluate the effect of adding rice straw, cellulose, silica, (extracted from rice straw [15]) and K-humate as soil additives on the nutrient availability and absorption behavior in sandy soil. It focuses on the relationship between the absorption of Fe and Si by sesame and wheat and the available and total macronutrients: N, P, and K.

2. MATERIALS AND METHODS

A field experiment for two successive seasons under sprinkler irrigation was carried out using sesame (*Sesamum indicum* L.) cv. Shandaul-3 (summer season 2015) and wheat (*Triticum*

sativa) cv. Sakha 93 (winter season 2016), respectively, under the conditions of sandy soil (Typic Torripsamment; Entisol [Arenosol AR] [16] of the Ismailia Agricultural Research Station, (30° 35' 30" N 32° 14' 50" E elevation 3 m, characterized by moderate climate during the whole year, affected by the Mediterranean Sea climate. Rainfall ~180-200 mm per annum) Agricultural Research Center (ARC) - Egypt. Some characteristics of the experiment soil were determined in the upper 30 cm layer according to Page [17] and shown in Table 1.

2.1. Planting

The present study includes five treatments where single applications at a rate of 1190.48 kg/ha for rice straw, cellulose, silica and 4.76 kg/ha for K-humate were applied plus control. Plots (3 × 3 m²) were prepared for cultivation. Treatments were applied in a completely randomized design with three replicates consisted of 15 plots. Sesame seeds and/or wheat grains were hand sown whereas the other agronomic practices were applied as recommended.

Table 1 Some characteristics of the experiment soil before cultivation

Character		
Particle size distribution (%)	Coarse sand	72.12
	Fine sand	14.32
	Silt	3.22
	Clay	10.34
Texture class		Sandy
CaCO ₃ (%)		0.36
Organic Matter (OM, %)		0.23
pH (1:2.5 soil : water suspension)		8.01
Saturation Percent (SP, g water : g soil)		25.00
Electrical Conductivity (EC, dS/m) (1:5 soil : water extract)		0.30
Available nutrients (mg/kg)	N	20.50
	P	2.01
	K	50.13

The applied materials were mixed with the soil surface before cultivation and then covered with a thin layer of soil. All treatments received a constant level of nitrogen (i.e. 95.2 kg N/ha for sesame, 238 kg N/ha for wheat, while 119 kg/ha of K₂SO₄ (48% K₂O) for both sesame and wheat was applied in two equal doses after sowing.

2.2. Analysis of Soil and Plant Samples

A half gram of the ground seeds was wet digested using acid mixture (1:1 H₂SO₄/HClO₄) [18]. After harvesting, soil available N, P and K were extracted by (1%) K₂SO₄, 0.5 N NaHCO₃ and 1 N NH₄OAc (pH 7.0), respectively. Total

percentage of N, P and K in digested plant samples and the available in the soil extracts were estimated by distillation using Kjeldahl apparatus, colorimetrically by UV-Vis. Spectrophotometer (JENWAY UV/Vis. Spectrophotometer 6405, UK) using SnCl₂ indicator and by flame photometer (EEL Flame Photometer, EVANS Electro Selenium, England), respectively [19, 20]. Total concentration of Fe and Si was measured for seeds by ICP Spectrometry (ICP-OES Ultima 2 JY Plasma, HORIBA, France).

2.3. Statistical Analysis

The one-way analysis of variance (ANOVA) was carried out using the Co-State software to determine the statistical significance of the treatments effects at a significance level of 0.05 [21]. Treatments means were compared using LSD test at 5% of probability. Correlation coefficient (r) was calculated to find possible relationship between the percent of Fe and Si in seeds and grains and total and available macronutrients.

3. RESULTS AND DISCUSSION

Four types of soil additives were used to study the relation between the Fe and/or Si absorption from sandy soil and the total and available macronutrients. Rice straw, cellulose, silica (extracted from rice straw [15]) and K-humate were used due to their different effects on

nutrients absorption. Sesame and wheat were grown for two successive seasons to follow the residual effect of additives on the Fe and Si absorption by plant.

3.1. Behavior of Soil Available NPK

Fig. 1 (a-c) shows the behavior of soil available NPK in presence of the different additives for the first season and their residual effect. For the 1st season, cellulose enhanced the available N while silica and K-humate enhanced the available P and K compared to the control. Their residual effect sharply decreased compared to the control and to their effect of the 1st application except for the residual effect of cellulose on the available K and P and silica and K-humate on the available P. Some crops like sesame increase the N availability in soil [1,2].

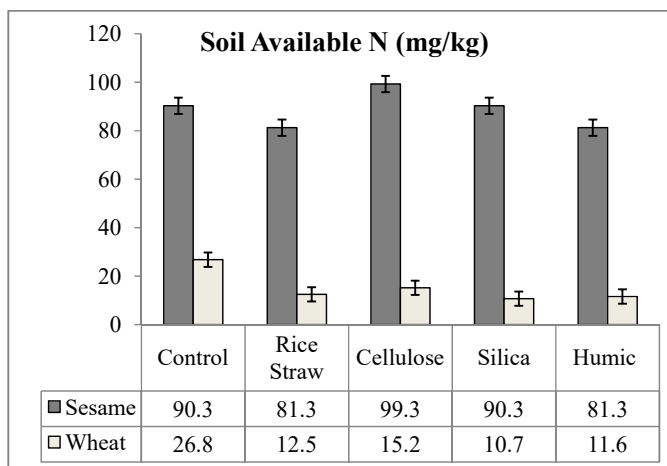


Fig. 1a Effect of the applied soil additives on the soil available N (mg/kg) after plant harvest in the two successive seasons

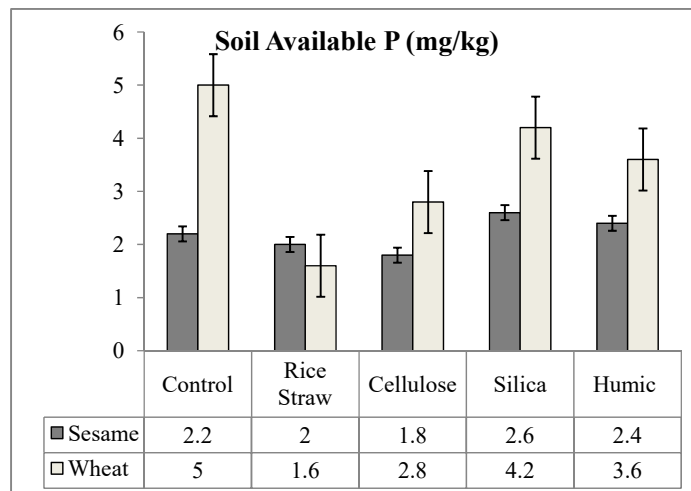


Fig. 1b Effect of the applied soil additives on the soil available P (mg/kg) after plant harvest in the two successive seasons

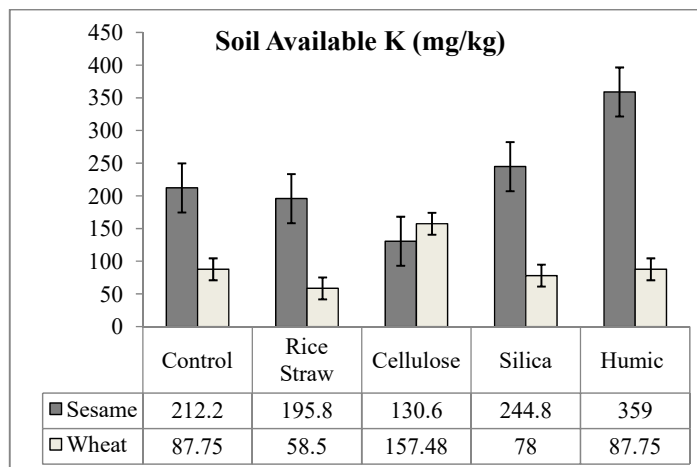


Fig. 1c Effect of the applied soil additives on the soil available K (mg/kg) after plant harvest in the two successive seasons

3.2. Macronutrients' content of Seeds and Grains

Fig. 2 (a-c) presents the total NPK content of the sesame seeds and the wheat grains for the different treatments. For sesame seeds, both of the rice straw and cellulose treatments have

increased the total N (g/kg) while silica has increased the total K compared to the control.

Cellulose and K-humate have increased the wheat grains' total N (g/kg). Again silica and K-humate have increased the total P (g/kg), which may be their residual effect on the available P

(g/kg) in the previous season. Rice straw and cellulose have increased the total K (g/kg) of the wheat grains compared to the control.

The residual effect of all treatments on the total NPK content was lower than their effect at the first application.

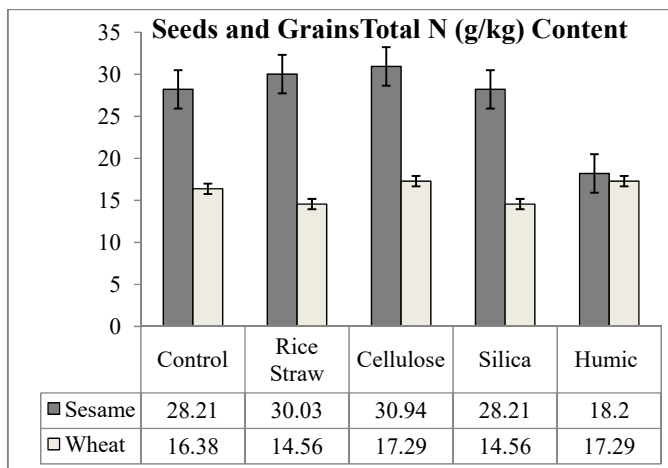


Fig. 2a Effect of the applied soil additives on the total N (mg/kg) content of both sesame seeds and wheat grains

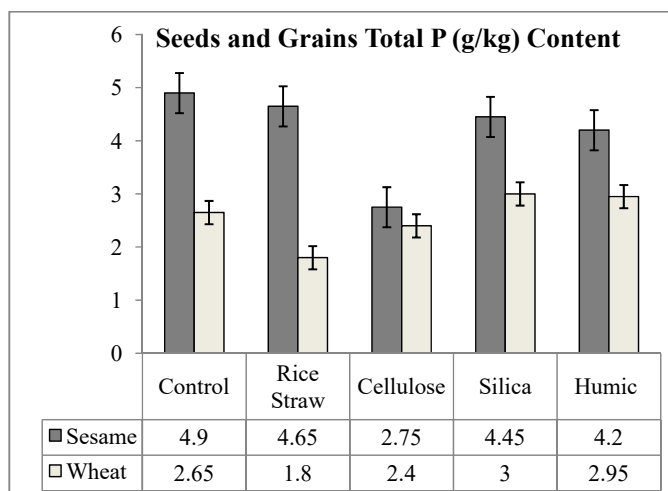


Fig. 2b Effect of the applied soil additives on the total P (mg/kg) content of both sesame seeds and wheat grains

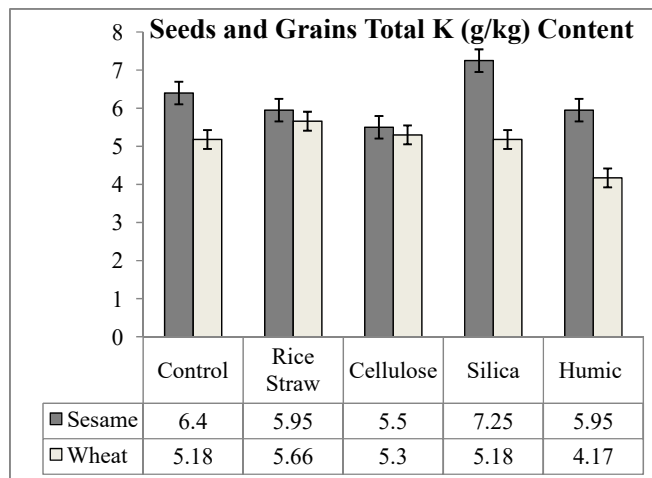


Fig. 2c Effect of the applied soil additives on the total K (mg/kg) content of both sesame seeds and wheat grains

3.3. Behavior of the Total Fe Content

According to Fig. 3, the different treatments decreased the content of Fe (g/kg) in sesame seeds in the order control > silica > rice straw > K-humate > cellulose.

In an opposite trend, the Fe (g/kg) content in the wheat grains was enhanced by the applied treatments compared to the control in the direction: K-humate > silica > rice straw > cellulose > control. Sensitivity of wheat to Fe indicates that it is a Fe accumulator.

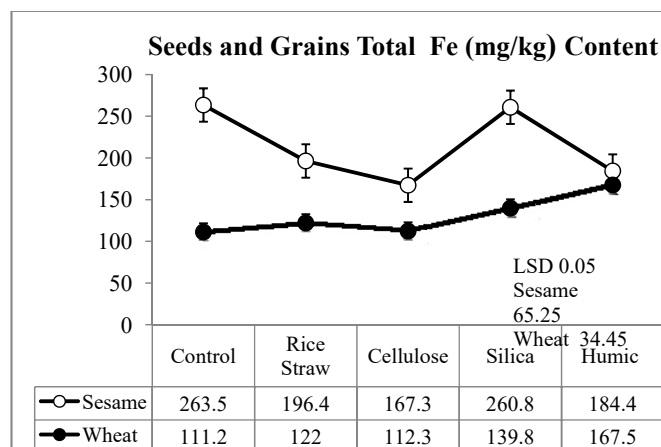


Fig. 3 Effect of the applied soil additives on the total Fe (mg/kg) content of both sesame seeds and wheat grains

3.4. Behavior of the Total Si Content

Fig. 4 indicates that the Si (g/kg) content in the sesame seeds is inhibited affected by all treatments compared to the control in the order:

Control > rice straw > K-humate > silica > cellulose.

For the wheat grains, the Si (g/kg) content was enhanced compared to the control in the order: K-humate > cellulose > rice straw > silica = control. The sensitivity and affinity of a crop differ from sesame to wheat and play a role in its Si content.

Additionally, the type of a soil additive used has its own effect. Silicon from K-humate is an organo form readily available and more compatible for plant nutrition. Cellulose and rice straw are fibrous materials and their fibers mixed with soil particles enhance Si

availability or keep Si if available from loss and/or restrict fixation. Solubilized Si may be adsorbed on their fibers or chemically bind to the hydroxyl

moieties of the rice straw and cellulose to be as Si-exchangers ($\text{Si} - \text{OH}^-$) or a donor of silicic acid moieties. The soluble form of Si as a weakly acidic orthosilicic acid monomer $[\text{Si}(\text{OH})_4]$ (or its ionized form, $\text{Si}(\text{OH})_3\text{O}_2^-$) allow its uptake by plants from the soil. Weak effects considering the low content of soil OM and degradation of such fibers by microorganisms may occur. Another suggested mechanism is the fibers dissolution under the effect of soil solution conditions (ionic composition and pH).

Although silica is a pure SiO_2 , it showed a poor effect on the absorbed Si by seeds or grains. Its Si moiety is either unavailable (insoluble or precipitated) since it is extracted at a pH range of 7-8 which is the same as that of soil. However, SiO_2 dissolution is possible under the conditions of soil solution [1-3].

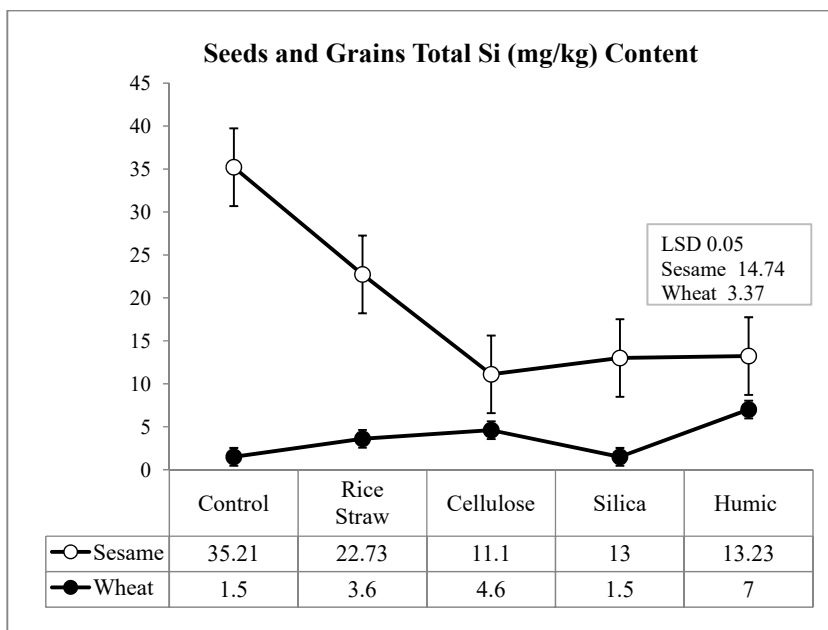


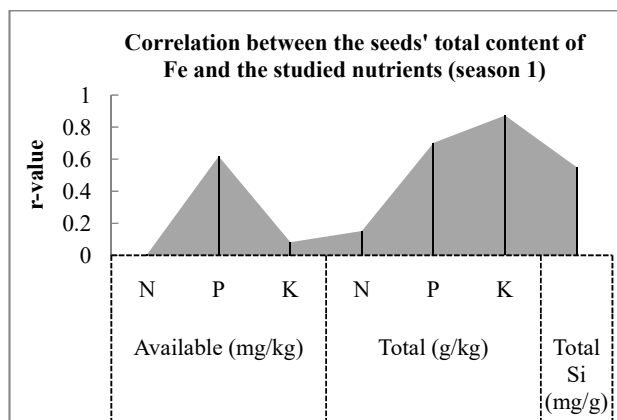
Fig. 4 Effect of the applied soil additives on the total Si (mg/kg) content in both sesame seeds and wheat grains

3.5. Correlation between the Content of Fe and/or Si and the Macronutrients in Seeds and Grains

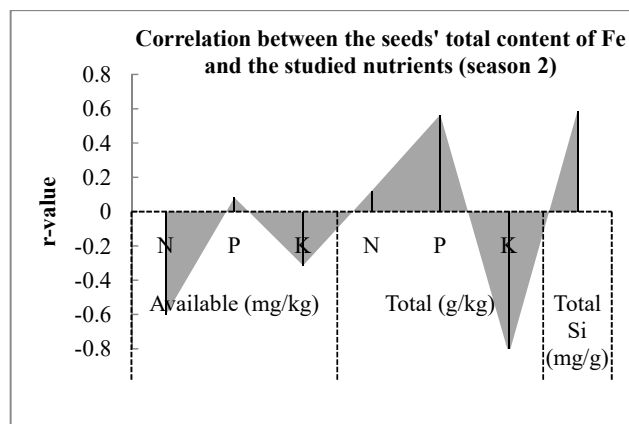
Fig. 5 (a, b) gives a view of the correlation between the Fe (g/kg) content and the different nutrients. Positive correlation coefficient (r) exists between the Fe (g/kg) content in the sesame seeds and both the available and the total NPK

but only with the available P (mg/kg) and total NP (g/kg) in the case of the wheat. Positive correlation coefficient (r) exists between Fe and Si contents (g/kg) in both crops in the successive seasons. It is higher for the wheat than the sesame [7, 10].

Fig. 6 (a, b) indicates negative r values between the total Si (g/kg) content with the available NPK and positive ones with the total NPK (g/kg) content in seeds. Positive values of correlation coefficient (r) are observed with the available K (mg/kg) and the total N and P (g/kg) with small values in the case of wheat [13].

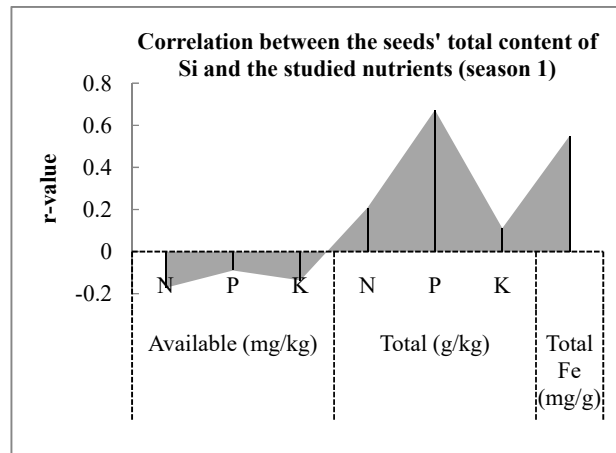


(a)

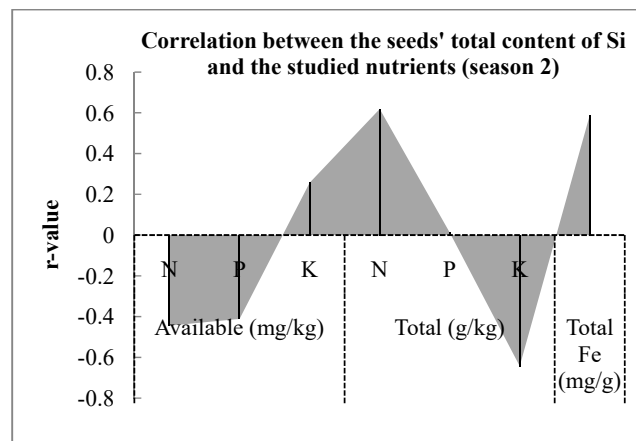


(b)

Fig. 5 Correlation between the seeds' and/or grains' total content of Fe and the studied nutrients during two successive seasons



(a)



(b)

Fig. 6 Correlation between the seeds' and/or grains' total content of Si and the studied nutrients during two successive seasons

4. CONCLUSION

The results indicate that the applied additives have affected the absorbed Fe and Si by sesame seeds and wheat grains and were related to the available and total macronutrients. Positive correlation coefficient (r) exists between Fe and/or Si content and the total NPK in the sesame seeds but an irregular trend was

observed for wheat grains. Also, positive correlation exists between Fe and Si percents in both sesame and wheat during the successive seasons with higher for wheat than sesame.

The correlation with the available NPK was positive (r) for the seeds' Fe content but negative for the Si content while an irregular trend was observed for wheat grains. So, it can be said that

although some availability problems related to Si and Fe as plant nutrients, additional factors are to be taken into account. Excess fertilization by NPK and excess availability in sandy soil may have adverse effect on the absorption of Fe and Si even if they were available. On the other hand, the suitable absorption of Fe and Si by plant is sometimes dependent on enough NPK fertilization. Their absorption was positively correlated with total NPK for sesame seeds and with total NP for wheat grains, but it was negatively correlated with total K.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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