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INFLUENCE OF INTEGRATED APPLICATION OF NANO-CHELATED TRACE ELEMENTS AND SULFUR ON DESI CHICKPEA IN THE SHORT-SEASON MEDITERRANEAN-TYPE ENVIRONMENT

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Abstract

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Chickpea is one of the most important legume crops in the Mediterranean semiarid regions. Soils of these regions generally have free $CaCO_3$, high pH and low organic matter, which reduce the availability of micronutrients and cause their deficiencies. In order to study the effects of integrated application of different level of elemental sulfur (0, 15, 30 $kg \cdot ha^{-1}$) and nano-chelated micronutrients (Zn, Fe, Mn) on growth and agro-morphological traits of chickpea (*Cicer arietinum* L.), a field experiment was conducted in the semiarid regions of the northwestern part of Iran. Evaluation of morphological traits showed that application of high level of sulfur significantly improved plant height, the number of primary branches and canopy width compared to the control. The longest growth period was recorded for plants grown by application of high level of sulfur and nano-chelated Zn fertilizer. The obtained data revealed that application of nano-chelated Zn fertilizer resulted in a significant increase in seed number per plant and seed weight compared to other nano-micronutrient fertilizers. Overall, the best growth performance and the highest seed yield were obtained from the integrated application of Zn and high level of sulfur. The findings showed that soil micronutrient deficiencies are partly due to high alkalinity of the soil, and application of sulfur beyond 15 $kg \cdot ha^{-1}$ can be an effective method to increase the efficacy of nanofertilizers. Integrated application of micronutrient and sulfur should be considered as an efficient agronomic management option for chickpea production systems in semiarid region.

Keywords: Desi-type chickpea, micronutrients, nanofertilizers, nanoparticles, semiarid region.

INTRODUCTION

Chickpea (*Cicer arietinum* L.), an ancient pulse crop of the Mediterranean Basin, was first cultivated at the Fertile Crescent, from Turkey to Iran, at the beginning of agriculture (Yadav et al., 2007). Chickpea is a vital part of the crop rotations in the west of Iran and is a major source of dietary protein. However, there are some different limiting factors, which decrease the chickpea yield in this area. So that at the end of the growing season, crop plants are encountered with high temperatures and soil moisture deficit, which is resulting in low and variable yields (Pasandi et al., 2014). Although water availability can be a major limiting factor in chickpea production, there are other factors such as micronutrient deficiency that can have a significant impact on chickpea yield and water use efficiency (Yadav et al., 2007). Although the micronutrients are needed in very small quantities for optimum plant growth, they are imperative to world agriculture and play a vital role in human health. The lack of trace elements or imbalance between different elements may result in growth suppression or even complete inhibition of crop production (Farooq et al., 2012). Despite the importance of this crop, few studies have analysed the application of new generation of micronutrient fertilizers to chickpea and agronomic managements for improving the availability of micronutrients.

Trace elements are imperative to world agriculture and play a vital role in human health. Between the micronutrients, the deficiencies of zinc (Zn), iron (Fe) and manganese (Mn) have become the most distinguished yield-limiting factors in the semiarid Mediterranean highland areas and are partly responsible for low food nutrition (Ryan, 2008). In relation to the importance of micronutrients, it is interesting to note that over two billion people across the world suffer from micronutrient deficiencies and hidden hunger (Tulchinsky, 2010). However, the availability of micronutrients greatly depends on soil pH and high pH ties up trace elements such as iron, manganese, zinc and others, leading to micronutrient deficiencies (Plaster, 2013). It seems that sulfur application can be suitable option for longer lasting pH reduction. So that following the application of sulfur, oxidizing bacteria, particularly *Thiobacillus* spp., would accelerate the oxidation process and convert sulfur to sulfuric acid, which leads to soil pH decline (Mohammady et al., 2010). The availability of trace elements will be affected by sulfuric acid. Therefore, sulfur is an essential element for plant development and it can affect the plant growth both directly and indirectly. Although it is classified as a secondary element, it has become more important as a limiting nutrient in crop production in recent years (Jez, 2008). Sulfur plays some critical rules in plants. So that it is used in the formation of amino acids, proteins and oils. Sulfur is necessary for chlorophyll formation, promotes nodulation in legumes, helps to develop and activate certain enzymes and vitamins, and is a structural component of amino acids such as cysteine and histidine (Marschner, 2011).

Although fertilizers have a fundamental role in improving the productivity across the spectrum of crops, the nutrient use efficiencies of conventional fertilizers is relatively low (Subramanian et al., 2015). Given the importance of chickpea in the Mediterranean-type environment**,** it seems that one way of improving the low productivity of chickpea can be the application of new generation of micronutrient fertilizers. Derosa et al. (2010) have suggested that nanofertilizers, nanoparticles-based fertilizers*,* are one potential output that could be a major innovation for agriculture; large surface area and small size of nanomaterials could allow enhanced interaction and efficient uptake of nutrients for crop fertilization. Furthermore, nanofertilizers could be more soluble or more reactive than bulk conventional fertilizers. Also this modern fertilizer can exactly release their active ingredients in responding to environmental triggers and biological requirements (Mastronardi et al., 2015). Subsequently, supply of plant nutrients as nano-sized active particles could be perhaps predicted to have a considerable effect on fertilizer efficiency and crop productivity. Although some researchers previously have studied the effect of concomitant application of sulfur and micronutrients in different cropping system (Islam, 2012; Sabbagh Tazeh et al., 2012; Lal et al., 2014), there is very little information about the interaction between the different levels of sulfur and micronutrients in nanoform.

However, in the last few years, some researchers have tried to examine the potential of nanobiotechnology to improve micronutrient use efficiency and strategies that result in the design and development of efficient new nanofertilizer delivery platforms for use at the farm level (Naderi & Danesh-Shahraki, 2013; Rameshaiah & Jpallavi, 2015). However, due to the relative infancy of the field of nano-micronutrient fertilizer inputs, it is particularly important to understand their fate and effects under variable condition of sulfur application. Therefore, this experiment was conducted to study the effect of integrated application of nano-micronutrient fertilizers (Zn, Fe, Mn) and sulfur on growth, seed yield and yield component of Desi type chickpea in the short-season Mediterranean-type environment.

MATERIALS AND METHODS

To evaluate the effect of different nano-chelated micronutrients and sulfur on chickpea growth, the field experiments were conducted using Desi type of chickpea (variety 'Kakaie') in Takab district (47°70' E; 36°23' N), the northwest of Iran. Takab is located at an altitude of 1765 metres above sea level and is a representative of semiarid mountainous region. The climate of the location is described as cold semiarid; an average annual rainfall is 340 mm, including 66% of rain and 34% of snow in winter and early spring. The mean annual temperature is 12.3°C. Rainfall is not generally well-distributed during the year and the occurrence of rainfall in late winter and early spring is frequent, with about 13 days per month on average. Rainfall from June to October is relatively rare, and the highest rate of evapotranspiration can be recordable. The precipitation is 120.5 mm during the cropping season. The relative humidity ranges between 33–63% during growing season. The previous crop on the plots was wheat (*Tiriticum aestivum* L.). The soil texture of the experimental site in 0–40 cm layer is sandy loam, pH 7.8, EC 0.78 dS/m, Total Neutralizing Value 11.88%, total nitrogen 0.044%, organic carbon 0.44%, available P 4.34 $mg\cdot kg^{-1}$, available K 227 $mg\cdot kg^{-1}$, available B 0.83 mg·kg-1, available Zn 1.04 $mg\cdot kg^{-1}$, available Fe 4.91 $mg\cdot kg^{-1}$, available Mn 10.6 $mg\cdot kg^{-1}$ and available Cu 1.74 $mg\cdot kg^{-1}$.

The experimental fields were ploughed once in early autumn and harrowed twice to bring the soil to fine tilth one week before planting. The recommended dose of fertilizer (30 kg N and 75 kg P_2O_5 ha^{-1}) was applied in the form of urea and triple superphosphate at the time of seed bed preparation. The trial was laid out in randomized complete block design with three replications in split plot arrangement (plot size 2 × 2 m^2) keeping sulfur in main plots and nano-chelated micronutrient in sub-plots.

Nano-chelated micronutrients, including nano-chelated zinc (N_1), nano-chelated iron (N_2), nano-chelated manganese (N_3) and sulfur of three levels (S_1: no application, S_2: 15 $kg\cdot ha^{-1}$, S_3: 30 $kg\cdot ha^{-1}$), were mixed with top soil. Elemental S was spread by hand on the surface of the soil before sowing the crop, and was incorporated into the top 10 cm of the soil using rotary hoe. Nano-chelated fertilizers were applied at a rate of 1 $kg\cdot ha^{-1}$ through fertigation 30 and 60 days after sowing date. Nano-chelated fertilizers were obtained from the Sepeher Parmis Company, Iran, which contained zinc oxide, ferric oxide and manganese (II) oxide nanoparticles. Synthesized nanoparticles were characterized morphologically using scanning electron microscope (Fig. 1).

Chickpea was sown manually in the third week of April. In each plot, seeds were sown into 10 rows, at 20 cm row-to-row spacing and 8 cm plant-to-plant spacing. Two seeds were sown per hill and after germination; the plants were thinned to one seedling per hill. There was no incidence of pest or disease on plants during the experiment. Weeds were controlled by frequent hand weeding. The field was immediately irrigated after planting to ensure uniform germination, and irrigation was applied four times during the growth period. Phenological growth phases were monitored at 1–2-day intervals throughout the season and in days of 50% flowering, the vegetative growth period and the day to maturity were recorded for each treatment. The plant canopy width was calculated by measuring the length and the breadth of canopy surface for each plant from which the mean canopy width assuming the shape of the canopy as rectangle was computed and expressed in centimetres. Chickpeas were harvested at ground level by hand from late June to early July, and some agronomic traits including branches $plant^{-1}$, plant height (cm), pods $plant^{-1}$, grains pod^{-1}, 100-grains weight (g), root number of the primary and secondary branches were recorded on 15 randomly selected plants in each plot. Grain and biological yield was determined by

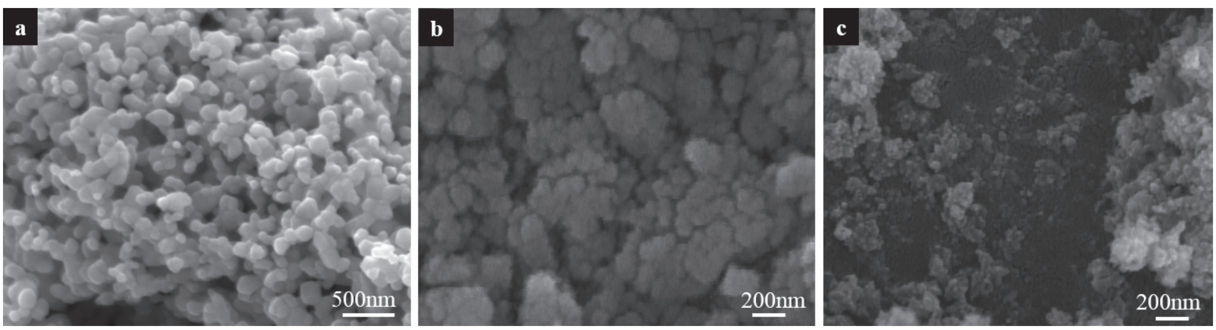

Fig. 1. Scanning Electron Microscope (SEM) image of synthesized nanoparticles of zinc oxide (a), ferric oxide (b) and manganese (II) oxide (c) and utilized for nano-chelated fertilizers

harvesting the middle three rows of each plot after avoiding border effects. The shoots were dried in hot air dryers at 45°C for three days, and biological yield was recorded. Harvest index (HI) of each plot was calculated according to the following formula: HI = (grain yield/biological yield) ×100. For root studying, the soil samples containing roots were soaked in water overnight in plastic buckets. The 100-seed weight, the number of seeds per plant and the total seed weight per plant were measured two weeks after harvesting and drying. At maturity, the crop per square metre in the middle of each plot was harvested separately. The plant samples were dried, and the data were recorded for seed yield. The data on all observations were subjected to the analysis of variance (ANOVA) by using software SAS. Treatment means were compared by the least significant difference (LSD) test.

RESULTS

The obtained results revealed that utilization of nano-chelated micronutrient affected considerably some agro-morphological traits, while the effect of sulfur (S) on the evaluated traits was more prominent (Tables 1, 2). Plant height was affected significantly by both sulfur and micronutrient applications, so that the tallest plant was recorded under application of 30 kg S·ha^{-1} along with Zn nano-chelated fertilizer and the shortest plant was recorded under no application of sulfur. Treatments could not affect the height of the first pod (Table 1). The number of primary branches was affected significantly by sulfur application, so that utilization of 30 kg S·ha^{-1} leads to a 25% increase in the number of primary branches. However, application of 15 kg·ha^{-1} had no significant effect on this trait. Analysis of variance showed that both factors affected considerably the number of secondary branches, and the interaction of sulfur and micronutrient had significant effect ($p < 0.05$) on this trait. The comparison of means revealed that the highest number of secondary branches was obtained by application of 30 kg·ha^{-1} sulfur and Zn nano-chelated fertilizer, while the lowest number was recorded under control conditions (no application of sulfur) by utilization of Mn nano-chelated fertilizer (Fig. 2). Canopy width was affected significantly by both sulfur ($p < 0.05$) and micronutrient application ($p < 0.01$). The comparison of means between the different sulfur application levels showed that application of 30 kg·ha^{-1} increased the canopy width up to 11% over control condition. On the other hand, the largest canopy width was recorded for chickpea plants

Table 1. Effect of sulfur and nano-chelated micronutrient fertilizers on some agro-morphological traits of chickpea

Sulfur (S)	PH	FPH	PBP	SBP	CW	VGP	DF	DM
0	30.23	11.59	3.37	12.00	30.44	53.36	62.22	108.33
15	32.92	12.16	3.89	13.92	31.77	58.26	63	112.88
30	39.69	12.47	4.23	15.45	33.94	57.25	65.22	114.33
Nano-chelated micronutrient (N)								
Zn	37.17	12.45	3.99	15.23	34.44	56.67	64.17	113.44
Fe	33.88	11.56	3.70	13.34	31.72	56.10	63.55	111.77
Mn	31.88	12.11	3.79	12.80	30.00	56.04	62.11	110.33
LSD	3.71	2.04	0.87	1.60	2.11	4.07	1.54	2.42
Significance Level								
R	*	*	NS	NS	NS	NS	NS	NS
S	**	NS	**	**	*	**	**	**
N	**	NS	NS	**	**	NS	**	**
S×N	*	NS	NS	*	NS	**	NS	*
CV%	6.26	9.79	13.15	6.73	7.91	3.96	1.41	1.25

PH = plant height (cm), FPH = first pod height (cm), PBP = primary branch per plant, SBP = secondary branch per plant, CW = canopy width (cm), VGP = vegetative growth period (day), DF = days to flowering, DM = days to maturity. If the difference between two treatment means is greater than the LSD, then those treatment means are significantly different at the 95% level of confidence. *: statistically significant with 95% confidence level and **: statistically significant with 99% confidence level, respectively.

Table 2. Influence of sulfur fertilizer and nano-micronutrients on yield components of chickpea

Sulfur (S)	NPP	EPP	NSP	HSW	SY	BY	STY	HI
0	21.62	3.28	22.91	15.26	1198.33	3850.02	2651.69	31.16
15	23.63	3.09	23.75	15.88	1220.00	4024.43	2804.43	30.33
30	23.86	2.86	23.80	16.63	1254.16	4192.07	2937.90	29.87
Nano-chelated micronutrient (N)								
Zn	23.19	2.88	23.59	16.38	1260.00	4185.65	2925.65	30.09
Fe	23.63	3.43	23.52	15.62	1217.50	3960.68	2743.17	30.77
Mn	22.30	2.92	23.30	15.77	1195.00	3920.20	2725.20	30.50
LSD	2.02	0.39	0.71	0.67	50.42	217.37	202.2	1.66
Significance Level								
R	NS	NS	NS	NS	NS	NS	NS	NS
S	*	NS	*	**	*	**	**	NS
N	NS	**	NS	**	*	**	**	NS
S×N	NS	*	NS	*	*	NS	NS	NS
CV%	8.59	4.67	6.19	2.43	5.21	3.12	4.18	5.06

NPP = number of pods per plant, EPP = number of empty pod per plant, NSP = number of seeds per plant, HSW = 100-seed weight (g), SY = Seed yield ($kg \cdot ha^{-1}$), BY = biological yield ($kg \cdot ha^{-1}$), STY = straw yield ($kg \cdot ha^{-1}$), HI = harvest index, *: statistically significant with 95% confidence level and **: statistically significant with 99% confidence level, respectively.

grown by applying Zn nano-chelated fertilizer (Table 1). Assessment of phenological traits showed that the application of sulfur fertilizer affected noticeably both vegetative and floral development. Sulfur application increased the vegetative growth period and partially delayed the beginning of flowering stage, compared to control treatment. Also application of Zn nano-chelated fertilizer delayed significantly the flowering stage compared to other micronutrients (Table 1). The interaction effect of sulfur and micronutrients was statistically significant ($p < 0.05$) for days to maturity, and the maximum number of the days to maturity was recorded for plant grown with 30 $kg\ S \cdot ha^{-1}$ and Zn nano-chelated fertilizer, which followed by 15 $kg\ S \cdot ha^{-1}$ along with Zn and with 30 $kg\ S \cdot ha^{-1}$ along with Fe (Fig. 3). However, the earliest maturity was observed for plants grown with Mn and Fe nano-chelated fertilizer under no application of sulfur.

Evaluation of seed yield components showed that all traits, except for the number of empty pod per plant, were affected by sulfur application (Table 2), by contrast, the nano-chelated micronutrients only influenced the number of empty pod and seed weight. Comparison of the means of pod number between different sulfur levels showed that application of 15 $kg \cdot ha^{-1}$ increased this yield component up to 9% over the control. However, no difference was ob-

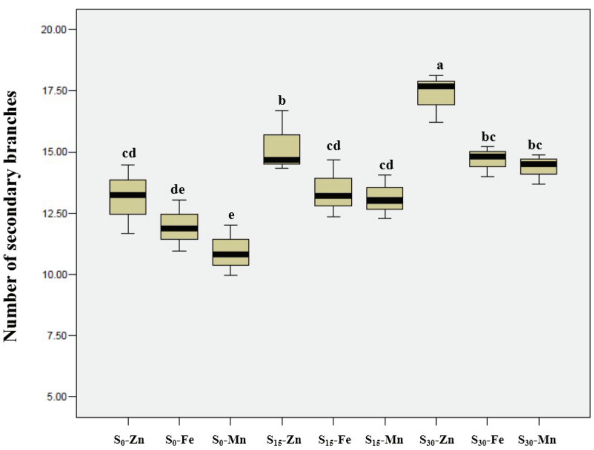

Fig. 2. Number of secondary branches affected by application of sulfur and nano-chelated micronutrients

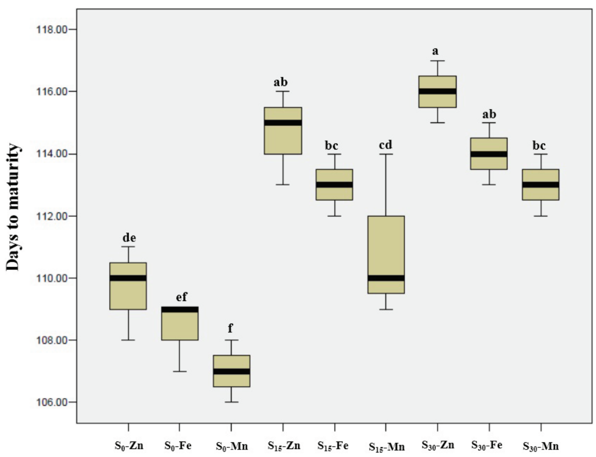

Fig. 3. Influence of sulfur and nano-chelated micronutrients on the number of days to maturity in chickpea

served between 15 and 30 kg S·ha^{-1}. A similar trend was also observed for the number of seeds per plant (Table 2). The interaction effect of sulfur and micronutrient was significant for the number of empty pod per plant. Comparison of the averages of this trait between combined treatments showed that the lowest number of empty pod was obtained by application of 30 kg S·ha^{-1} along with Zn nano-chelated fertilizer, while the highest number of empty pods was recorded for plants grown with Fe nano-chelated fertilizer. Overall, application of 30 kg S·ha^{-1} decreased the number of empty pods up to 13% over control (Fig. 4). The seed weight was most responsive component to the treatment. Assessments of 100-seed weight between combined treatments showed that the heaviest seeds were obtained by application of 30 kg S·ha^{-1} along with Zn nano-chelated fertilizer. However, the lightest seeds were related to plants grown under no-sulfur applied condition (Fig. 5). Also the highest seed yield was obtained by application of 30 kg·ha^{-1} sulfur along with Zn nano-chelated fertilizer (Fig. 6). The interesting thing is that under high sulfur consumption condition (30 kg·ha^{-1}), the difference between micronutrients was more prominent and the best performance was related to Zn nano-chelated fertilizer. Evaluation of biological yield and straw yield revealed that sulfur application improves significantly these traits, however, there was no significant difference between 15 and 30 kg·ha^{-1}. The effect of micronutrient also was significant on these traits and the highest value was recorded for plants grown with Zn nano-chelated fertilizer (Table 2).

In the current study, the principal component analysis (PCA) described a considerable amount of the total variation. The correlation coefficient between any two traits is approximated by the cosine of the angle between their vectors. In Fig. 7, the most prominent relations are: a strong positive association between seed yield, first pod height, days to 50% flowering, 100-seed weight, biological yield, the number of seeds per plant, as indicated by the small obtuse angles between their vectors (r = cos 0 = +1). Also a positive correlation was observed between straw yield, plant height, the number of branches (primary and secondary), canopy width, and day to maturity. There was a negative correlation between the number of the empty pod per plant and seed yield, also between the vegetative growth

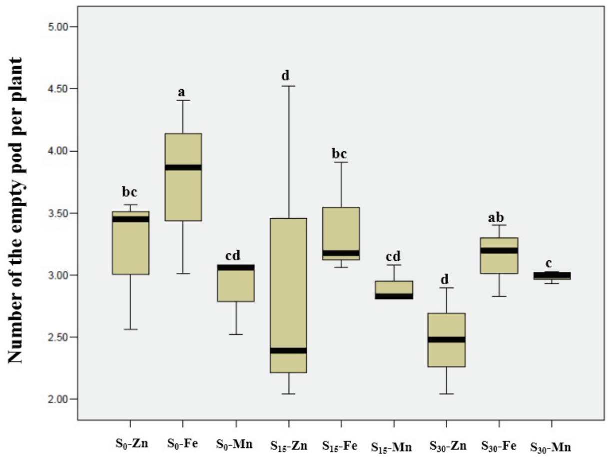

Fig. 4. Influence of integrated application of sulfur and nano-chelated micronutrients on the number of empty pod per plant in chickpea

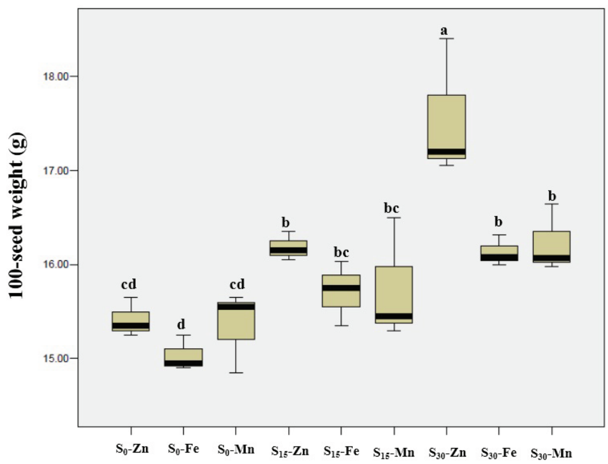

Fig. 5. Effect of sulfur and nano-chelated micronutrients on 100-seed weight

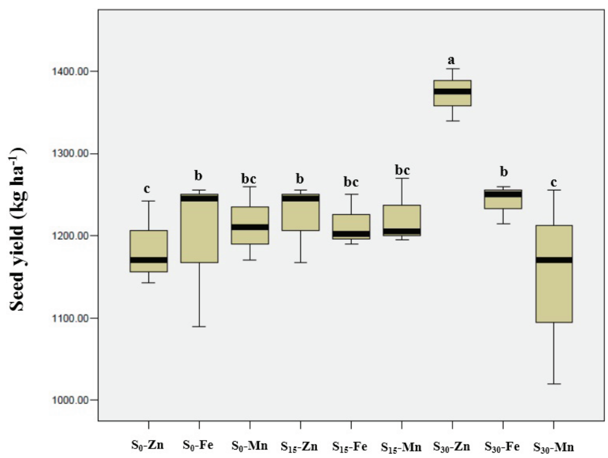

Fig. 6. Influence of integrated application of sulfur and nano-chelated trace elements on seed yield of chickpea

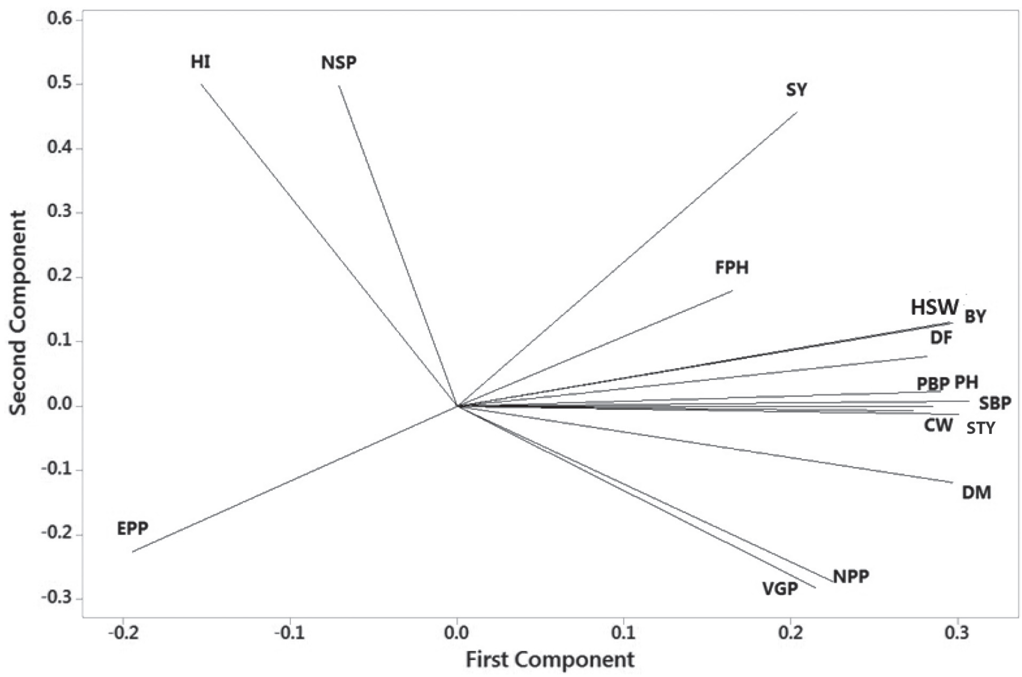

Fig. 7. Plot of the first two PCAs showing relation among various agro-morphological traits of chickpea. PH = plant height, FPH = first pod height, PBP = primary branch per plant, SBP = secondary branch per plant, CW = canopy width, VGP = vegetative growth period, DF = days to flowering, DM = days to maturity, NPP = number of pods per plant, EPP = number of empty pod per plant, NSP = number of seeds per plant, HSW = 100-seed weight, SY = seed yield, BY = biological yield, STY = straw yield, HI = harvest index.

period and harvest index (Fig. 7) as indicated by the near perpendicular vectors (r = cos180 = -1).

Moreover, first four main PCAs were extracted from the complicated components, the total cumulative variance of these five factors amounted to 97% and these components had Eigen values > 1 (Table 3). The PCA simplifies the complex data by transforming the number of associated traits into a smaller number of variables as PCAs. The first principal component (PC1) is growth characteristics such as straw yield, primary and secondary branches, plant height that explained 65% of total variability (Table 3). The second principal component (PC2) explains 16% of total variability and among the property vectors of PC2, the number of seeds per plant and seed yield have higher values. The third principal component (PC3) is seed yield component that explains about 6% of total variability. Among the property vectors of PC3, the number of pods per plant, the numbers of empty pods and the harvest index have higher values. The fourth and fifth principal component was related to vegetative growth characteristics and each of these explains about 5% of total variability (Table 3).

DISCUSSION

Our results showed that the combined application of micronutrients and high level of sulfur improved both growth traits and yield components. The findings of the current study are consistent with those of Islam (2012), who found that availability of soil zinc and copper increased with sulfur application and it resulted to the improvement of seed yield in semiarid region. This suggests that probably because of unfavourable soil conditions in semiarid region, soil fertilization for micronutrients is problematic; hence it seems application of soil amendments, foliar feeding or breeding for tolerance remain the possible solutions (Rashid & Ryan, 2004). This also accords with our earlier observations, which showed that integrated application of zinc and macronutrients increased both vegetative and grain yield of chickpea in a semiarid highland region (Janmohammadi et al., 2011).

In relation to the effect of soil amendments, the results indicated that sulfur application increased significantly both vegetative growth and seed yield. Comparison of the averages of different traits between sulfur

Table 3. Loadings of PCA for the estimated traits of chickpea

Variable	PC1	PC2	PC3	PC4	PC5
PH	0.29	0.023	0.039	0.179	-0.2
FPH	0.165	0.18	-0.342	0.359	0.733
DF	0.282	0.078	0.196	0.327	-0.13
CW	0.274	-0.007	0.074	0.404	-0.078
PBP	0.286	0	-0.038	-0.334	-0.03
SBP	0.307	0.008	0.053	0.07	0.018
VGP	0.215	-0.281	0.039	-0.442	0.401
DM	0.297	-0.119	0.141	-0.063	0.158
NPP	0.225	-0.272	0.46	-0.101	0.241
EPP	-0.194	-0.226	0.614	0.326	0.118
NSP	-0.071	0.498	0.356	-0.344	0.113
HSW	0.295	0.131	-0.163	0.008	0.025
SY	0.204	0.458	0.164	-0.051	-0.061
BY	0.297	0.129	0.029	-0.08	-0.192
STY	0.301	-0.012	-0.026	-0.083	-0.222
HI	-0.154	0.501	0.203	0.05	0.193
Eigenvalue	10.407	2.476	0.993	0.855	0.741
Proportion	0.65	0.16	0.06	0.05	0.05
Cumulative	0.65	0.81	0.87	0.92	0.97

PH = plant height, FPH = first pod height, PBP = primary branch per plant, SBP = secondary branch per plant, CW = canopy width, VGP = vegetative growth period, DF = days to flowering, DM = days to maturity, NP P = number of pods per plant, EPP = number of empty pod per plant, NSP = number of seeds per plant, HSW = 100-seed weight, SY = seed yield, BY = biological yield, STY = straw yield, HI = harvest index.

levels revealed that the highest number of branches, pod number per plant and seed number per plant were obtained by application of 30 kg·ha^{-1} sulfur. However, the lowest values of grain yield and biological yield were found in control plots. This finding corroborates the findings of Singh et al. (2004), who has reported that the best performance of chickpea is obtained from 40 kg S·ha^{-1} application. Nevertheless, the sulfur requirement depends on very different factors, of which the balance between S and other nutrient elements is important in view of possible synergistic or antagonistic effects (Abdin et al., 2003). However, this result may be explained by the fact that application of high level of sulfur fertilizer decreases pH in calcareous and alkaline soils, increases the intake of other nutritional elements, and, thus, facilitates the enhancement of productivity and yield.

The evaluation of plant phenology provides valuable information about the trend of plant growth and development as well as the effects of selective factors such as fertilizers on developmental behaviour. Our results showed that application of sulfur or micronutrient fertilizer affected significantly the phenological trend, so that plant grown with utilization of high level of sulfur along with Zn nano-chelated fertilizer considerably prolonged the period of vegetative and reproductive growth compared to other treatments. This finding supports previous research into this brain area, which showed a significant increase of phenological periods in chickpea by precise nutrient managements (Namvar & Sharifi, 2011). The time available for chickpea crops to produce adequate vegetative structures and then yield components is often restricted by unfavourable environmental conditions such as terminal drought stress and nutrient deficiencies. It seems that the optimal nutritional conditions can elongate considerably the plant development and at the same time increase the growth indices such as total dry matter, leaf area index, crop growth rate, relative growth rate and net assimilation rate (Namvar et al., 2011).

Although some studies have examined the interaction of sulfur and conventional micronutrient fertilizers (Abdin et al., 2003; Islam, 2012), the innovative aspect of this study was the use of nanofertilizers. Application of nano-chelated micronutrient nanoparticles has recently received considerable attention and has been attempted to enable the targeted delivery of nutrients (Rai et al., 2015). It has been suggested that absorption and transport of these fertilizers is much higher than conventional types (Naderi & Danesh-Shahraki, 2013; Mastronardi et al., 2015). Cell wall of the plant roots is very permeable on the nanometre scale. Pores on the order of one to a few tens of nanometres in diameter, essential for ionic and molecular transport process, have been observed in roots. Nano-sized nutrients may then experience enhanced adsorption through these pores, or uptake could be improved by complexation with molecular transporters or root exudates, through the creation of new pores, or by exploitation of endocytosis or ion channels (Rico et al., 2011; Mastronardi et al., 2015). Solubility, mobilization and release of micronutrients from conventional fertilizers are highly dependent on the soil moisture content (Imtiaz et al., 2010). Indeed one way of improving the low productivity of chickpea in semiarid region, where the availability of micronutrient is limited, is to develop fertilizers based on nanotechnology, which have controlled nutrient release and to be less affected by pH and soil moisture. Nano-chelated micronutrient sources stay available for plant uptake over long periods by preventing rapid reactions of the elements with soil clay colloids. The difference in impact of micronutrients on plant growth can result from their interaction with soil particles. Therefore, further study on the interaction of nanoparticles with soil colloids and potential effects of nano-fertilizers on the soil microbiota is critical to any evaluation of the risks and benefits of nanotechnology in agriculture (Mastronardi et al., 2015). Also it is important to note that differences in size, shape, and surface of active ingredient in nano-fertilizers can lead to dramatic differences in their impact on plant performance.

The current results showed that chickpea plants noticeably responded to application of Zn nano-chelated fertilizer. This probably refers to severe deficiency of this element in soil. Considering the local conditions, zinc deficiency may be due to the calcareous nature of soil, high pH, low organic matter, salt stress, continuous drought, high bicarbonate content in irrigation water, and imbalanced application of fertilizers. Taken together, in soils with relatively high pH, the acidity caused by the addition of many fertilizers or from small quantities of elemental sulfur to a portion of the root zone can often provide adequate micronutrients to plants. It seems the technology applied in nano-fertilizers provided a possibility for synchronizing the nutrient release from fertilizer according to crop demand during the growing season. Despite all the advantages of nano-fertilizers, some nanoparticles such as sulfate, silicon dioxide and titanium oxide can be added to them during the synthesis. These materials due to reducing the soil pH, stimulating the defence system and photocatalytic characteristics can improve the plant's resistance to stress and thus increases the crop yield (Derosa et al., 2010; Kumar & Pandey, 2014). However, the positive effects of combined application of Zn nano-chelated fertilizer and sulfur are directly related to some changes in cellular process, and, thus, to be evaluated in depth. This would accelerate the recognition of nutritional behaviour of nano-chelated micronutrients with sulfur application, and may provide guidelines for producing suitable nano-fertilizers in order to optimize chickpea yield in the Mediterranean semiarid areas.

CONCLUSION

The study shows that applications of 30 kg S·ha^{-1} along with Zn nano-chelated fertilizer increase total biological yield and seed yield, primarily due to the increase in seed weight and the number of pods per plant. Although the growth analysis showed that elemental Zn nano-chelated application solely improved the vegetative growth and elongated the reproductive growth, while based on these results for maximum chickpea yields, the optimal combination of micronutrients and sulfur fertilizer seems to be necessary. Significant enhancement of plant growth and yield component by application of micronutrient under high level of sulfur confirms the role of sulfur in improving the availability of trace elements. Soil Zn deficiency not only reduces crop productivity, but also low micronutrient concentrations in plant food adversely affect human health. This will be more important in the Mediterranean semiarid areas with alkaline soils. However, the lowest growth and seed yield of chickpea was recorded for Mn nano-chelated fertilizer under no-sulfur application condition. The number of empty pods(?) was affected significantly by the application of micronutrients and sulfur. This suggests the unavailability of micronutrients in slightly alkaline soils can affect the abortion of reproductive structures by reducing seed formation or decreasing the availability of assimilates. Our finding revealed that combined application of nano-micronutrient fertilizers and high level of elemental sulfur can be an effective agronomic management option for increasing the yield of Desi chickpea cultivated in short-season semiarid highland region.

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INTEGRUOTAS NANOCHELATUOTŲ MIKROELEMENTŲ IR SIEROS POVEIKIS SĖJAMOJO AVINŽIRNIO AUGIMUI PER TRUMPĄ, VIDURŽEMIO JŪROS REGIONUI BŪDINGĄ VYSTYMOSI SEZONĄ

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Santrauka

Pusiau sausringuose Viduržemio regionuose sėjamasis avinžirnis (*Cicer arietinum* L.) yra vienas svarbiausių ankštinių augalų. Šių regionų dirvožemiai paprastai turi daug $CaCO_3$, didelį pH ir mažai organinės medžiagos, dėl to sumažėja mikroelementų prieinamumas ir atsiranda jų trūkumas. Norint ištirti skirtingų koncentracijų sieros (0, 15, 30 kg ha^{-1}) ir nanochelatuotų mikroelementų (Zn, Fe, Mn) integruotą poveikį avinžirnio augimui ir vystymuisi pusiau sausringuose Šiaurės Vakarų Irano regionuose buvo atliktas lauko eksperimentas. Įvertinus morfologines savybes parodyta, kad didelio sieros kiekio įterpimas žymiai pagerino augalų augimą, pirminių šakų skaičių ir lapų dangos plotį, lyginant su kontroliniais augalais. Ilgiausias vegetacijos tarpsnis buvo užfiksuotas augalams, auginamiems taikant aukštą sieros ir nanochelatuotų Zn trąšų kiekį. Nustatyta, kad naudojant nanochelatuotas Zn trąšas ženkliai padidėja sėklų svoris ir skaičius vienam augalui, lyginant su kitomis mikroelementinėmis nanotrąšomis. Apskritai, geriausi augimo rezultatai ir didžiausias sėklų derlius buvo gautas integruotai taikant Zn ir dideles sieros koncentracijas. Parodyta, kad dirvožemio mikroelementų trūkumas atsiranda dėl didelio dirvožemio šarmingumo, todėl sieros panaudojimas, taikant virš 15 kg ha^{-1}, gali veiksmingai padidinti nanotrąšų efektyvumą. Pusiau sausringame regione integruotas mikroelementų ir sieros panaudojimas turėtų būti laikomas veiksminga agrarine avinžirnių produktyvumo valdymo sistema.