Asian Research Journal of Agriculture

Volume 17, Issue 4, Page 1032-1044, 2024; Article no.ARJA.128559
ISSN: 2456-561X

Sources and Levels of Zinc Fertilization on Soil Zinc Availability and Zinc Uptake by Small Onion (*Allium cepa* L. var. *aggregatum*)

P. Malathi [a*], R. Keerthana [a] and K.M. Sellamuthu [a]

[a] *Department of Soil Science and Agricultural Chemistry, Directorate of Natural Resource Management, Tamil Nadu Agricultural University, Coimbatore-641003, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/arja/2024/v17i4617

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/128559

Original Research Article

Received: 14/10/2024
Accepted: 18/12/2024
Published: 20/12/2024

ABSTRACT

Onion, the King of vegetable is one among the oldest cultivated vegetables. The quality and yield of crops are affected by micronutrient deficiencies in soil. Micronutrients which enhance the efficiency of macronutrients are equally important for the growth of a crop. Indian soils are deficient in zinc by an average deficiency of about 50 % at present. It is revealed that the presence of zinc has direct effect on yield and growth parameters of aggregatum onion. To study the Zn uptake and Zn availability to onion, different levels and sources of Zinc was evaluated in a pot culture experiment with onion var. CO(On) 5 in a soil with andy clay loam in texture, non-calcareous and deficient in soil available Zn with 16 treatments comprising different sources of Zn ($ZnSO_4$, Zn-EDTA and Zn citrate) and levels of Zn (1,2.5,5.0, 7.5 and 10.0 kg Zn ha^{-1} for $ZnSO_4$ and 0.1,0.25, 0.5, 0.75 and

**Corresponding author: E-mail: pmalathisellamuthu@gmail.com;*

Cite as: *Malathi, P., R. Keerthana, and K.M. Sellamuthu. 2024. "Sources and Levels of Zinc Fertilization on Soil Zinc Availability and Zinc Uptake by Small Onion (Allium Cepa L. Var. Aggregatum)". Asian Research Journal of Agriculture 17 (4):1032-44. https://doi.org/10.9734/arja/2024/v17i4617.*

1.0 kg Zn ha^{-1} for Zn-EDTA and Zn citrate). Significantly highest plant Zn at bulb initiation and harvest stages was observed with $ZnSO_4$ application 10 kg Zn ha^{-1} followed by Zn-EDTA @ 1 kg Zn $ha^{-1}$and both were comparable. Uptake of Zn by onion was significantly higher with Zn-EDTA @ 1 kg Zn ha^{-1} and it was comparable with $ZnSO_4$ @ 10 kg Zn $ha^{-1}$and Zn-EDTA @ 0.75 kg Zn ha^{-1}. Regarding the Zn content and uptake by onion at the same level of 1 kg Zn ha^{-1}, it was observed that Zn-EDTA performed better than Zn citrate and $ZnSO_4$. The soil available Zn at bulb initiation and harvest stages was the highest with the application of $ZnSO_4$ @ 10 kg Zn ha^{-1} followed by $ZnSO_4$ @ 7.5 kg Zn $ha^{-1}$and $ZnSO_4$ @ 5 kg Zn ha^{-1}. With the application of same level of Zn at 1 kg Zn ha^{-1}, Zn-EDTA showed significantly higher soil available Zn which was on par with Zn citrate. From the results obtained, it can be inferred that Zn fertilization had a significant influence on Zn content, Zn uptake and soil available Zn by onion. The performance of 1 kg Zn ha^{-1} as Zn-EDTA and 10 kg Zn ha^{-1} as $ZnSO_4$ in improving the Zn uptake of onion was comparable. Hence, it can be concluded that application of either Zn-EDTA @ 1 kg Zn ha^{-1} or $ZnSO_4$ @ 10 kg Zn ha^{-1} can be recommended for obtaining higher growth and Zn uptake of onion.

Keywords: Onion; soil zn availability; zn uptake; zinc- EDTA; zn-citrate; $ZnSO_4$.

1. INTRODUCTION

Onion is most widely used vegetable owing to its flavour, pungency and medicinal value. Onion belonging to the family Alliaceae and native to Asia known as the "Queen of Kitchen. The pungency of the onion is due to the enzyme allinase in combination with isoalliin which produces an unstable compound and forms thiosulfinates and thiosulfonates while it is disturbed. Onion is a source of antioxidants due the presence of flavanoids such as quercetin and kaempferol which helps avoiding many diseases. Also the bulbs of onion contain fructo-oligosaccharides that acts as osmoregulators which helps the plant to overcome drought stress [1]. Understanding the distribution of various zinc fractions in soils help to characterize the dynamics of Zn in soils as well as possible contribution of individual zinc fractions towards plant availability [2].

"Zinc (Zn) deficiency in crops is a global issue, particularly in plants grown in calcareous soils, where Zn is often adsorbed or precipitated by calcium carbonates" [3,4]. "Zn deficiency is caused by various reasons starting from the prevalence of Zn-deficient soil (30% of world soils) to the Zn malabsorption in humans" [5]. "Low supply of micronutrients is the main cause of malnutrition in many countires. Understanding the molecular mechanisms of biofortification in crops is challenging" [6]. "Zinc found to be a metal of life which play crucial roles in both plant and human physiology. Its requirement ranges from photosynthesis in plants to proper functioning of human brain. Inadequate Zn supply in soil causes lower crop productivity and poor nutritional quality leads to Zn depletion in food chain, ultimately, affecting health and reproductivity in human being. Seriousness of Zinc deficiency understood by claiming millions of lives, especially children, every year. Therefore, in order to maintain the soil nutrients and better crop productivity, the basal application of major nutrients and basal application of Zn @ 5.0 kg ha^{-1} is recommended for rice" [7].

In India, onion is cultivated in an area of 17.34 lakh hectare with production and productivity of 302.07 lakh MT and 17.36 MT per hectare respectively in the year 2022-2023. Next to China, India occupies second position in world in production of onion. In Tamil Nadu, onion is being produced at about 5,24,880 MT in 2022-23 and productivity of about 11.93 MT per hectare (Indiastat.com).

"Zinc has direct effect on bulb yield and growth of aggregatum onion" [8]. "Zinc plays a vital role to produce good quality onion bulb. Onion is very sensitive to zinc deficient soils" [9] and also onion responds to zinc fertilizer application. "Zinc favours onion production due to its involvement in cellular functions and physiological processes. Zinc is involved in protein synthesis and it is required for maintenance of the stability of the enzymes.

Varied sources and levels of Zn exerted significant influence on soil available Zn and Zn uptake by onion. With the application of N:P:K:S:Zn - 100:100:100:20:5 kg ha^{-1} there was an increase in Zn uptake in onion @ 35, 70 and 110 DAT when compared to other treatments [10]. Application of $ZnSO_4.7H_2O$ showed an increase in Zn uptake of onion bulbs when compared to control [11].

Thangasamy [12] concluded that uptake of zinc was highest at 64 DAT (1.75 g ha^{-1}) and the uptake of zinc by onion followed a sigmoid pattern curve. Sarker et al. [13] found that application of $ZnSO_4.7H_2O$ @ 3 kg Zn ha^{-1} along with other micronutrients (Cu: Mn: Fe – 2: 2: 3 kg ha^{-1}) showed maximum total Zn uptake of 395 g ha^{-1} in potato.

With the application of increased levels of $ZnSO_4.7H_2O$ @ 0, 2, 4, 8 and 16 mg Zn kg^{-1} there was an increase in Zn concentration in whole shoots, leaves, tops and bulbs in different cultivars of onion and Zn uptake in tops and bulbs were found highest in $ZnSO_4.7H_2O$ application @ 16 mg Zn kg^{-1} [11].

2. MATERIALS AND METHODS

A pot culture experiment was conducted in the Department of Soil Science & Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore to investigate the response of onion to different sources and levels of zinc fertilizers. To initiate the experiment, ten kilogram of processed and homogenized soil collected and filled in well cleaned earthen pots individually and two seedlings per pot were planted and maintained. Soil samples were analysed as per the standard procedures (Table 1).

Table 1. Analytical procedures used in analysis of soil samples

Parameters	Procedure	Reference
Physical Properties		
Mechanical analysis	Robinson pipette method	Piper [14]
Physico-chemical properties		
Soil reaction (pH)	Potentiometry (1:2.5 soil:water suspension)	Jackson [15]
Electrical Conductivity	Conductometry (1:2.5 soil: water suspension)	Jackson [15]
Free $CaCO_3$	Rapid Titration Method	Piper [16]
Chemical properties		
Soil organic carbon	Chromic acid wet digestion method	Walkley and Black [17]
Cation exchange capacity (CEC)	Neutral normal ammonium acetate (pH-7.0)	Jackson [15]
Available Nitrogen	Alkaline permanganate method	Subbiah and Asija [18]
Available Phosphorus	0.5 M $NaHCO_3$ (pH 8.5)	Olsen [19]
Available Potassium	Neutral normal ammonium acetate method	Stanford and English [20]
DTPA extractable micronutrients	Atomic absorption spectrophotometer	Lindsay and Norvell [21]

The seeds were sown and mulching was given until the seedlings raised to a height of 1-2 cm and watering was done with rose cane periodically. Completely Randomized Block Design was adopted with three replications with 16 treatments.

T_1 : Control
T_2 : 1.00 kg Zn ha^{-1} as ZnSO4
T_3 : 2.50 kg Zn ha^{-1} as ZnSO4
T_4 : 5.00 kg Zn ha^{-1} as ZnSO4
T_5 : 7.50 kg Zn ha^{-1} as ZnSO4
T_6 : 10.0 kg Zn ha^{-1} as ZnSO4
T_7 : 0.10 kg Zn ha^{-1} as Zn-EDTA
T_8 : 0.25 kg Zn ha^{-1} as Zn-EDTA
T_9 : 0.50 kg Zn ha^{-1} as Zn-EDTA
T_{10} : 0.75 kg Zn ha^{-1} as Zn-EDTA
T_{11} : 1.00 kg Zn ha^{-1} as Zn-EDTA
T_{12} : 0.10 kg Zn ha^{-1} as Zn citrate
T_{13} : 0.25 kg Zn ha^{-1} as Zn citrate
T14 : 0.50 kg Zn ha^{-1} as Zn citrate
T15 : 0.75 kg Zn ha^{-1} as Zn citrate
T16 : 1.00 kg Zn ha^{-1} as Zn citrate

STCR based fertilizer prescription was calculated based on the initial soil test values and the NPK requirement was worked out as per equation already developed for onion as furnished below.

STCR- NPK alone equation for calculating the fertilizer dose:

FN= 0.99 T- 0.37 SN FP_2O_5= 0.58 T- 1.43 SP FK_20= 0.67 T- 0.25 SK

Where,

FN= Fertilizer N; FP_2O_5 = Fertilizer P_2O_5; FK_2O = Fertilizer K_2O
T= Targetted yield in q ha^{-1}; SN, SP and SK = Soil test value of N, P and K in kg ha^{-1}

The fertilizer dose for the yield target of 200 q ha^{-1} was 120: 68.2: 15 kg N: P_2O_5: K_2O ha^{-1}. The N, P and K converted into Urea, SSP and MOP. Calculated quantities of SSP and MOP were applied as basal to the pots before transplanting of seedlings. Urea was applied in two splits at basal and 30 days after transplantation of seedlings. The sources and levels of zinc applied basally as per the treatment schedule.

Seedlings of forty days old were transplanted to pots. Two seedlings were maintained in each pot. All the cultivation practices were followed until harvest as per the crop production guide of TNAU.

Soil samples were collected during bulb initiation and harvest stages of the crop from each treatment from the pot. Collected soil samples were dried, processed using 2 mm sieve and were analysed for available zinc contents as per the procedure outlined in Table 1.

The plant samples were collected during bulb initiation and harvest stages of the crop. Plant samples were washed with distilled water air dried in oven at 60°C until constant weight is reached. For harvest stage samples, leaves and bulbs were separated, dry weight was recorded. Dried leaves and bulbs were ground in a wiley mill and stored for further chemical analysis.

A known quantity of the plant samples was digested with 15 ml of the triple acid mixture (Nitric acid: Sulphuric acid: Perchloric acid - 9:2:1) and made to the desired volume. The zinc content in the triacid extract was estimated in Atomic Absorption Spectrophotometer [15]. Zn uptake was calculated by multiplying the Zn content of the plant with its dry matter production and expressed in g $plant^{-1}$.

The data obtained were statistically analysed for finding out the significance and to draw meaningful conclusions [22].

3. RESULTS AND DISCUSSION

3.1 Physico-Chemical Characteristics of Initial Soil

The surface sample (0-15 cm) was collected from the Orchard, TNAU, Coimbatore for conducting pot culture experiment. The experimental soil was sandy clay loam in texture, slightly alkaline in nature (pH 7.81) with permissible amount of soluble salts (EC 0.23 dSm^{-1}). The soil was non-calcareous with a free $CaCO_3$ content of 1.51 %. The organic carbon content of the soil was medium (5.2 g kg^{-1}) and the CEC of the soil was 28.2 C mol (p+) kg^{-1}.

The experimental soil was low in available N (123 kg ha^{-1}), high in available P (33.4 kg ha^{-1}) and high in available K (844 kg ha^{-1}). The soil was deficient in DTPA-Zn (1.09 mg kg^{-1}), DTPA-Cu (1.12 mg kg^{-1}) and sufficient in DTPA-Fe (7.53 mg kg^{-1}), DTPA-Mn (3.87 mg kg^{-1}). Different fractions of Zn in experimental soil were water soluble +exchangeable Zn (0.23 mg kg^{-1}), organically bound Zn (2.56 mg kg^{-1}), carbonate bound Zn (1.52 mg kg^{-1}), Fe-Mn oxide bound Zn (13.8 mg kg^{-1}), residual Zn (79.3 mg kg^{-1}) and total Zn (97.5 mg kg^{-1})

3.2 Dry Matter Production, Zn Content and Zn Uptake at Bulb Initiation Stage of Onion

3.2.1 Dry matter production

The values obtained from the experiment revealed a significant variation in dry matter production with the treatments imposed (Table 2). Dry matter production was significantly highest in the treatment 1.0 kg Zn ha^{-1} as Zn-EDTA (2.08 g $plant^{-1}$) followed by 10 kg Zn ha^{-1} as $ZnSO_4$ (2.05 g $plant^{-1}$) and 0.75 kg Zn ha^{-1} as Zn EDTA (2.01 g $plant^{-1}$) respectively. The minimum dry matter was observed in control (1.74 g $plant^{-1}$) which was statistically comparable with 0.1 kg Zn ha^{-1} as Zn citrate (1.78 g $plant^{-1}$). Application of $ZnSO_4$ @ 5, 7.5

and 10 kg Zn ha^{-1} was on par with Zn-EDTA @ 0.5 and 0.75 kg Zn ha^{-1} and Zn- citrate @ 0.75 and 1 kg Zn ha^{-1}. At the level of 1.0 kg Zn ha^{-1}, Zn-EDTA (2.08 g plant^{-1}) documented the highest DMP followed by Zn citrate (1.96 g plant^{-1}) and $ZnSO_4$ (1.84 g plant^{-1}). DMP significantly increased with applied Zn levels regardless of the sources used.

This is in close association with the findings of Meena and Singh [23] who noted a positive relationship with dry matter of the tops and Zn application. In support of this, highly significant and positive correlation was observed between soil available Zn and DMP (0.533** and 0.750** at bulb initiation and harvest stages respectively). Also, the relationship between Zn uptake and DMP was highly significant and positive (0.972** and 0.990** at bulb initiation and harvest stages respectively).

3.2.2 Plant Zn content

Significant difference was obtained in plant Zn with different sources and levels of Zn applied (Table 2). $ZnSO_4$ @ 10 kg Zn ha^{-1} (28.3 mg kg^{-1}) scored the maximum plant Zn content followed by Zn-EDTA @ 1 kg Zn ha^{-1} (27.9 mg kg^{-1}). Control recorded the lowest plant Zn (24.1 mg kg^{-1}) which was on par with 0.1 and 0.25 kg Zn ha^{-1} as Zn-EDTA and Zn citrate. Zn-EDTA @ 0.75 and 1 kg Zn ha^{-1} and $ZnSO_4$ @ 2.5, 5.0 and 7.5 kg Zn ha^{-1} were statistically comparable with each other. An increment in plant Zn was seen with increase in Zn levels. With same dosage of fertilization @ 1 kg Zn ha^{-1}, Zn-EDTA (27.9 mg kg^{-1}) registered the highest plant Zn whereas the lowest being $ZnSO_4$ (25.7 mg kg^{-1}).

The positive effect of Zn on photosynthates and its transportation to various parts of the plant might have improved the Zn content in onion tops [24]. Tops and bulb Zn increased with increasing levels of Zn application in considerating the sources applied. Similar trends were recorded by Rafique et al. [11] and Singh et al. [24]. The application of Zn in onion was positively correlated with bulb Zn content as reported by Fouda [25]. Zinc playing a major role in moisture absorption and its role in different enzymes might have increased the bulb Zn upto a certain limit [24]. The results could be further strengthened by highly significant and positive correlation existed between soil Zn at bulb initiation stage and plant Zn content (0.679**, 0.660** and 0.685** for plant Zn at bulb initiation stage, tops and bulb Zn at harvest stages respectively).

Table 2. Effect of sources and levels of Zn on dry matter production, Zn content and uptake at bulb initiation stage of onion

Treatments	Dry matter production (g plant^{-1})	Zn content (mg kg^{-1})	Zn uptake (µg plant^{-1})
T_1 -Control (NPK)	1.74	24.1	42.0
T_2 - 1.00 kg Zn ha^{-1}as ZnSO4	1.84	25.7	47.6
T_3 - 2.50 kg Zn ha^{-1}as ZnSO4	1.85	26.6	49.8
T_4 - 5.00 kg Zn ha^{-1}as ZnSO4	1.95	26.7	52.9
T_5 - 7.50 kg Zn ha^{-1}as ZnSO4	1.98	26.8	53.4
T_6 - 10.0 kg Zn ha^{-1}as ZnSO4	2.05	28.3	57.5
T_7 - 0.10 kg Zn ha^{-1}as Zn-EDTA	1.85	25.3	47.3
T_8 - 0.25 kg Zn ha^{-1}as Zn-EDTA	1.87	25.4	47.8
T_9 - 0.50 kg Zn ha^{-1}as Zn-EDTA	1.97	25.8	51.6
T_{10} - 0.75 kg Zn ha^{-1}as Zn-EDTA	2.01	26.7	53.7
T_{11} - 1.00 kg Zn ha^{-1}as Zn-EDTA	2.08	27.9	58.6
T_{12} - 0.10 kg Zn ha^{-1}as Zn citrate	1.78	24.2	43.1
T_{13} - 0.25 kg Zn ha^{-1}as Zn citrate	1.84	25.4	47.3
T_{14} - 0.50 kg Zn ha^{-1}as Zn citrate	1.86	25.6	48.2
T_{15} - 0.75 kg Zn ha^{-1}as Zn citrate	1.95	26.5	52.8
T_{16} - 1.00 kg Zn ha^{-1}as Zn citrate	1.96	26.6	52.9
SEd	0.04	0.6	2.5
CD (P=0.05)	0.09	1.3	5.1

3.2.3 Plant Zn uptake

Zn uptake also had a significant influence with different levels and sources of Zn (Table 2). The maximal Zn uptake of plant was noticed in Zn-EDTA @ 1.0 kg Zn ha^{-1} (58.6 µg $plant^{-1}$) followed by $ZnSO_4$ @ 10 kg Zn ha^{-1} (57.5 µg $plant^{-1}$) and 0.75 kg Zn ha^{-1} as Zn-EDTA (53.7 µg $plant^{-1}$). The least Zn uptake (42.0 µg $plant^{-1}$) was observed in control which was statistically on par with 0.1 kg Zn ha^{-1} as Zn citrate (43.1 µg $plant^{-1}$). The treatments containing 5, 7.5 and 10 kg Zn ha^{-1} as $ZnSO_4$ was on par with 0.75 kg Zn ha^{-1} as Zn-EDTA and 0.75 and 1.0 kg Zn ha^{-1} as Zn citrate. At same level of 1 kg Zn ha^{-1}, the maximum Zn uptake was found in Zn-EDTA (58.6 µg $plant^{-1}$) followed by Zn citrate (52.9 µg $plant^{-1}$) and $ZnSO_4$ (47.6 µg $plant^{-1}$). With increasing levels of Zn, Zn uptake of plants gradually increased.

The increased Zn uptake with Zn-EDTA application could be due to higher available Zn in soil which is again confirmed by the significant and positive correlation between soil available Zn at bulb initiation stage and Zn uptake at different stages of onion (0.616**, 0.605**, 0.619** and 0.614** for Zn uptake in bulb initiation stage, tops, bulbs and total Zn uptake at harvest stage respectively). The application of zinc increased the zinc uptake regardless of the sources which might be due to the availability of Zn in rhizosphere region with Zn addition [24]. Rafique et al*.* [11] also observed increased in Zn uptake in tops and bulbs of onion with increasing levels of Zn. Control documented the lowest Zn uptake at bulb initiation and harvest stages of onion which might be due to the low availability of Zn in the rhizosphere region. Zn-EDTA showed highest Zn uptake as compared to other sources of Zn at the level of 1 kg Zn ha^{-1} owing to its high availability coefficient and stability in soils. Similar results in rice crop were reported by Karak et al*.* [26] observed that Zn content and uptake of rice were in the order Zn-EDTA>Zn-DTPA> $ZnSO_4$. Chelates are easily absorbed and translocated within the plants [27].

3.3 Dry Matter Production, Zn Content and Zn Uptake at Harvest Stage of Onion

3.3.1 Dry matter production in tops

Marked variation was found in dry matter production of the plant at harvest stage due to the sources and levels of Zn applied (Table 3). Dry matter production in tops was highest when Zn was applied as Zn-EDTA @ 1.0 kg Zn ha^{-1} (4.70 g $plant^{-1}$) followed by 0.75 kg Zn ha^{-1} as Zn-EDTA (4.65 g $plant^{-1}$) and 10 kg Zn ha^{-1} as $ZnSO_4$ (4.58 g $plant^{-1}$) and all the above mentioned treatments were statistically on par with each other. The minimal DMP was noted in control (3.68 g $plant^{-1}$) and was on par with 0.1 kg Zn ha^{-1} as Zn citrate (3.79 g $plant^{-1}$). Zn-EDTA showed the maximal DMP compared to other Zn sources at the same dosage of 1.0 kg Zn ha^{-1} application. $ZnSO_4$ @ 5.0 and 7.5 kg Zn ha^{-1} was on par with 0.75 and 1.0 kg Zn ha^{-1} as Zn citrate and 0.5 kg Zn ha^{-1} as Zn-EDTA. While enhancing Zn levels, there was a rise in DMP.

The increment in dry matter content of leaves with increasing Zn levels was proved with the findings of Meena and Singh [23] who noted a positive relationship with dry matter of the tops and Zn application. In support of this, highly significant and positive correlation was observed between soil available Zn and DMP (0.533** at bulb initiation stage). Also, the relationship between Zn uptake and DMP was highly significant and positive (0.972** at bulb initiation stage).

3.3.2 Dry Matter Production in Bulbs

Different sources and levels of Zn showed a significant variation in the dry matter production of onion bulbs (Table 3) and the highest DMP noticed in Zn-EDTA @ 1.0 kg Zn ha^{-1} (11.4 g $plant^{-1}$) followed by 10 kg Zn ha^{-1} as $ZnSO_4$ (11.1 g $plant^{-1}$) and 0.75 kg Zn ha^{-1} as Zn-EDTA (11.1 g $plant^{-1}$) which were on par. $ZnSO_4$ @ 7.5 and 10 kg Zn ha^{-1} and Zn-EDTA @ 0.5 and 0.75 kg Zn ha^{-1} and Zn-citrate @ 0.75 and 1.0 kg Zn ha^{-1} were comparable with each other. The minimal DMP was found in control (9.4 g $plant^{-1}$). At the level of 1 kg Zn ha^{-1}, $ZnSO_4$ documented the lowest DMP in bulbs compared to other sources. With increasing Zn levels, DMP of bulbs also increased regardless of the sources tried.

Meena and Singh [23] found a close relationship with dry matter of the tops and Zn application. Highly significant and positive correlation was observed between soil available Zn and DMP (0.750** at harvest stage). Also, the relationship between Zn uptake and DMP was highly significant and positive (0.990** at harvest stage). Lowest dry matter production in both the stages with no Zn application revealed the impact of Zn application in enhancing dry matter production. This in in conformity with the findings of El-Gamili et al*.* [28] and Assefa et al*.* [29].

Table 3. Effect of sources and levels of Zn on dry matter production, Zn content and uptake at harvest stage of onion

Treatments	Dry matter production (g plant^{-1})			Zn content (mg kg^{-1})		Zn uptake (µg plant^{-1})		
	Tops	Bulbs	Total	Tops	Bulbs	Tops	Bulbs	Total
T_1 -Control (NPK)	3.68	9.4	13.1	18.7	13.0	68.9	122	191
T_2 – 1.00 kg Zn ha^{-1}as ZnSO4	3.95	10.0	14.0	19.9	14.1	78.7	141	220
T_3 – 2.50 kg Zn ha^{-1}as ZnSO4	4.11	10.1	14.2	20.8	14.9	85.5	151	236
T_4 – 5.00 kg Zn ha^{-1}as ZnSO4	4.35	10.5	14.9	21.2	15.3	92.3	161	253
T_5 – 7.50 kg Zn ha^{-1}as ZnSO4	4.36	10.6	15.0	21.3	15.5	92.9	164	257
T_6 – 10.0 kg Zn ha^{-1}as ZnSO4	4.58	11.1	15.7	22.6	16.5	103.6	183	287
T_7 – 0.10 kg Zn ha^{-1}as Zn-EDTA	4.00	10.0	14.0	19.7	13.9	78.8	139	218
T_8 – 0.25 kg Zn ha^{-1}as Zn-EDTA	4.13	10.1	14.2	20.0	14.2	82.7	144	226
T_9 – 0.50 kg Zn ha^{-1}as Zn-EDTA	4.36	10.7	15.1	20.5	14.8	89.4	158	248
T_{10} – 0.75 kg Zn ha^{-1}as Zn-EDTA	4.65	11.1	15.8	21.9	15.7	101.9	174	276
T_{11} – 1.00 kg Zn ha^{-1}as Zn-EDTA	4.70	11.4	16.1	22.4	16.4	105.3	187	292
T_{12} – 0.10 kg Zn ha^{-1}as Zn citrate	3.79	9.7	13.5	19.3	13.7	73.2	133	206
T_{13} – 0.25 kg Zn ha^{-1}as Zn citrate	3.98	10.0	14.0	19.9	13.9	79.3	139	218
T_{14} – 0.50 kg Zn ha^{-1}as Zn citrate	4.12	10.1	14.2	20.2	14.5	83.3	147	230
T_{15} – 0.75 kg Zn ha^{-1}as Zn citrate	4.34	10.6	14.9	21.1	15.2	91.6	161	253
T_{16} – 1.00 kg Zn ha^{-1}as Zn citrate	4.35	10.7	15.1	21.2	15.3	92.3	164	256
Sed	0.10	0.3	0.4	0.5	0.4	4.3	8	12
CD (P=0.05)	0.21	0.5	0.8	1.0	0.7	8.8	16	24

3.3.3 Total dry matter production

The values recorded showed a significant variation in DMP due to the treatments investigated (Table 3). Zn-EDTA @ 1.0 kg Zn ha^{-1} (16.1 g plant^{-1}) registered highest total DMP of onion followed by 0.75 kg Zn ha^{-1} as Zn- EDTA (15.8 g plant^{-1}) and 10 kg Zn ha^{-1} as $ZnSO_4$ (15.7 g plant^{-1}) and they were statistically on par. Control which received no Zn exhibited the minimum DMP of 13.1 g plant^{-1}. 0.1 kg Zn ha^{-1} as Zn-citrate (13.5 g plant^{-1}) was comparable with control. $ZnSO_4$ exhibited the lowest DMP in onion when same dosage of 1 kg Zn ha^{-1} was imposed with different sources of Zn. $ZnSO_4$ @ 10 kg Zn ha^{-1} was statistically comparable with 0.5 and 0.75 kg Zn ha^{-1} as Zn- EDTA and 1 kg Zn ha^{-1} as Zn- citrate. Total DMP of onion improved with rising levels of Zn. The studies by Meena and Singh [23] El-Gamili et al. [28] and Assefa et al. [29] confirms the relationship between Zn content, uptake and dry matter production of onion.

3.3.4 Zinc content in tops and bulbs

Sources and levels of Zn exerted significant influence on the zinc content in tops at harvest stage (Table 3). $ZnSO_4$ applied at 10 kg Zn ha^{-1} (22.6 mg kg^{-1}) registered the highest zinc content in tops followed by Zn-EDTA @ 1.0 kg Zn ha^{-1} (22.4 mg kg^{-1}) and 0.75 kg Zn ha^{-1} as Zn-EDTA

(21.9 mg kg^{-1}) respectively which were statistically on par. The treatment which received no Zn recorded the minimal Zn content in tops (18.7 mg kg^{-1}) which was statistically comparable with 0.1 kg Zn ha^{-1} as Zn-EDTA and Zn-citrate. $ZnSO_4$ @ 5.0 and 7.5 kg Zn ha^{-1} and Zn citrate @ 0.75 and 1.0 kg Zn ha^{-1} were on par with Zn-EDTA @ 0.75 kg Zn ha^{-1}. At 1 kg Zn ha^{-1} level, Zn-EDTA recorded significantly the highest Zn content in tops. With increment in Zn levels, Zn content in tops gradually increased.

Bulb content varied markedly with the sources and levels of Zn tried (Table 3). The highest bulb Zn content was registered in $ZnSO_4$ @ 10 kg Zn ha^{-1} (16.5 mg kg^{-1}) followed by 1.0 kg Zn ha^{-1} as Zn-EDTA (16.4 mg kg^{-1}) and both the treatments were statistically comparable. Zn-EDTA @ 1 kg Zn ha^{-1} was on par with the same source at 0.75 kg Zn ha^{-1}. The minimum bulb Zn content was documented in control (13.0 mg kg^{-1}) which was on par with 0.1 kg Zn ha^{-1} as Zn citrate (13.7 mg kg^{-1}). With Zn dose applied at 1 kg Zn ha^{-1}, Zn-EDTA recorded the significantly highest bulb Zn content when compared with other sources.

The application of Zn in onion was positively correlated with bulb Zn content as reported by Fouda [25]. Zinc playing a major role in moisture absorption and its role in different enzymes might have increased the bulb Zn upto a certain limit [24]. The results could be further strengthened by highly significant and positive correlation existed between soil Zn at bulb initiation stage and plant Zn content (0.679**, 0.660** and 0.685** for plant Zn at bulb initiation stage, tops and bulb Zn at harvest stages respectively).

3.3.5 Zinc uptake in tops

Zinc uptake in tops varied notably with different levels and sources of Zn (Table 3). The highest Zn uptake was noticed in Zn-EDTA @ 1.0 kg Zn ha^{-1} (105.3 µg $plant^{-1}$) followed by $ZnSO_4$ @ 10 kg Zn ha^{-1} (103.6 µg $plant^{-1}$) and Zn- EDTA @ 0.75 kg Zn ha^{-1} (101.9 µg $plant^{-1}$) which were on par. Control registered the lowest Zn uptake in tops of about 68.9 µg $plant^{-1}$. The treatments with 2.5, 5.0 and 7.5 kg Zn ha^{-1} as $ZnSO_4$ was on par with 0.75 and 1.0 kg Zn ha^{-1} as Zn-citrate and 0.5 kg Zn ha^{-1} as Zn-EDTA. Amongst the sources, Zn-EDTA documented the significantly highest Zn uptake in tops compared to other sources at equal dosage of Zn application @ 1.0 kg Zn ha^{-1}.

3.3.6 Zinc uptake in bulbs

Significant difference was found in the bulb Zn content with the treatments under investigation (Table 3). Zn-EDTA @ 1.0 kg Zn ha^{-1} (187 µg $plant^{-1}$) recorded the highest Zn uptake in bulbs followed by $ZnSO_4$ @ 10 kg Zn ha^{-1} (183 µg $plant^{-1}$) and 0.75 kg Zn ha^{-1} as Zn- EDTA (174 µg $plant^{-1}$) which were on par with each other. The treatments containing $ZnSO_4$ @ 5.0 and 7.5 kg Zn ha^{-1} were on par with Zn-EDTA @ 0.75 kg Zn ha^{-1} and Zn-citrate @ 0.75 and 1.0 kg Zn ha^{-1}. The minimum bulb Zn content was noticed in control receiving no Zn (122 µg $plant^{-1}$). The significantly highest Zn uptake in bulbs was noticed in Zn-EDTA over other sources at the level of 1 kg Zn ha^{-1} application. Zn uptake in bulbs raised with increment in Zn levels.

3.3.7 Total Zn uptake

Total Zn uptake of onion also varied markedly with different sources and levels of Zn (Table 3). Application of 1.0 kg Zn ha^{-1} as Zn-EDTA (292 µg $plant^{-1}$) recorded the maximum Zn uptake in plants followed by $ZnSO_4$ @ 10 kg Zn ha^{-1} (287 µg $plant^{-1}$) and 0.75 kg Zn ha^{-1} as Zn citrate (276 µg $plant^{-1}$). Control registered the lowest Zn uptake (191 µg $plant^{-1}$) which was comparable with 0.1 kg Zn ha^{-1} as Zn citrate (206 µg $plant^{-1}$). $ZnSO_4$ @ 5.0 and 7.5 kg Zn ha^{-1} was on par with 0.75 and 1.0 kg Zn ha^{-1} as Zn-citrate and 0.75 kg Zn ha^{-1} as Zn-EDTA. Zn-EDTA showed significantly highest Zn uptake when compared to other sources when Zn was applied at the level of 1.0 kg Zn ha^{-1}. Total Zn uptake gradually raised, with rise in Zn levels regardless of the sources imposed.

The application of zinc increased the zinc uptake regardless of the sources which might be due to the availability of Zn in rhizosphere region with Zn addition [24]. Rafique et al. [11] also observed increased in Zn uptake in tops and bulbs of onion with increasing levels of Zn. Control documented the lowest Zn uptake at bulb initiation and harvest stages of onion which might be due to the low availability of Zn in the rhizosphere region. Zn-EDTA showed highest Zn uptake as compared to other sources of Zn at the level of 1 kg Zn ha^{-1} owing to its high availability coefficient and stability in soils. Similar results in rice crop were reported by Karak et al. [26].

3.4 Effect of Sources and Levels of Zn on Soil Available Zn at different Onion Growth Stages

At bulb initiation stage, sources and levels of Zn had a significant influence on soil available Zn at bulb initiation stage (Table 4). Significantly highest available Zn was noticed in $ZnSO_4$ @ 10 kg Zn ha^{-1} (2.04 mg kg^{-1}) followed by 7.5 kg Zn ha^{-1} as $ZnSO_4$ (1.79 mg kg^{-1}) and $ZnSO_4$ @ 5 kg Zn ha^{-1} (1.53 mg kg^{-1}) respectively. Soil available Zn was lowest in treatment with no Zn (1.04 mg kg^{-1}) which was statistically comparable with 0.1 kg Zn ha^{-1} as Zn citrate (1.10 mg kg^{-1}). At the same dose of 1 kg Zn ha^{-1}, Zn-EDTA (1.27 mg kg^{-1}) registered the maximal Zn content followed by Zn citrate (1.24 mg kg^{-1}) and the least being $ZnSO_4$ (1.15 mg kg^{-1}). Addition of Zn showed escalation in soil available Zn irrespective of the sources used.

At harvest stage sources and levels of Zn markedly influenced the soil available Zn at harvest stage (Table 4). The soil available Zn was significantly highest in the treatment that received $ZnSO_4$ @ 10 kg Zn ha^{-1} (1.30 mg kg^{-1}) followed by 7.5 kg Zn ha^{-1} as $ZnSO_4$ (1.24 mg kg^{-1}). Control recorded minimal soil available Zn content of 0.99 mg kg^{-1} which was on par with Zn citrate @ 0.1 kg Zn ha^{-1} (1.04 mg kg^{-1}). Zn-EDTA (1.14 mg kg^{-1}) documented the highest available soil Zn followed by Zn citrate (1.11 mg kg^{-1}) and $ZnSO_4$ (1.09 mg kg^{-1}) at equal dosage of Zn application @ 1 kg Zn ha^{-1}. $ZnSO_4$ @ 2.5 and 5 kg Zn ha^{-1} was statistically comparable with Zn-EDTA @ 0.75 and 1 kg Zn ha^{-1}. Regardless of the sources applied, there was an increment in soil available Zn with increasing Zn levels.

Zn-EDTA performed better than Zn citrate probably due to greater fixation and stability of Zn-EDTA chelates in soil than Zn citrate. Stability constants (Log K values) of Zn-EDTA and Zn citrate complexes were 17.5 and 5.0 respectively [30]. Zinc in soil as a result of application of inorganic sources such as $ZnSO_4$, due to the interaction of Zn with soil constituents leads to reduced Zn availability. To reduce Zn fixation in soil, it is recommended to be applied as organic or synthetic chelates which will enhance their availability to plants [31]. Effectiveness of chelated micronutrient compounds was already reported by Sekhon [27]. Increasing Zn levels,

Table 4. Effect of sources and levels of Zn on soil available Zn at different growth stages of onion

Treatments	Soil available Zn (mg kg^{-1})	
	Bulb initiation stage	Harvest stage
T_1 -Control (NPK)	1.04	0.99
T_2 - 1.00 kg Zn ha^{-1}as ZnSO4	1.15	1.09
T_3 - 2.50 kg Zn ha^{-1}as ZnSO4	1.28	1.12
T_4 - 5.00 kg Zn ha^{-1}as ZnSO4	1.53	1.17
T_5 - 7.50 kg Zn ha^{-1}as ZnSO4	1.79	1.24
T_6 - 10.0 kg Zn ha^{-1}as ZnSO4	2.04	1.30
T_7 - 0.10 kg Zn ha^{-1}as Zn-EDTA	1.12	1.07
T_8 - 0.25 kg Zn ha^{-1}as Zn-EDTA	1.14	1.09
T_9 - 0.50 kg Zn ha^{-1}as Zn-EDTA	1.17	1.11
T_{10} - 0.75 kg Zn ha^{-1}as Zn-EDTA	1.23	1.12
T_{11} - 1.00 kg Zn ha^{-1}as Zn-EDTA	1.27	1.14
T_{12} - 0.10 kg Zn ha^{-1}as Zn citrate	1.10	1.04
T_{13} - 0.25 kg Zn ha^{-1}as Zn citrate	1.13	1.07
T_{14} - 0.50 kg Zn ha^{-1}as Zn citrate	1.14	1.08
T_{15} - 0.75 kg Zn ha^{-1}as Zn citrate	1.19	1.10
T_{16} - 1.00 kg Zn ha^{-1}as Zn citrate	1.24	1.11
SEd	0.03	0.02
CD (P=0.05)	0.06	0.05

Table 5. Correlation between soil available Zn at bulb initiation stage and content and uptake of Zn at different stages of onion

	Zn content			Zn uptake			
	Bulb initiation stage	Harvest stage		Bulb initiation stage	Harvest stage		
	Plant Zn	Tops	Bulbs	Total	Tops	Bulbs	Total
Soil Zn-BI	0.679**	0.660**	0.685**	0.616**	0.605**	0.619**	0.614**

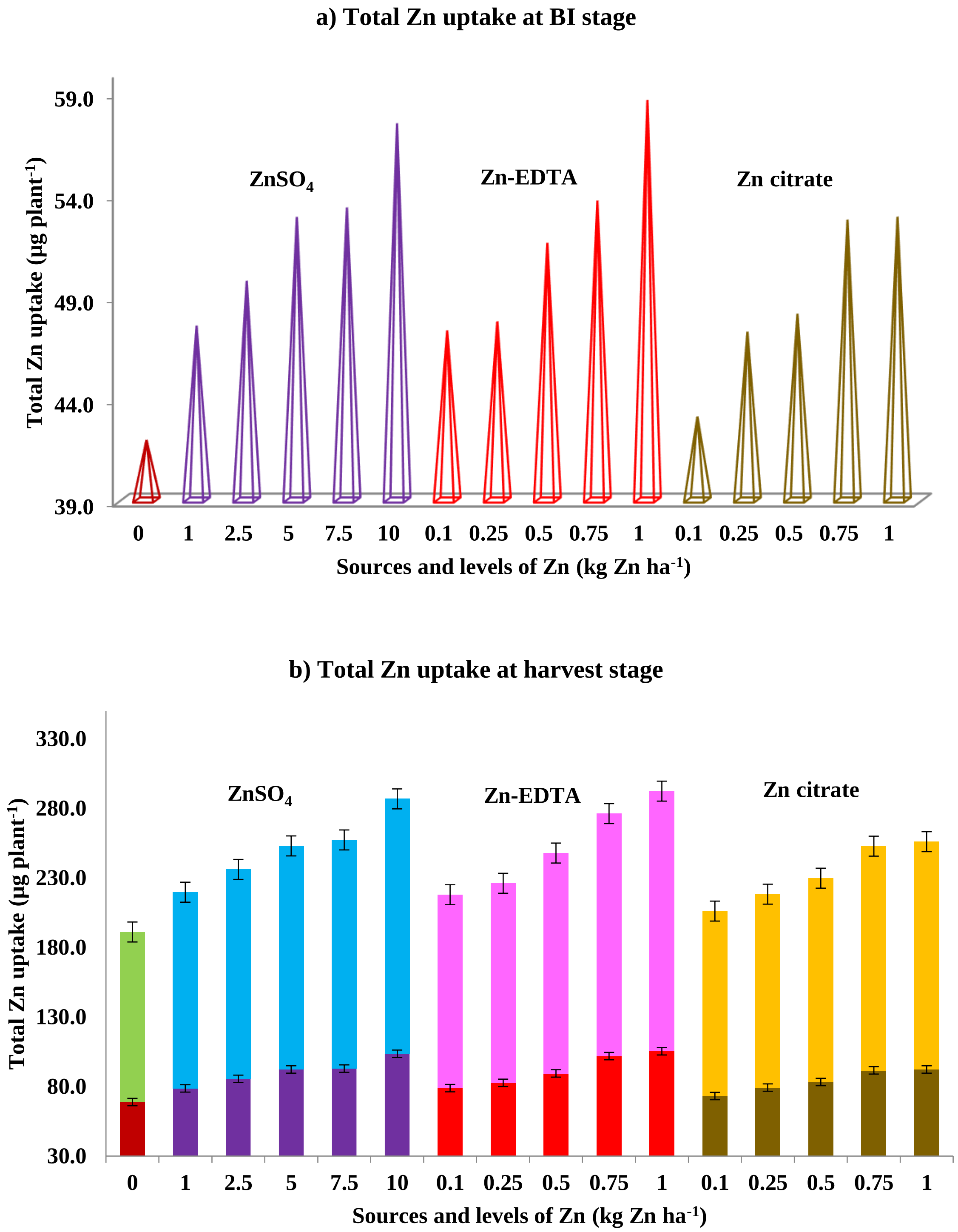

Fig. 1. Effect of different sources (a) and levels of Zn on total Zn uptake (b) at different stages of onion

enhanced soil available Zn content which is in line with the findings of Gonzalez et al. (2016). At harvest stage, $ZnSO_4$ @ 2.5 and 5 kg Zn ha^{-1} was on par with Zn-EDTA @ 0.75 and kg Zn ha^{-1} which indicates that Zn- EDTA is 3.33 to 6.66 times more effective than $ZnSO_4$ owing to the higher rate of diffusion and extractability of Zn-EDTA than $ZnSO_4$ [32]. Zn chelates were more effective in lesser doses than inorganic $ZnSO_4$ fertilizer. Similar trends were noticed by Anderson et al. [33].

4. SUMMARY AND CONCLUSIONS

The results of the pot culture experiment indicated that different sources and levels of Zn had significant influence on Zn content, uptake of onion and soil available Zn. A marked variation was noticed in Zn content of onion at bulb initiation and harvest stages. Significantly highest plant Zn at bulb initiation and harvest stages was observed with $ZnSO_4$ application 10 kg Zn ha^{-1} followed by Zn-EDTA @ 1 kg Zn $ha^{-1}$and both were comparable. Uptake of Zn by onion was significantly higher with Zn-EDTA @ 1 kg Zn ha^{-1} and it was comparable with $ZnSO_4$ @ 10 kg Zn $ha^{-1}$and Zn-EDTA @ 0.75 kg Zn ha^{-1}. Regarding the Zn content and uptake by onion at the same level of 1 kg Zn ha^{-1}, it was observed that Zn-EDTA performed better than Zn citrate and $ZnSO_4$. Zn content and uptake by onion was the lowest in no Zn application. The soil available Zn at bulb initiation and harvest stages was the highest with the application of $ZnSO_4$ @ 10 kg Zn ha^{-1} followed by $ZnSO_4$ @ 7.5 kg Zn $ha^{-1}$and $ZnSO_4$ @ 5 kg Zn ha^{-1}. With the application of same level of Zn at 1 kg Zn ha^{-1}, Zn-EDTA showed significantly higher soil available Zn which was on par with Zn citrate. No Zn application (Control) and Zn citrate @ 0.1 kg Zn ha^{-1} registered significantly lowest soil available Zn at both the stages of onion. From the results obtained, it can be inferred that Zn fertilization had a significant influence on Zn content, Zn uptake and soil available Zn by onion. The performance of 1 kg Zn ha^{-1} as Zn-EDTA and 10 kg Zn ha^{-1} as $ZnSO_4$ in improving the Zn uptake of onion was comparable. Hence, it can be concluded that application of either Zn-EDTA @ 1 kg Zn ha^{-1} or $ZnSO_4$ @ 10 kg Zn ha^{-1} can be recommended for obtaining higher growth and Zn uptake of onion.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) here by declares that NO generative AI technologies such as Large Language Models (Chat GPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

ACKNOWLEDGEMENT

We would like to thank Tamil Nadu Agricultural University, Coimbatore for funding this research.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Shiomi N, Benkeblia N and Onodera S. The metabolism of the fructooligosaccharides in onion bulbs: a comprehensive review. Journal of Applied Glycoscience. 2005;52(2):121-127.
2. Ranjan Borah S, Basumatary A, Ojha N, Saikia R, Bhattacharjya S, Jyoti Konwar M, Baruah M. Dynamics of Zinc Fractions in Soil as Affected by Zinc Fertilization in a Maize-maize Cropping Sequence in Upper Brahmaputra Valley Zone of Assam, India. International. Journal of Environment and Climate Change, 12(12):1761-70. Available:https://journalijecc.com/index.php/IJECC/article/view/1623
3. Singh SP, Dutta SK, Jha S, Prasad SS, Chaudhary SK, Sahi V, Majumdar K. Nutrient management in calcareous soil improves rice–maize sustainable yield index, performance indicators. Journal of Plant Nutrition. 2021;44:1571–1586.
4. Martínez-Ríos O, Bravo-Vinaja Á, San-MartínHernández C, Hidalgo-Moreno CI, Sánchez-de-Jesús MA, LlampallasDíaz JD, Santillan-Balderas DR, García-Preciado JC. Zinc Deficiency in Calcareous Soils: A Bibliometric Analysis from 1989 to 2024. Agriculture. 2024; (14)2285:1-19. Available:https:// doi.org/10.3390/agriculture14122285
5. Khan ST, Malik A, Alwarthan A, Shaik MR. The enormity of the zinc deficiency problem and available solutions; an overview. Arababian Journal of Chemistry. 2022;15:103668:1-31. Available:https://doi.org/10.1016/j.arabjc.2021.103668
6. Krishna TA, Maharajan T, Ceasar SA. The role of membrane transporters in the biofortification of zinc and iron in plants. Biological Trace Element Research. 2023;201:464–478.
7. Lal Regar K, Kumar V, Chandra Chandola J, Shankar Patel S, Kumar Singh A, Kundu MS, Kumar Singh S. Zinc Fertilization: Effects on Nutrients Availability and Productivity of Rice (*Oryza sativa* L.). International Journal of Plant and Soil Science. 2022;34(12):41-7.

Available:https://journalijpss.com/index.php/IJPSS/article/view/1757
8. Maurya PK. Effect of micronutrient application on growth, yield and quality of Kharif onion (*Allium cepa* L.). Dr. Rajendra Prasad Central Agricultural University, Pusa (Samastipur); 2017.
9. Tisdale SL, Nelson WL, Beaton JD, Havlin JL. Soil Fertility and Fertilizers. 5 th (ed) Macmillan Publishing Company. New York. 1995;684.
10. Nasreen S, Hossain AKM. Nutrient uptake and yield of onion as influenced by chemical fertilizer and organic manure. Indian Journal of Agricultural Research. 2004;38(3):164-170.
11. Rafique E, Mahmood-ul-Hassan M, Khokhar KM, Nabi G and Tabassam T. Zinc nutrition of onion: proposed diagnostic criteria. Journal of Plant Nutrition. 2008;31 (2):307-316.
12. Thangasamy A. 4R Nutrient Management for Onion in India; 2016.
13. Sarker MMH, Moslehuddin AZM, Jahiruddin M, Islam MR. Effects of micronutrient application on different attributes of potato in floodplain soils of Bangladesh. SAARC Journal of Agriculture. 2018;16(2):97-108.
14. Piper CS. Soil and plant analysis: Hans Publishers; Bombay. 1966;368.
15. Jackson ML. Methods of chemical analysis. Prentic Hall., EngleWood Cliffs, NTJ. 1973.Pp 521
16. Piper CS. Soil and Plant Analysis 1944. Soil and Plant Analysis. 1931;294.
17. Walkley A, Black AI. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science. 1934; 37(1):29-38.
18. Subbiah BV, Asija GL. A rapid method for the estimation of nitrogen in soil. Current Science. 1956;26:259-260.
19. Olsen SR. Estimation of available phosphorus in soils by extraction with sodium bicarbonate: Cicular No. 939, United States Department of Agriculture, Washington. 1954;1-22
20. Stanford G, English L. Use of the flame photometer in rapid soil tests for K and Ca. Agronomy Journal. 1949;41(9):446-447.
21. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Science Society of America Journal. 1978;42(3):421-428.
22. Panse VG, Sukhatme PV, Shaw FJF. Statistical Methods for Agricultural Workers: By VG Panse and PV Sukhatme: Indian Council of Agricultural Research. 1967;381.
23. Meena OS, Singh D. Effect of sulphur and zinc application on onion yield and sulphur and zinc uptake in three soil orders. Journal of the Indian Society of Soil Science (India). 1998;46(4): 636-640.
24. Singh VB, Maiti CS, Trudy A. Sangma, Kanaujia SP, Singh, PK. Effect of zinc and boron on growth, yield and quality of onion (*Allium cepa* L.) cv. Agrifound dark red. Progressive Horticulture. 2017;49(2):138-145.
25. Fouda KF. Response of Onion Yield and Its Chemical Content to NPK Fertilization and Foliar Application of Some Micronutrients. Egyptian Journal of Soil Science. 2016;7(1-12).
26. Karak, Tanmoy, Uttam Kumar Singh, Sampa Das, Dilip Kumar Das, and Yakov Kuzyakov. Comparative efficacy of ZnSO4 and Zn-EDTA application for fertilization of rice (*Oryza sativa* L.). Archives of Agronomy and Soil Science. 2005;51(3): 253-264.
27. Sekhon BS. Chelates for micronutrient nutrition among crops. Resonance. 2003;8 (7):46-53.
28. El-Gamili AE, Hanna, AB and El-Hadi, AHA. The effect of some foliar fertilizers application on growth, bulb yield, quality and storageability of Giza 20 onion cultivar (*Allium cepa* L.). Annals of Agricultural Science, Moshtohor. 2000;38(3):1727-1737.
29. Assefa, Abraha Gebrekiros, Solomon Habtu Mesgina, and Yirga Weldu Abrha. Response of onion (*Allium cepa* L.) growth and yield to different combinations of N, P, S, Zn fertilizers and compost in northern Ethiopia. 2015;4(2):985-989.
30. Smith RM, Martell AE. Critical stability constants. Springer. 1976;4:257.
31. Udeigwe, Theophilus K, Madeleine Eichmann, and Matthew C Menkiti. Fixation kinetics of chelated and non-chelated zinc in semi-arid alkaline soils: application to zinc management. Solid Earth. 2016;7(4):1023-1031.
32. Modaihsh AS. Zinc diffusion and extractability as affected by zinc carrier and soil chemical properties. Fertilizer research. 1990;25(2):85-91.

33. Anderson, Sarah, Jeff Schoenau, and Albert Vandenberg. Effects of zinc fertilizer amendments on yield and grain zinc concentration under controlled environment conditions. Journal of Plant Nutrition. 2018;41(14):1842-1850.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/128559