The Journal of Agricultural Science

cambridge.org/ags

Crops and Soils Review

Cite this article: Kandil EE, Lamlom SF, Gheith E-SMS, Javed T, Ghareeb RY, Abdelsalam NR, Hussain S (2023). Biofortification of maize growth, productivity and quality using nano-silver, silicon and zinc particles with different irrigation intervals. *The Journal of Agricultural Science* **161**, 339–355. https://doi.org/10.1017/S0021859623000345

Received: 17 November 2022
Revised: 25 April 2023
Accepted: 30 April 2023
First published online: 29 June 2023

Keywords:
drought; Egypt; harvest index; irrigation; nanoparticles; proline; *Zea mays* L

Corresponding author:
Sadam Hussain;
Email: Ch.sadam423@gmail.com

Biofortification of maize growth, productivity and quality using nano-silver, silicon and zinc particles with different irrigation intervals

Essam E. Kandil[1], Sobhi F. Lamlom[1], El-Sayed M.S. Gheith[2], Talha Javed[3], Rehab Y. Ghareeb[4], Nader R. Abdelsalam[5] and Sadam Hussain[6]

[1]Department of Plant Production, Faculty of Agriculture (Saba Basha), Alexandria University, 21531 Alexandria, Egypt; [2]Agronomy Department, Faculty of Agriculture, Cairo University, Egypt; [3]College of Agriculture, Fujian Agriculture and Forestry University, Fuzhou 350002, China; [4]Plant Protection and Biomolecular Diagnosis Department, Arid Lands Cultivation Research Institute, The City of Scientific Research and Technological Applications, New Borg El Arab, Alexandria 21934, Egypt; [5]Agricultural Botany Department, Faculty of Agriculture (Saba Basha), Alexandria University, Alexandria 21531, Egypt and [6]College of Agronomy, Northwest A&F University, Yangling, China

Abstract

The current study aimed to investigate biofortification of maize grown under different irrigation intervals, i.e. 15, 20 and 25 days (hereinafter referred to as IR15, IR20 and IR25, respectively), using foliar application treatments (silicon (Si), zinc (Zn), silver nanoparticles (AgNPs), Si + Zn, Si + AgNPs, Zn + AgNPs and Si + Zn + AgNPs) in two growing seasons, 2020 and 2021. A split-plot design with four replications was used, where irrigation intervals and foliar treatments were assigned in main plots and subplots, respectively. IR15 received a total of 7925 m^3/ha irrigation water divided over seven irrigations, while IR20 received 5690 m^3/ha divided over five irrigations and IR25 received 4564 m^3/ha divided over four irrigations. The highest yield and grain quality were observed in plants irrigated at 15-day intervals. Spraying the canopy with Si, Zn and AgNPs, either individually or in combination, reduced the negative impact of water stress caused by longer irrigation intervals on plant growth, yield, yield components and grain protein content. In IR15 + AgNPs + Zn, most of the studied parameters, except for proline content, showed a high positive impact, especially on 100-kernel weight (KW). In contrast, IR25 + Si + AgNPs + Zn showed the highest positive effects on proline and protein contents but a negative impact on the harvest index. Collectively, IR15 + Si + AgNPs + Zn resulted in the highest values of all studied parameters, followed by IR15 + Si + AgNPs and IR15 + Si + Zn. In conclusion, our results suggest that an irrigation interval of 15 days combined with application of Si, Zn and AgNPs has the potential to improve yield and quality of maize under water deficit stress.

Introduction

Egypt's agriculture, like that of the rest of the world, confronts several issues, including water shortage and climate change (Sowers *et al.*, 2011; Abdelghany *et al.*, 2021; Abd-Elaty *et al.*, 2022). One of the difficulties is to increase agricultural production to feed the world's population of 9.8 billion by 2050 (Gennari *et al.*, 2019; Elmardy *et al.*, 2021). Maize (*Zea mays* L.) is one of the world's most significant strategic and economic crops (Kandil *et al.*, 2020; Gomaa *et al.*, 2021; Guo *et al.*, 2022; Siddique *et al.*, 2022) followed by wheat and rice. It is regarded as the third most important crop in terms of economic value. Maize is a cereal crop that belongs to the Poaceae family and is one of the most productive and economically important crops (El-Sorady *et al.*, 2022; Yousaf *et al.*, 2022).

The irrigation duration and cultivation method affect the distribution of water in the soil, and the water distribution in the soil affects the growth and distribution of the root system in its size, which then affects the growth of above and below-soil plants' parts (Hussain *et al.*, 2021; Neupane *et al.*, 2022). Silicon application has been reported to improve the agro-morphological and physiological characteristics of maize plants, including growth parameters like plant height, stem diameter and the number of leaves (Amin *et al.*, 2018; Galindo *et al.*, 2021). It also increased yield-related parameters such as cob length, number of grains per cob, 100-grain weight, grain yield and total yield in hybrid P-33H25 and FH-810 plants experiencing drought stress. Moreover, Si treatment boosted photosynthetic rate and reduced transpiration rate under drought conditions (Abdelsalam *et al.*, 2018; Amin *et al.*, 2018; Youssef *et al.*, 2021). Drought stress in the root zone is one of the most detrimental stressors for plant growth, development and productivity (Gomaa *et al.*, 2021, 2021; Sanjari *et al.*, 2021; Zhao *et al.*, 2021; Ahmad *et al.*, 2022). The exogenous application of inorganic fertilizers is a potential strategy to counteract the adverse impact of drought on plant growth and development (Ashraf and Foolad, 2007; Hassan *et al.*, 2022; Nasar *et al.*, 2022; Sattar *et al.*, 2022).

For a sandy soil, irrigation intervals for a long period of about 15 days recorded the greatest maize yield, its components and water saved (Ahmed *et al.*, 2020). One way to enhance the efficiency of water use in maize farming is by irrigating the crops every 14 days without causing any reduction in maize production (Abbasi *et al.*, 2022; Abdelghany *et al.*, 2022; Ma *et al.*, 2022). It has been well established that regulating irrigation with varying irrigation intervals and fertilizer levels has had a significant impact on crop performance (Muhammad *et al.*, 2022). Although Si is not generally included in the list of essential elements, it is considered one of the important beneficial nutrients for plant growth and physiochemical process (Laing *et al.*, 2006; Kandil *et al.*, 2020; Abdelsalam *et al.*, 2022b). Despite its deposition on cell walls, its active involvement in a multitude of physiological and metabolic processes is also evident (Moussa, 2006). In general, crops belonging to the family Poaceae accumulate much more Si than that other species belonging to other families (Abbasi *et al.*, 2022). Exogenous application of Si has also been reported to improve crop performance even under stressful conditions (Kojić *et al.*, 2012). Tuna *et al.* (2008) studied the supplements of Si to plants subjected to salt-affected soils and reported beneficial improvement in crop tolerance to stress conditions.

Zinc is an important micronutrient because it plays a key role in photosynthesis-related enzymatic processes (Bashir *et al.*, 2019; Hassan *et al.*, 2021; Hassain *et al.*, 2021; Zafar *et al.*, 2023). It is a cofactor and structural component of a variety of enzymes involved in a wide variety of metabolic processes. Also, it is involved in photosynthesis, glucose metabolism, protein metabolism, pollen generation, auxin metabolism, membrane integrity maintenance and stress tolerance induction in plants (Alloway, 2008; Jan *et al.*, 2023). Furthermore, it also has been reported to boost germination rates, product quality and crop productivity (Kausar *et al.*, 2023). Its involvement in the acceleration of catalytic actions to enhance growth and development throughout critical periods of development is also well reported (Naeem, 2015).

Plant growth, developmental processes and productivity can benefit from Zn treatment. It helps in the control of pests including plant insects and diseases, the restriction of pollutant absorption and the tolerance of environmental stress (Rehman *et al.*, 2018). It is also required for the regulation of gene expression required for plant biotic as well as abiotic stress tolerance. Zinc supplementation helps to increase the transpiration rate; a shortage would lower a leaf's transpiration efficiency (Sarwar *et al.*, 2017).

Furthermore, Zn supplementation is important for increasing the efficiency of water utilization. It was shown that adequate nutritional practices resulted in a 20–25% increase in water use efficiency (Waraich *et al.*, 2011; Iqbal *et al.*, 2022; Mustafa *et al.*, 2022). Zinc's action is crucial for enhanced seed yield and quality (Estrada-Urbina *et al.*, 2018). Zinc application has a greater impact on chlorophyll formation and carbonic anhydrase activity, which helps the transfer of CO_2 from the liquid phase of a cell into the chloroplast, hence enhancing the photosynthetic rate (Hernández *et al.*, 2020).

Nanoparticles have unique features that distinguish them from their bulk counterparts, such as higher solubility, surface area and reactivity, making them potentially useful in mitigating the negative impacts of abiotic and biotic stresses on crop production (Javed *et al.*, 2022). They can improve crop stress tolerance by addressing nutritional deficits, increasing enzyme activities and promoting the adherence of plant growth-promoting bacteria under abiotic stresses. This has led to a new era of using nanoparticles to enhance agricultural production, but their potential harmful effects on the environment and vegetation should not be ignored (Iqbal *et al.*, 2020; Abdelghany *et al.*, 2022). Silver nanoparticles (AgNPs) have a lot of potential in agriculture, especially when it comes to increasing the pace and development of diploid and triploid seeds (Khafaga *et al.*, 2022; Sabra *et al.*, 2022; Abdelsalam *et al.*, 2022a). Capping phytochemicals in green nanoparticle manufacturing has a positive impact on agriculture. They can improve plant growth, crop production and seed germination without affecting the plant's intrinsic characteristics (Acharya *et al.*, 2020). Nanoparticles are being used in plants to promote their development, which is a new strategy in agriculture. It is, without a doubt, an innovative and promising technique for safeguarding the plant while it is under stress (Gohari *et al.*, 2020). AgNPs improved the growth characteristics of the fenugreek plant (e.g., shoot length, number of leaves/plant and dry weights) and increased photosynthetic pigment (i.e., chlorophyll and carotenoid contents) and indole acetic acid contents, which in turn resulted in increased yield and quality (Sadak, 2019). The hypothesis of this work was whether the improved water stress resistance by Si, Zn and AgNPs and their combination are mediated via the enhanced photosynthetic rate and lowered transpiration in drought stressed maize crop. The aim of this study was to investigate the effect of foliar application of Si, Zn and AgNPs on yield and quality traits and their ability to counter water deficiency effects on maize.

Materials and methods

Experimental setup

Two field experiments were conducted at El-Horreya village, Abou El-Matamir, El-Behira governorate, Egypt, during the 2020 and 2021 growing seasons to study the role of Si, Zn and AgNPs to promote biofortification of maize growth, yield, yield components and quality under different irrigation intervals and amount (Table 1). The preceding crop was Egyptian clover (Berseem) in both seasons. The climate of the study site is characterized by a hot summer and mild winters (Fig. 1). Some physical and chemical soil properties of the surface layer (0–60 cm) of the experimental site were determined before sowing according to the method described by Chapman and Pratt (1962), and illustrated in Table 2.

Yellow maize hybrid (single cross Pioneer 3444/SC P3444) was obtained from Pioneer Seed Co. and sown on 15th of May in 2020 and 2021 seasons. The field plants were hand thinned at 21 days from sowing to maintain one plant/hill. The field was sprayed with two herbicides (Harness 84% EC at 2.5 litres/ha and Gesaprim 80% WP at 1.8 kg/ha) after sowing, then irrigated on the same day. Other agricultural practices were carried out as recommended by the Ministry of Agriculture and Land Reclamation, Egypt.

The furrow irrigation requirements in the two seasons are presented in Table 1. The average values of seasonal applied water (m^3/ha) of maize plants were 7925 m^3/ha (at 15 days irrigation interval) which represents the total amount applied over seven irrigations with variable amounts. The irrigation with 20-day interval received a total amount of 5690 m^3/ha irrigation water divided over five irrigations with variable amounts while the irrigation interval of 25 days received a total amount of 4564 m^3/ha

https://doi.org/10.1017/S0021859623000345 Published online by Cambridge University Press

Table 1. Irrigation water applied at different growth stages (days after sowing) under different irrigation treatments during two seasons 2020 and 2021

Irrigations	Growth stage	Irrigation					
		15 days	Applied water (m^3/ha)	20 days	Applied water (m^3/ha)	25 days	Applied water (m^3/ha)
1st irrigation	VE-V5	21 DAS	796.5	21 DAS	796.5	21 DAS	796.5
2nd irrigation	V6-V11	36 DAS	975	41 DAS	975	46 DAS	975
3rd irrigation	V12-VT	51 DAS	1489	61 DAS	1489	71 DAS	1489
4th irrigation	R1-2	66 DAS	1304	81 DAS	1304	96 DAS	1304
5th irrigation	R3-R4	81 DAS	1126	101 DAS	1126	–	
6th irrigation	R5	96 DAS	1191	–		–	
7th irrigation	RM	111 DAS	1044	–		–	
Total		7	7925	5	5690	4	4564

DAS, days after sowing; VE, emergence stage; Vn, vegetative stages; VT, tasseling stage; R1, silking stage; R2, blister stage; R3, milking stage; R4, dough stage; R5 dent stage; RM, maturity stage.

irrigation water divided over four irrigations with variable amounts. The first irrigation amount was the same (796.5 m^3/ha) for all irrigation intervals and applied on day 21 after sowing. Thereafter, irrigation numbers 2, 3, 4, etc., were applied on different days but with the same amount of irrigation water.

The amount of actual irrigation water applied under each irrigation treatment was determined using the following equation:

$$\mathrm{I.Ra} = \frac{\mathrm{ETc} + \mathrm{Lf}}{\mathrm{Er}} \quad (1)$$

where I.Ra is the total actual irrigation water applied (mm/interval); ETc is the crop evapotranspiration estimated from the Penman–Monteith equation using CROPWAT model 8.0; Lf is the leaching factor (10%) and Er is the irrigation system efficiency.

Experimental design

A split plot design with three replications was used in this experiment. The three irrigation intervals of 15, 20 and 25 days were allocated to the main plots and foliar treatments of (i) water spray (control), (ii) Si (at 150 mg/l by using potassium silicate (K_2O_3Si; MW = 154.3 g/M; pH = 12.7)), (iii) Zn (at 5 g/l from zinc sulphate heptahydrate ($ZnSO_4{\cdot}7H_2O$; MW = 287.5 g/M)), (iv) AgNPs (at 50 mg/l), (v) Si + AgNPs, (vi) Si + Zn, (vii) Zn + AgNPs and (viii) Si + Zn + AgNPs, applied four times at 30 DAS (vegetative stage), 50 DAS (tasseling stage), 70 DAS (silking stage) and 90 DAS (milking stage). Each subplot consisted of six ridges of 3.50 m in length and 70 cm in width and the plot area was 14.7 m^2.

The application of three types of fertilizer and their interaction was carried out in a liquid form using a backpack sprayer (foliar application) on maize plants. This was done four times, with foliar spraying done at sunset to avoid damage from strong sunlight and high temperatures. The spraying application was done at the rate of 750 litres/hectare where each plot received 1.2 litres/spraying time. The study consisted 63 plots, consisting of nine control plots and nine plots each for Zn (270 g/plot/season), silicon (8 g/plot/season), AgNPs (2.7 g/plot/season), Si (8 g/plot/season) + Zn (270 g/plot/season), Zn (270 g/plot/season) + AgNPs (2.7 g/plot/season) and Si (8 g/plot/season) + Zn (270 g/plot/season) + AgNPs (2.7 g/plot/season).

Application of fertilizers

Potassium sulphate (K_2SO_4) was applied at the rate of 120 kg/ha during both seasons. Phosphorus fertilizer at the rate of 60 kg P_2O_5/ha was applied before planting in the form of calcium superphosphate (15.5% P_2O_5). Ammonium nitrate (33.5% N) at the rate of 288 kg/ha was used as the N source and applied in two equal doses, the first dose was applied at sowing and the second one was added at 21 DAS during both cropping seasons.

Data collection

Growth parameters

At harvest, five random plants from each experimental plot were harvested to measure plant height. Measurement was taken from the soil surface to the top of the plant. Leaf area index (LAI), the ratio of leaf area to the ground area occupied by the crop plants, was calculated at 90 DAS according to Radford (1967) as follows:

$$\mathrm{LAI} = \frac{\text{Leaf area/plant}}{\text{plant ground area}}$$

where leaf area = K ($L \times W$), where K is the constant value (0.75), L is the maximum leaf length (cm) and W is the maximum leaf width (cm).

The crop growth rate was calculated using dry weight of the two periods (60–75 and 75–90 DAS) according to the formula suggested by Radford (1967).

$$\mathrm{CGR}\ (\mathrm{g/m^2/day}) = \frac{W2 - W1}{T2 - T1}$$

where $W1$ and $W2$ are plant dry weights at $T1$ and $T2$ corresponding days.

Total chlorophyll index was calculated using a SPAD meter (SPAD 502 Meter) based on ten random leaves taken from each subplot at 90 DAS, following the method described by Minolta (1989).

Yield and yield characteristics

Yield and its components were determined at 120 DAS. Ten plants from each subplot were harvested to measure the ear height, ear length, the number of rows/ears and the number of

https://doi.org/10.1017/S0021859623000345 Published online by Cambridge University Press

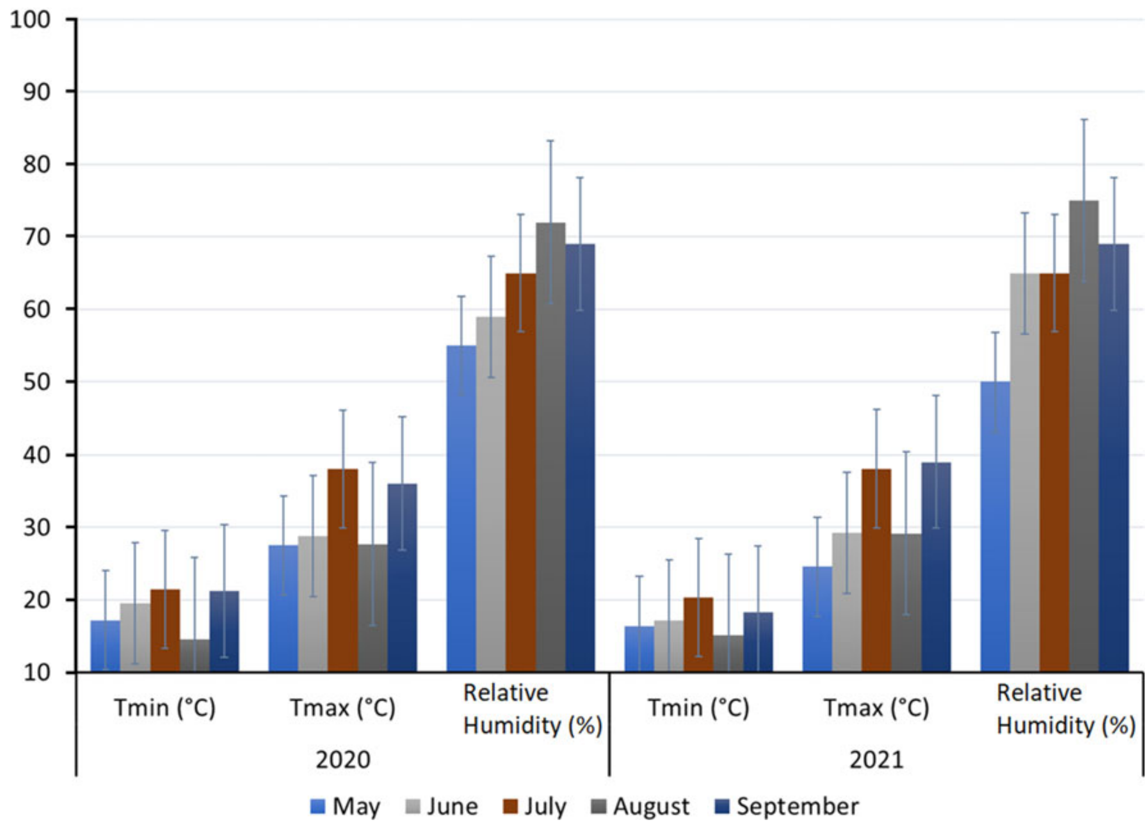

Figure 1. Weather conditions (minimum temperature (Tmin), maximum temperature (Tmax), relative humidity (%) and rainfall) during the two growing seasons of maize cultivation. Error bars refer to the standard deviation.
Note: no rainfall was received during these months.

grains/rows. One hundred-grain weight was obtained from three samples of each subplot. The total yield was calculated as the weight of grains and straw in each subplot. The grain yield was determined from all plants in each subplot. The straw yield (SY) was recorded according to the following formula:

$$\text{Straw yield (t/ha)} = \text{Final grain yield} + \text{straw yield} - \text{grain yield}.$$

The harvest index was calculated according to the following formula:

$$\text{Harvest index} = \frac{\text{Grain yield (t/ha)}}{\text{Straw} + \text{grain yield (t/ha)}}$$

Chemical analyses

At harvest, the chemical constituents of leaves/grains were determined as follows:

Crude grain protein content was calculated using the following formula of Salo-väänänen and Koivistoinen (1996) as:

$$\text{Crude protein (\%)} = \text{Nitrogen} \times 6.25$$

Nitrogen content in maize grain was determined by the Micro-Kjeldhal method as described by Helrich (1990).

Leaf proline content: Three fresh leaf samples were taken at 90 DAS between 11:00 and 14:00 h. Firstly, leaf disks were taken from two plants in each plot. The leaf disks were immersed immediately in a cooled proline extraction solution (3% aqueous sulfosalicylic acid solution). Next, the samples were kept refrigerated prior to extraction and determination of leaf proline content, following the method of Bates *et al.* (1973). The proline content was determined spectrophotometrically.

Statistical analysis

All collected data were subjected to analysis of variance (ANOVA) according to the method of Gomez and Gomez (1984), using the CoStat computer software package (CoStat, 2005). The least significant difference (LSD at 5% probability) was used to compare the treatment means.

Results

There was a significant ($P < 0.05$) effect of the studied factors, i.e. irrigation intervals, foliar application treatments and their interaction on plant height, LAI, chlorophyll contents (SPAD value), ear height, leaf proline content, ear length, the number of grains/row, number of grains/ear, 100-grain weight, grain yield, SY, total yield, harvest index and grain protein content of maize cv. SC P3444 during both study years (Tables 3–6).

Concerning the significant effect of irrigation intervals on the studied parameters, the data revealed that an irrigation interval of 15 days with the highest amount of irrigation water applied recorded the highest mean values of growth, yield and yield components. Irrigation interval of 15 days increased plant height by

Table 2. Soil physical and chemical properties of the experimental sites in 2020 and 2021 seasons

	Seasons	
Soil properties	2020	2021
(A) Mechanical analyses		
Clay (%)	28.9	30.5
Sand (%)	60.0	59.0
Silt (%)	11.1	10.5
Soil texture	Sandy loam soil	
(B) Chemical properties		
pH (1:1)	8.00	8.01
E.C. (dS/m) (1:2)	3.00	2.90
(1) Soluble cations (1:2) (mg/l)		
K^+	0.52	0.65
Ca^{++}	8.40	9.11
Mg^{++}	12.0	12.2
Na^+	11.5	10.5
(2) Soluble anions (1:2) (mg/l)		
$CO_3^{--} + HCO_3^-$	2.90	2.80
Cl^-	18.0	17.9
SO_4^-	11.5	11.7
Calcium carbonate (%)	6.60	6.40
Total nitrogen (%)	1.00	0.91
Available phosphate (mg/kg)	1.70	1.55
Available zinc (mg/kg)	0.55	0.60
Organic matter (%)	1.41	1.40

EC (dS/m) (1:2), electrical conductivity. The (1:2) ratio refers to the soil-to-water ratio.

5.23 and 6.53%, LAI by 30.7 and 24.1%, chlorophyll content by 21.4 and 26.1%, ear height by 9.58 and 10.3%, ear length by 13.8 and 14.4%, number of grains/row by 4.90 and 5.24%, number of grains/ear by 8.93 and 11.0%, 100-grain weight by 4.83 and 5.19%, grain yield by 16.5 and 21.1%, SY by 13.9 and 16.4% and total yield by 15.5 and 18.5% in 2020 and 2021, respectively, compared with irrigation interval of 25 days which depicted minimum values of these traits while consumed lowest amount of irrigation water. This was followed by an irrigation interval of 20 days, which received less amount of irrigation amount than the 15 days intervals but more than the 20 days interval (Tables 3–6).

Regarding the significant effect of foliar spraying treatments on the studied parameters, the recorded data showed that the highest mean values of growth, yield and yield components such as plant height, LAI, ear height, leaf proline content and ear length during both years were recorded with foliar application of Si + Zn + AgNPs. Nonetheless, Zn + AgNPs depicted significantly the highest values of chlorophyll content during both study years (Tables 3 and 4).

The highest values for the number of grains/row, number of grains/ear, 100-grain weight (Table 5), grain yield, SY, total yield, harvest index and grain protein content during both study years were recorded for Zn + AgNPs treatment followed by Si + Zn + AgNPs treatment. Meanwhile, the lowest values for the growth, yield and its components and protein content were obtained with the control treatment in which no Si, Zn and AgNPs were applied.

The highest values of harvest index (47.8 and 47.4% in 2020 and 2021, respectively) were obtained with an irrigation interval of 20 days together with Si + Zn + AgNPs treatment (Table 7). In addition, irrigation of 15 days together with Si + Zn + AgNPs treatment recorded the highest grain protein content (9.47 and 9.67%, in the first and second season, respectively) followed by Zn + AgNPs treatment which had no significant difference with Si + Zn + AgNPs in most of the studied parameters. Meanwhile, the lowest values for harvest index and protein content were obtained with irrigation of 25 days which received the lowest amount of irrigation water in both seasons. Moreover, there was no significant difference between irrigation of 15 and 20 days and foliar spray of Si + Zn + AgNPs for most of the studied parameters during both seasons.

The analysis of variance over the two growing seasons

ANOVA for the combined effect of irrigation intervals/amount and foliar spraying treatments is shown in Tables 8 and 9. The results showed that the interaction of irrigation intervals/amount and foliar spraying treatments significantly ($P \leq 0.001$) affected the plant height, LAI, chlorophyll content, 100-grain weight, ear height, proline content, number of grains per row, ear length, number of grains per ear, total yield, grain yield and SY during both seasons. The application of Si + Zn + AgNPs combined with 15-day irrigation interval treatment which has the highest amount of irrigation water recorded the highest value for plant height (202.7 cm), LAI (7.83 cm), number of grains per row (47.8), 100-grain weight (46.9 g), ear length (27.5 cm), number of grains per ear (733.1), total yield (18.1 t/ha), grain yield (8.63 t/ha) and SY (9.95 t/ha).

The AgNPs foliar application associated with 15-day irrigation interval treatment recorded the highest values for chlorophyll content (55.7), ear height (89.5 cm) and 100-grain weight (46.9 g). The results also showed that there was a non-significant difference between Si + Zn + AgNPs and Zn + AgNPs foliar application treatments for most of the measured parameters. The 25-day irrigation interval (received the lowest irrigation amount) together with AgNPs, Si + AgNPs, Si + Zn, Zn + AgNPs, Si + Zn + AgNPs foliar application treatments produced the highest values for proline content.

Correlations among crop parameters under the interaction of irrigation intervals and nano-foliar spraying treatments

An analysis of the interactions between irrigation and foliar spraying treatments was carried out using Pearson's correlation coefficients as well as a clustered map visualization (Figs 2 and 3). The correlation coefficients showed that there was a strong positive link among grain yield and total yield ($r = 0.99$), 100-grain weight ($r = 0.81$), plant height ($r = 0.70$), harvest index ($r = 0.68$), ear height ($r = 0.84$), LAI ($r = 0.84$) and protein content ($r = 0.70$) (Fig. 1). Crude protein was significantly and highly positively correlated with different measured parameters including total yield ($r = 0.69$), SY ($r = 0.66$) and ear length ($r = 0.72$) (Fig. 2). Negative correlations were detected between proline content and all measured parameters except protein content (Fig. 2).

The correlation coefficients also indicated that there was a highly and significant correlation among various parameters.

https://doi.org/10.1017/S0021859623000345 Published online by Cambridge University Press

Table 3. Plant height, leaf area index and chlorophyll content of maize (*Zea mays* L. cv. SC P3444) as affected by irrigation intervals, foliar application of silicon (Si), zinc (Zn) and silver nanoparticles (AgNPs), and their interaction in both seasons 2020 and 2021

		Plant height (cm)				Leaf area index				Chlorophyll index (SPAD)			
		Irrigation interval (days) (B)				Irrigation interval (days) (B)				Irrigation interval (days) (B)			
Season	Treatments (A)	15	20	25	Mean (A)	15	20	25	Mean (A)	15	20	25	Mean (A)
2020	CK	175.3	180.0	175.0	176.8 d	3.71	3.52	2.99	3.41 e	35.2	34.0	30.5	33.3 e
	Si	188.0	181.7	174.3	181.3 c	4.26	3.43	3.18	3.62 d	47.4	43.7	37.7	43.0 d
	Zn	192.3	178.3	177.9	182.9 c	4.51	3.73	3.19	3.81 cd	56.8	38.6	41.0	45.5 c
	AgNPs	196.0	182.0	183.3	187.1 b	4.68	3.83	3.61	4.04 bc	57.1	44.7	44.0	48.6 b
	Si + AgNPs	196.0	188.3	182.2	188.9 b	3.78	4.24	3.53	3.85 bc	49.8	48.0	43.8	47.2 bc
	Si + Zn	192.8	190.1	186.8	189.9 b	4.24	4.16	3.64	4.01 bc	53.7	47.1	43.3	48.1 bc
	Zn + AgNPs	196.0	186.8	189.1	190.6 b	4.29	4.25	3.69	4.08 b	54.3	53.2	47.9	51.8 a
	Si + Zn + AgNPs	202.2	190.0	193.2	195.2 a	4.63	4.58	3.87	4.36 a	54.5	52.6	48.3	51.8 a
	Mean (B)	192.3 a	184.7 b	182.7 c		4.26 a	3.97 b	3.46 c		51.1 a	45.2 b	42.1 c	
	$LSD_{0.05}$ (A)	3.86				0.21				2.58			
	$LSD_{0.05}$ (B)	1.52				0.17				2.84			
	$LSD_{0.05}$ (A×B)	6.68				0.37				4.46			
2021	CK	182.0	181.0	176.3	179.8 d	3.67	3.63	2.96	3.42 d	37.3	36.7	29.2	34.4 f
	Si	189.3	189.3	174.7	184.4 c	4.10	3.30	3.44	3.61 cd	47.0	44.5	35.3	42.3 e
	Zn	189.7	175.0	175.7	180.1 d	4.55	3.20	3.41	3.72 c	56.0	40.7	37.9	44.9 d
	AgNPs	194.7	183.3	185.6	187.9 b	4.99	3.77	3.53	4.10 b	54.3	44.8	41.8	47.0 cd
	Si + AgNPs	196.7	193.9	183.3	191.3 ab	4.24	4.24	3.50	3.99 b	52.3	50.1	42.5	48.3 bc
	Si + Zn	198.1	193.2	183.3	191.6 a	4.59	4.35	3.72	4.22 c	56.6	50.0	44.3	50.3 ab
	Zn + AgNPs	197.9	185.3	188.0	190.4 ab	4.55	4.18	3.95	4.23 b	57.4	51.3	48.2	52.3 a
	Si + Zn + AgNPs	203.3	187.0	189.7	193.3 a	4.77	4.59	4.08	4.48 a	55.4	55.3	47.2	52.6 a
	Mean (B)	194.0 a	186.0 b	182.1 b		4.43 a	3.91 b	3.57 c		51.5 a	46.7 b	40.8 c	
	$LSD_{0.05}$ (A)	3.36				0.22				2.38			
	$LSD_{0.05}$ (B)	5.02				0.18				1.95			
	$LSD_{0.05}$ (A×B)	5.82				0.38				4.12			
Years (p value)		0.02				0.05				0.39			

CK, control treatment. Means in the same column (s)/row(s) followed by the same letters are not significantly different at 5% probability level.

Table 4. Ear length, ear height and leaf proline content of maize (*Zea mays* L. cv. SC P3444) as affected by irrigation intervals, foliar application of silicon (Si), zinc (Zn) and silver nanoparticles (AgNPs), and their interaction in both seasons, i.e. 2020 and 2021

		Ear height (cm)				Leaf proline content (%)				Ear length (cm)			
		Irrigation interval (days) (B)				Irrigation interval (days) (B)				Irrigation interval (days) (B)			
Season	Treatments (A)	15	20	25	Mean (A)	15	20	25	Mean (A)	15	20	25	Mean (A)
2020	CK	73.0	73.3	71.0	72.4 e	4.30	5.61	6.91	5.61 b	18.8	16.3	17.8	17.7 e
	Si	85.0	76.7	68.0	76.6 d	4.12	5.45	5.65	5.07 c	19.2	18.1	18.6	18.6 e
	Zn	85.7	77.0	73.3	78.7 cd	4.24	5.58	6.69	5.50 b	20.3	18.0	17.3	18.5 e
	AgNPs	88.7	84.3	76.7	83.2 ab	4.33	5.52	6.77	5.54 b	23.3	18.2	18.0	19.8 d
	Si + AgNPs	83.7	76.0	78.0	79.2 c	4.35	5.43	7.04	5.61 b	19.6	20.5	19.7	19.9 d
	Si + Zn	84.3	81.0	81.3	82.2 b	5.09	5.86	6.39	5.78 ab	23.0	21.5	21.0	21.8 c
	Zn + AgNPs	88.0	81.3	84.0	84.4 ab	5.53	5.41	6.83	5.92 a	25.0	23.5	20.3	22.9 b
	Si + Zn + AgNPs	86.0	85.7	83.0	84.9 a	5.51	5.63	6.98	6.04 a	26.7	25.2	21.8	24.6 a
	Mean (B)	84.3 a	79.4 b	76.9 c		4.68 c	5.56 b	6.66 a		22.0 a	20.2 b	19.33 b	
	$LSD_{0.05}$ (A)	2.45				0.29				1.11			
	$LSD_{0.05}$ (B)	1.98				0.08				0.91			
	$LSD_{0.05}$ (A×B)	4.25				0.51				1.92			
2021	CK	73.7	75.0	73.0	73.9 f	4.95	5.63	6.63	5.70 abc	20.0	16.9	18.4	18.5 d
	Si	85.7	74.2	68.7	76.1 f	4.86	5.58	6.00	5.50 c	20.3	18.5	18.8	19.2 d
	Zn	85.7	76.0	74.3	78.7 e	4.89	5.93	6.41	5.70 abc	21.8	18.2	18.6	19.5 d
	AgNPs	90.3	85.5	75.2	83.7 bc	4.98	5.87	6.49	5.80 ab	24.2	19.3	19.6	21.0 c
	Si + AgNPs	85.7	78.7	77.8	80.7 de	5.00	5.45	6.61	5.70 bc	20.0	22.0	20.8	20.9 c
	Si + Zn	85.7	81.0	82.0	82.9 cd	5.32	5.73	6.32	5.80 ab	24.5	23.0	22.0	23.2 b
	Zn + AgNPs	90.0	83.0	84.6	85.9 ab	5.55	5.65	6.55	5.90 ab	27.0	25.5	21.8	24.8 a
	Si + Zn + AgNPs	88.0	87.8	83.5	86.4 a	5.53	5.98	6.53	6.0 a	28.3	25.8	22.7	25.6 a
	Mean (B)	85.6 a	80.2 b	77.4 c		5.14 c	5.73 b	6.44 a		23.3 a	21.2 b	20.3 b	
	$LSD_{0.05}$ (A)	2.38				0.09				1.16			
	$LSD_{0.05}$ (B)	1.77				0.25				0.99			
	$LSD_{0.05}$ (A×B)	4.12				0.43				2.01			
Years (*p* value)		0.052				0.007				0.0001			

CK, control treatment. Means in the same column (s)/row(s) followed by the same letters are not significantly different at 5% probability level.

https://doi.org/10.1017/S0021859623000345 Published online by Cambridge University Press

Table 5. Number of grains and 100-grain weight of maize (*Zea mays* L. cv. SC P3444) as affected by irrigation intervals, foliar application of silicon (Si), zinc (Zn) and silver nanoparticles (AgNPs), and their interaction in both seasons, i.e. 2020 and 2021

		Number of grains per row				Number of grains per ear				100-grain weight (g)			
		Irrigation interval (days) (B)				Irrigation interval (days) (B)				Irrigation interval (days) (B)			
Season	Treatments (A)	15	20	25	Mean (A)	15	20	25	Mean (A)	15	20	25	Mean (A)
2020	CK	34.3	38.0	37.0	36.4 e	412.0	451.0	456.0	439.7 d	36.5	35.6	33.9	35.3 g
	Si	41.7	39.0	42.0	40.9 cd	574.0	497.7	549.7	540.5 c	37.3	38.3	37.3	37.7 f
	Zn	42.3	35.7	40.3	39.4 d	560.0	570.3	453.0	527.8 c	42.9	40.0	39.3	40.7 de
	AgNPs	45.0	40.3	43.7	43.0 bc	599.3	592.3	547.0	579.6 bc	45.8	40.4	39.0	41.7 cd
	Si + AgNPs	43.0	42.7	42.0	42.6 bc	602.0	593.0	542.7	579.2 bc	45.8	40.0	40.3	42.0 ef
	Si + Zn	44.3	44.0	43.3	43.9 ab	620.7	615.7	616.0	617.5 ab	38.0	41.0	43.9	41.0 bc
	Zn + AgNPs	44.3	42.7	43.3	43.4 ab	650.7	607.3	597.3	618.4 ab	46.2	43.5	44.8	44.8 ab
	Si + Zn + AgNPs	47.3	44.0	44.3	45.2 a	726.7	630.3	594.3	650.4 a	46.0	45.1	44.5	45.2 a
	Mean (B)	42.8 a	42.0 a	40.8 b		593.2 a	569.7 b	544.5 b		42.3 a	40.5 b	40.4 b	
	$LSD_{0.05}$ (A)	2.02				22.0				1.9			
	$LSD_{0.05}$ (B)	1.14				31.4				0.93			
	$LSD_{0.05}$ (A×B)	3.49				105.5				3.29			
2021	CK	37.3	36.0	37.7	37.0 d	448.0	447.0	452.0	449.0 d	38.3	36.7	35.2	36.7 e
	Si	42.7	43.7	40.0	42.1 c	606.7	529.3	561.7	565.9 c	38.6	39.6	38.6	38.9 d
	Zn	45.0	41.0	39.7	41.9 c	540.0	611.0	491.0	547.3 c	45.1	39.5	40.6	41.7 bc
	AgNPs	47.0	46.7	42.3	45.3 ab	662.7	632.3	577.7	624.2 b	47.3	42.1	38.8	42.7 b
	Si + AgNPs	44.7	43.0	45.7	44.5 b	676.0	602.7	609.3	629.3 ab	39.3	40.8	41.6	40.6 cd
	Si + Zn	47.3	46.3	45.7	46.4 a	693.3	638.7	639.3	657.1 ab	45.2	41.0	44.5	43.6 b
	Zn + AgNPs	47.3	46.0	44.7	46.0 ab	694.7	650.3	570.0	638.3 ab	47.7	45.3	46.4	46.4 a
	Si + Zn + AgNPs	48.3	45.7	46.0	46.7 a	739.5	644.0	657.7	680.4 a	47.0	46.6	45.5	46.4 a
	Mean (B)	44.6 a	43.5 b	42.7 c		632.6 a	594.4 b	569.8 b		43.5 a	41.5 b	41.4 b	
	$LSD_{0.05}$ (A)	1.61				28.0				2.06			
	$LSD_{0.05}$ (B)	0.74				49.9				0.81			
	$LSD_{0.05}$ (A×B)	2.79				87.6				3.67			
Years (*p* value)		0.0018				0.0001				0.003			

CK, control treatment. Means in the same column (s)/row(s) followed by the same letters are not significantly different at 5% probability level.

Table 6. Grain, straw and total yield of maize (*Zea mays* L. cv. SC P3444) as affected by irrigation intervals, foliar application of silicon (Si), zinc (Zn) and silver nanoparticles (AgNPs), and their interaction in both seasons, i.e. 2020 and 2021

		Grain yield (t/ha)				Straw yield (t/ha)				Total yield (t/ha)			
		Irrigation interval (days) (B)				Irrigation interval (days) (B)				Irrigation interval (days) (B)			
Season	Treatments (A)	15	20	25	Mean (A)	15	20	25	Mean (A)	15	20	25	Mean (A)
2020	CK	5.80	5.01	4.58	5.13 g	7.29	6.33	5.70	6.44 e	13.1	11.3	10.3	11.6 g
	Si	6.16	5.49	5.46	5.70 f	7.99	6.71	6.53	7.08 d	14.2	12.2	12.0	12.8 f
	Zn	7.07	5.69	5.40	6.05 e	8.29	7.17	6.63	7.36 d	15.3	12.9	12.0	13.4 e
	AgNPs	7.97	6.21	5.83	6.67 d	8.83	7.49	7.23	7.85 c	16.9	13.7	13.1	14.5 d
	Si + AgNPs	6.96	6.06	6.90	6.64 d	8.6	7.66	7.63	7.96 c	15.6	13.7	14.5	14.6 d
	Si + Zn	7.53	7.07	7.10	7.23 c	8.97	7.96	8.6	8.51 b	16.5	15.0	15.7	15.7 c
	Zn + AgNPs	8.12	7.29	7.37	7.59 b	9.43	8.29	8.83	8.85 a	17.6	15.6	16.2	16.4 b
	Si + Zn + AgNPs	8.72	8.04	7.40	8.05 a	9.53	8.53	9.07	9.04 a	18.3	16.6	16.5	17.1 a
	Mean (B)	7.29 a	6.36 b	6.26 b		8.62 a	7.52 b	7.53 b		15.9 a	13.9 b	13.8 b	
	$LSD_{0.05}$ (A)	0.31				0.32				0.51			
	$LSD_{0.05}$ (B)	0.1				0.27				0.24			
	$LSD_{0.05}$ (A×B)	0.53				0.55				0.88			
2021	CK	6.20	5.39	4.68	5.42 g	7.7	6.73	5.70	6.71 f	13.9	12.1	10.4	12.1 g
	Si	6.56	5.71	5.43	5.90 f	7.97	7.19	6.30	7.15 e	14.5	12.9	11.7	13.1 f
	Zn	7.36	5.95	5.63	6.31 e	8.35	7.43	6.87	7.55 d	15.7	13.4	12.5	13.9 e
	AgNPs	8.24	6.5	6.14	6.96 c	8.87	7.37	7.33	7.86 c	17.1	13.9	13.5	14.8 d
	Si + AgNPs	7.29	6.36	6.31	6.65 d	8.43	7.93	7.77	8.04 c	15.7	14.3	14.1	14.7 d
	Si + Zn	7.93	7.05	7.07	7.35 b	9.12	8.36	8.10	8.53 b	17.1	15.4	15.2	15.9 c
	Zn + AgNPs	8.14	7.26	7.27	7.56 b	9.52	8.69	8.63	8.95 a	17.7	16.0	15.9	16.5 b
	Si + Zn + AgNPs	8.53	8.17	7.20	7.97 a	9.47	8.57	8.97	9.00 a	18.0	16.7	16.2	17.0 a
	Mean (B)	7.53 a	6.55 b	6.22 c		8.68 a	7.78 b	7.46 c		16.2 a	14.3 b	13.7 c	
	$LSD_{0.05}$ (A)	0.27				0.3				0.46			
	$LSD_{0.05}$ (B)	0.24				0.12				0.16			
	$LSD_{0.05}$ (A×B)	0.46				0.51				0.79			
Years (p value)		0.01				0.11				0.01			

CK, control treatment. Means in the same column (s)/row(s) followed by the same letters are not significantly different at 5% probability level.

Table 7. Harvest index and grain protein content of maize (*Zea mays* L. cv. SC P3444) as affected by irrigation intervals, foliar application of silicon (Si), zinc (Zn) and silver nanoparticles (AgNPs), and their interaction in both seasons 2020 and 2021

		Harvest index (%)				Grain protein (%)			
		Irrigation interval (days) (B)				Irrigation interval (days) (B)			
Season	Treatments (A)	15	20	25	Mean (A)	15	20	25	Mean (A)
2020	CK	44.3	44.2	44.6	44.4 d	7.53	7.70	7.40	7.54 d
	Si	43.5	45.0	45.5	44.7 cd	8.00	7.20	8.18	7.79 d
	Zn	46.0	44.3	44.9	45.1 bcd	8.26	7.27	7.53	7.69 d
	AgNPs	47.4	45.3	44.7	45.9 abc	8.83	7.90	8.94	8.56 c
	Si + AgNPs	44.7	44.2	47.5	45.5 bcd	8.61	8.84	9.27	8.91 b
	Si + Zn	45.6	47.0	45.2	45.9 abc	8.94	9.43	8.64	9.00 ab
	Zn + AgNPs	46.3	46.8	45.5	46.2 ab	9.44	9.33	9.14	9.30 ab
	Si + Zn + AgNPs	47.8	48.5	45.0	47.1 a	9.47	8.63	9.67	9.26 a
	Mean (B)	45.7 a	45.7 a	45.3 a		8.64 a	8.29 a	8.60 b	
	$LSD_{0.05}$ (A)	ns				0.35			
	$LSD_{0.05}$ (B)	1.06				0.18			
	$LSD_{0.05}$ (A×B)	2.10				0.60			
2021	CK	44.6	44.5	45.1	44.7 c	7.40	7.71	7.93	7.68 d
	Si	45.2	44.3	46.3	45.2 bc	7.50	7.23	8.07	7.60 d
	Zn	46.9	44.5	45.0	45.5 bc	8.17	7.24	7.99	7.80 d
	AgNPs	48.2	46.9	45.6	46.9 a	8.93	7.67	8.9	8.50 c
	Si + AgNPs	46.4	44.5	44.8	45.2 bc	8.43	8.85	9.07	8.78 bc
	Si + Zn	46.5	45.8	46.6	46.3 ab	8.73	9.46	8.77	8.99 b
	Zn + AgNPs	46.1	45.5	45.7	45.8 abc	8.98	9.13	8.9	9.00 b
	Si + Zn + AgNPs	47.4	48.8	44.5	46.9 a	9.67	9.23	9.53	9.48 a
	Mean (B)	46.4 a	45.6 b	45.5 b		8.48 b	8.32 c	8.65 a	
	$LSD_{0.05}$ (A)	1.14				0.33			
	$LSD_{0.05}$ (B)	1.27				0.13			
	$LSD_{0.05}$ (A×B)	1.98				0.57			
Years (*p* value)		0.01				0.0018			

CK, control treatment. Means in the same column (s)/row(s) followed by the same letters are not significantly different at 5% probability level. Ns, not significant.

For example, plant height was significantly and positively correlated with total yield ($r = 0.81$), SY ($r = 0.80$), ear length ($r = 0.75$), 100-grain weight ($r = 0.58$), chlorophyll content ($r = 0.81$) and grain yield ($r = 0.79$). Harvest index was highly and positively correlated with grain yield ($r = 0.68$), total yield ($r = 0.55$) and other growth and yield-related parameters except for proline content.

Visualization and understanding of various treatment interactions through hierarchical clustering

The hierarchical clustering analysis (Fig. 3) clearly differentiated the interrelationship between combinations of foliar spraying treatments and irrigation intervals/amount of irrigation applied (24 combinations) according to their impact on yield, growth and chemical parameters (Fig. 3). Regarding the relationship between irrigation intervals/amount and foliar application treatments, two major clusters were characterized. The first cluster contains ten combinations which were divided into two subclusters where the first subcluster was formed by the combination of treatment A (25 days + Si), B (20 days + Si), C (25 days + Zn), D (20 days + Ag Nano), E (25 days + Ag Nano), F (25 days + Si + Nano), while the second subcluster recorded the lowest value of all parameters formed by the combination of G (25 days + water spray), H (15 days + water spray), I (20 days + water spray) and J (20 days + Zn). Treatments A, B and C give the lowest values for all measured parameters within this group, especially ear height and SY. For treatments D, E and F, the majority of parameters, except for proline content, expressed negative performance.

In the second subcluster of treatments G (25 days + water spray), H (15 days + water spray), I (20 days + water spray) and J (20 days + Zn), the combinations of fertilization treatments showed an opposite pattern to the treatment's combinations of

Table 8. Interactive effect of foliar application of silicon (Si), zinc (Zn) and silver nanoparticles (AgNPs), and irrigation intervals (days) on plant height, leaf area index, SPAD value, ear height, proline content and number of grains per row in maize during both study years

	Plant height (cm)			Leaf area index			Chlorophyll index (SPAD value)		
	Irrigation interval (days)			Irrigation interval (days)			Irrigation interval (days)		
Treatments	15	20	25	15	20	25	15	20	25
CK	178.7 h–g	180.5 e–h	175.6 gh	3.68 d–g	3.57 e–g	2.97 i	36.3 g	35.4 gh	29.9 h
Si	188.6 b–e	185.5 c–f	174.5 h	4.18 bd	3.363 gi	3.31 i	56.4 a	44.1 fe	36.5 g
Zn	191.0 b–d	176.6 hg	176.7 hg	4.53 a–c	3.46 f–i	3.30 i	47.2 de	39.7 fg	39.4 fg
AgNPs	195.3 a–c	182.7 f–j	184.4 d–h	4.70 a	3.80 d–i	3.75 g–j	55.8 a	44.8 d–f	42.9 ef
Si + AgNPs	197.7 ab	192.4 b–d	182.4 d–g	3.96 c–f	4.25 a–d	3.53 e–i	50.1 a–e	49.6 b–e	43.3 fe
Si + Zn	195.3 a–c	191.1 b–d	185.0 c–g	4.44 abc	4.11 bcde	3.70 d–g	54.2 a–c	50.2 a–e	44.4 fe
Zn + AgNPs	196.9 ab	186.1 c–f	188.6 b–e	4.42 a–c	4.21 a–d	3.81 d–g	55.9 ab	52.3 a–d	48.0 c–e
Si + Zn + AgNPs	202.7 a	188.5 b–e	191.4 b–d	4.83 a	4.58 ab	3.97 c–e	54.9 ab	53.9 a–c	47.8 c–e

	Ear height (cm)			Proline content (%)			Number of grain/row		
	Irrigation interval (days)			Irrigation interval (days)			Irrigation interval (days)		
Treatments	15	20	25	15	20	25	15	20	25
CK	73.3 h–j	74.2 hi	72.0 ij	4.62 d	5.61 bc	6.76 a	35.8 f	37.8 ef	36.5 f
Si	85.3 a–c	75.4 hi	73.8 h–j	4.53 d	5.51 bc	5.82 b	43.7 a–d	39.5 d–f	42.8 b–d
Zn	85.7 a–c	68.3 j	76.5 f–i	4.56 d	5.75 bc	6.13 ab	42.2 b–d	37.7 ef	40.7 c–e
AgNPs	89.5 a	84.9 a–c	75.9 g–i	4.65 ef	5.69 cd	6.63 a	46.0 ab	41.3 b–e	45.2 a–c
Si + AgNPs	84.7 a–c	77.3 e–i	77.9 e–g	4.64 d	5.41 bc	6.69 a	43.2 a–d	45.6 ab	43.2 a–d
Si + Zn	85.0 a–c	80.6 d–f	81.7 c–g	4.99 cd	5.75 bc	6.61 a	45.8 ab	45.2 a–c	44.2 a–d
Zn + AgNPs	89.0 a	82.2 c–e	84.3 a–c	5.54 bc	5.53 bc	6.54 a	45.8 ab	43.7 a–d	44.7 a–c
Si + Zn + AgNPs	87.0 ab	86.8 ab	83.3 b–d	5.52 bc	5.80 b	6.75 a	47.8 a	45.0 a–c	45.0 a–c

CK, control treatment. Means in the same column (s)/row(s) followed by the same letters are not significantly different at 5% probability level.

the other clusters, as all studied parameters were negatively affected, especially for the G treatment which indicated the lowest value for all measured parameters.

With respect to the second cluster, 14 treatment combinations were clustered together and further were separated into two subclusters: the first subcluster included treatments K (20 days + Si + Nao), L (15 days + Si) and M (15 days + Si + Nano), the second subcluster included N (15 days + Si + Nano + Zn), O (15 days + Nano + Zn), P (15 days + Si + Zn), Q (25 days + Nano + Zn), R (25 days + Si + Nano + Zn), S (25 days + Si + Zn), T (20 days + Nano + Zn), U (20 days + Si + Zn), V (15 days + Zn), W (15 days + Ag Nano) and X (20 days + Si + Nano + Zn).

Based on the results, it was noted that the second cluster showed a discrepant effect on all recorded parameters, as the majority were positively affected by treatments K, L and M (first subcluster), while the combination of N gave the highest values for all recorded parameters within this group, especially plant height and ear length. For treatment O, the majority of parameters, except for proline content, showed high impact, especially for 100-kernel weight which showed the highest positive response, indicating the best parameters under such treatment. In contrast, the combination treatment R showed the highest positive effect on proline content followed by protein, while showed a negative effect on harvest index. Collectively, the treatment combination N resulted in the highest values for all parameters, followed by treatment combinations O and P.

Discussion

The main objective of this study was to examine the impact of different irrigation intervals/amount on the growth, yield and quality of maize, as well as to investigate the efficacy of some foliar treatments (i.e. Si, Zn, AgNPs and their combinations) in reducing the negative effects of water stress. There is no doubt that water shortage is a significant factor limiting plant growth, development and final yield (Hussain *et al*., 2019). Water stress conditions affect plants at every stage of their growth, especially at the vegetative stage (El-Gedwy, 2020). The findings from the present study revealed that a significant reduction was noticed in different morphological and yield attributes due to using less irrigation water which was inconsistent with that found in previous investigations on maize, soybean, barley, wheat and rice (Hasanuzzaman *et al*., 2018; Gomaa *et al*., 2021).

Overall, according to the results of the current study, plant height and ear length had an increasing trend with increasing both foliar application and irrigation water applied during the growing seasons, while medium levels of both irrigation water and foliar application of Si, Zn and AgNPs recorded medium

https://doi.org/10.1017/S0021859623000345 Published online by Cambridge University Press

Table 9. Interactive effect of foliar application of silicon (Si), zinc (Zn) and silver nanoparticles (AgNPs), and irrigation intervals (days) on 100-grain weight, ear length, number of grains per ear, grain yield, straw yield, total yield, harvest index and protein content in maize during both study years

	100-grain weight (g)			Ear length (cm)			Number of grains/ear		
	Irrigation interval (days)			Irrigation interval (days)			Irrigation interval (days)		
Treatments	15	20	25	15	20	25	15	20	25
CK	37.4 e–g	34.5 fg	34.5 g	19.4 e–g	16.6 h	18.1gh	430.0 f	454.0 d–f	449.0 ef
Si	38.0 e–g	39.0 ef	37.9 e–g	19.7 e–g	18.7 f–h	18.3 gh	590.3 b–e	555.7 b–e	513.5 b–e
Zn	44.0 a–d	39.8 ef	39.9 d–f	21.1 d–f	18.0 gh	18.1 gh	550.0 b–e	472.0 c–f	590.7 b–e
AgNPs	46.6 a	41.3 b–g	38.9 g–i	23.8 b–d	18.9 g–i	18.8 g–i	631.0 a–c	562.3 b–e	612.3 a–c
Si + AgNPs	39.3 ef	38.3 e–g	41.6 b–e	20.0 e–g	20.2 d–g	21.0 d–g	649.1 a–c	598.0 a–e	601.2 a–d
Si + Zn	45.4 a–c	41.2 c–e	45.2 a–c	23.0 b–d	21.5 c–f	21.7 c–f	672.5 a–c	631.1 a–c	624.3 a–d
Zn + AgNPs	46.9 a	44.4 a–c	45.6 a–c	26.0 ab	21.1 d–f	24.5 bc	672.7 ab	583.7 b–e	628.8 a–c
Si + Zn + AgNPs	46.5 a	45.9 a–c	45.0 a–c	27.5 a	22.2 c–e	25.5 ab	733.1 a	626.0 a–c	637.2 a–c

	Grain yield			Straw yield			Total yield		
	Irrigation interval (days)			Irrigation interval (days)			Irrigation interval (days)		
Treatments	15	20	25	15	20	25	15	20	25
CK	6.0 g–i	5.2 jk	4.6 k	7.5 e–g	6.5 h	5.7 m	13.5 hi	11.7 m	10.3 n
Si	6.4 e–g	5.6 h–j	5.4 ij	8.0 c–f	7.0 gh	6.4 l	14.3 f–h	12.6 k–m	11.9 ml
Zn	7.2 cd	5.8 g–j	5.5 h–j	8.3 b–e	7.3 gf	6.8 kl	15.5 c–e	13.1 j–k	12.2 jk
AgNPs	8.1 ab	6.4 fg	5.9 f–i	8.9 a–d	7.4 j–k	7.3 j–k	17.0 bc	13.8 ij	13.3 j–l
Si + AgNPs	7.0 c–e	6.2 e–g	6.8 d–f	8.4 b–d	7.5 d–g	7.8 c–f	15.4 c–f	13.7 g–i	14.7 d–g
Si + Zn	7.7 bc	6.9 c–e	7.1 cd	9.10 ab	8.3 b–e	8.3 b–e	16.8 a–c	15.1 d–g	15.5 c–f
Zn + AgNPs	8.1 ab	7.3 cd	7.3 cd	9.5 a	8.5 bc	8.7 b	17.6 ab	15.8 c–e	16.0 cd
Si + Zn + AgNPs	8.6 a	8.1 ab	7.3 cd	10.0 a	8.6 bc	9.0 ab	18.1 a	16.7 bc	16.3 cd

Treatments	Harvest index			Protein content (%)		
	Irrigation interval (days)			Irrigation interval (days)		
	15	20	15	20	15	20
CK	44.5 d	44.3 d	44.7 d	7.5 hg	7.7 hg	7.7 hg
Si	44.3 d	44.6 d	45.9 b–d	7.8 hg	7.2 h	8.1 e–g
Zn	46.5 a–d	44.4 d	45.0 cd	8.2 d–g	7.3 h	7.8 f–g
AgNPs	47.8 ab	46.1 a–d	45.1 cd	8.9 a–e	7.8 h–g	8.9 a–d
Si + AgNPs	45.5 b–d	44.3 d	46.1 a–d	8.5 c–e	8.8 a–e	9.2 a–c
Si + Zn	46.1 a–d	46.4 a–d	45.9 b–d	8.8 b–e	9.4 ab	8.7 b–e
Zn + AgNPs	46.1 a–d	46.2 a–d	45.6 b–d	9.2 a–c	9.2 a–c	9.0 a–c

CK, control treatment; means in the same column (s)/row(s) followed by the same letters are not significantly different at 0.05 level of probability.

values of both traits. According to the results, the increase in irrigation interval up to 25 days and using less irrigation water led to a significant decrease in all the parameters under investigation, compared to the other intervals (15 and 20 days) that received more irrigation water and showed the highest values for all studied parameters. This suggests that appropriate irrigation management is crucial for achieving optimal maize growth and yield and that longer intervals between irrigations and reduced amount of irrigation water can have negative effects on plant performance (Çakir, 2004). Additionally, the foliar application of Si, Zn and AgNPs, either alone or in combination, may help to mitigate the negative impacts of water stress on maize production.

Our findings also suggest that water stress significantly reduces maize grain yield by decreasing the number of rows per ear, and grain weight, and shortening the length of the grain filling period, which leads to the development of small and wrinkled grains. The use of AgNPs has been established as a plant growth stimulator in previous studies (Ogutu *et al.*, 2018; Zhao *et al.*, 2018; Yuan *et al.*,

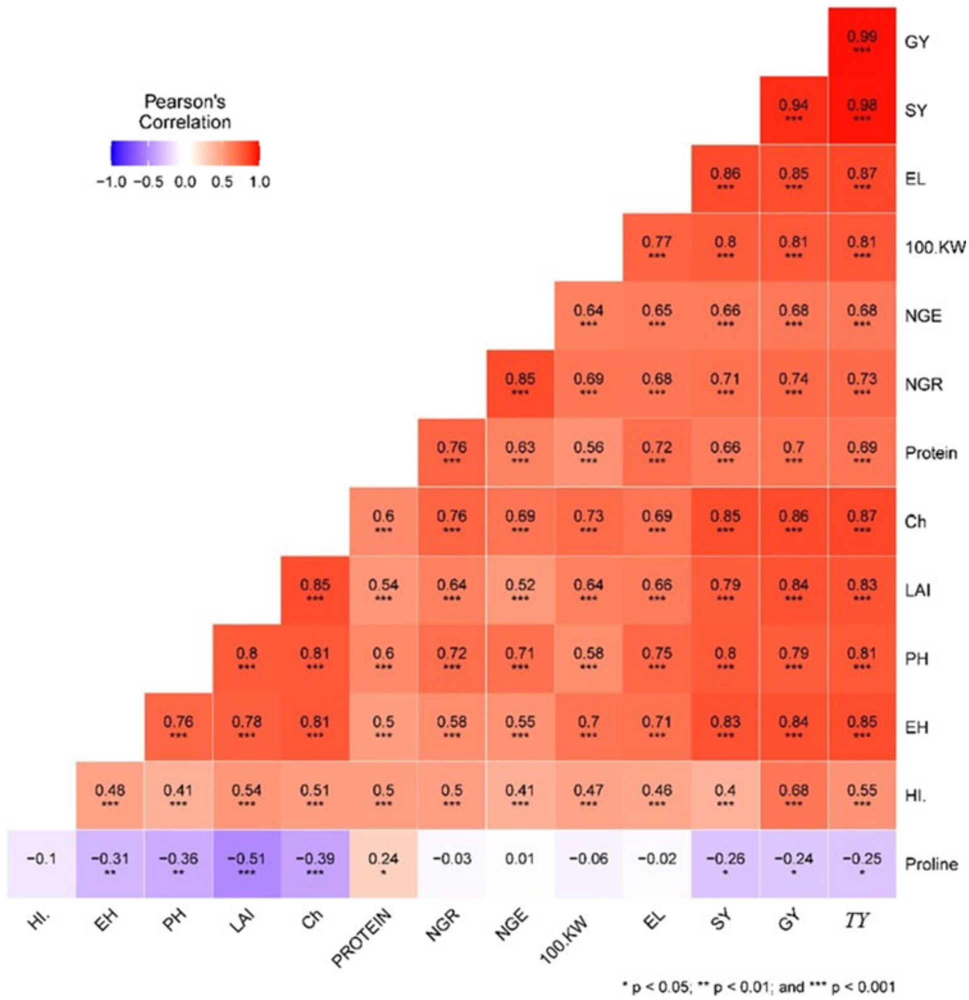

Figure 2. Pearson correlation coefficient for growth traits, yield and yield-related traits under different irrigation intervals and foliar application of silicon, zinc and silver nanoparticles. The correlation key: The blue colour indicates negative correlation, an orange colour indicates positive correlation, a white colour means no correlation, a light colour indicates lesser significance and a dark colour circle indicates a greater significance. The colour intensity is relative to the correlation coefficients. TY, total yield (ton/ha); GY, grain yield(ton/ha); SY, straw yield(ton/ha); EL, ear length (cm); 100.KW, 100-kernel/grain weight (g); NGE, number of grains per ear; NGR, number of grains per row; Ch, chlorophyll index (SPAD); LAI, leaf area index %; PH, plant height (cm); EH, ear height (cm); HI, harvest index %.

2019; Abdulhamed *et al*., 2021). Moreover, the current study indicates that the combined application of Zn, Si and AgNPs enhances the morphological and physiological characteristics of maize, particularly in alkaline calcareous soils where Zn deficiency is commonly found. Overall, these findings suggest that implementing appropriate irrigation and nutrient management strategies, along with the use of AgNPs and other growth-promoting agents, could potentially improve maize yield and quality in water-limited and nutrient-deficient environments (Abdelsalam *et al*., 2018; Abdelsalam *et al*., 2022b).

The improvement in growth characteristics of maize crop is due to the combined application of Si, Zn and AgNPs. Zn performs a critical role in the metabolic process, and protein synthesis in plants (Chaudhary *et al*., 2017). Furthermore, Zn application results in a significant increase in plant leaf area, chlorophyll content and other photosynthetic pigments, thus causing growth improvement and yield (Karim *et al*., 2012). Similarly, Sultana *et al*. (2016) indicated that Zn countered the adverse impact of drought stress by remarkably enhancing wheat productivity. In another study on maize, Chattha *et al*. (2017) stated that Zn improved the yield and harvest index under drought stress. Moreover, Hera *et al*. (2018) demonstrated that Zn as a foliar application reduced the negative influences of water deficit and enhanced the growth and yield of wheat. Zinc substantially enhances chlorophyll content and photosynthetic performance under drought stress (Peleg *et al*., 2008; Ma *et al*., 2017). Additionally, Zn improves chlorophyll content, starch content and grain yield. It is a fundamental component in maize crop for the biosynthesis of several proteins and enzymes (Balashouri and Prameeladevi, 1995; Bhattarai *et al*., 2008; Peleg *et al*., 2008).

According to the results of the correlation study, plant height was strongly and substantially associated with yield and related parameters, demonstrating that growing maize at the optimal density may result in the maximum yield. Furthermore, leaf area and grain protein contents were strongly and positively correlated, which is likely due to the vital role of plant leaves in the process of photosynthesis and the formation of photosynthates. Based on these findings, decreasing the amount of applied water to maize crop and use of nanoparticles in the form of foliar spray may be effective ways to enhance grain yield in water-limited

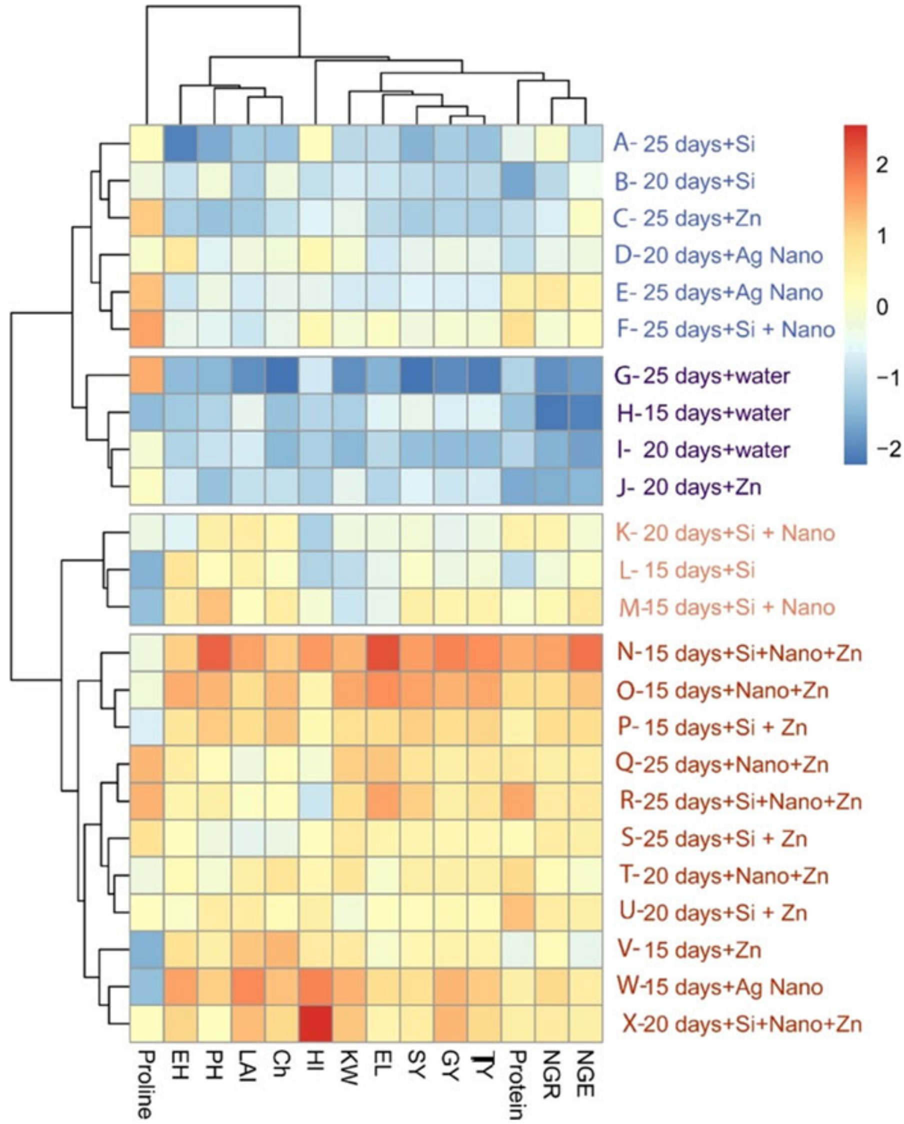

Figure 3. Hierarchical clustering heat map visualization for 24 treatments' combinations (irrigation intervals and foliar spray of nanoparticles) for 14 agronomical parameters. The orange colour represents high values, and the blue colour represents low values. High to low values are scaled according to the key above. TY, total yield (ton/ha); GY, grain yield (ton/ha); SY, straw yield (ton/ha); EL, ear length (cm); KW, 100-kernel weight (g); NGE, number of grain/ear; NGR, number of grain/row; Ch, chlorophyll index (SPAD); LAI, leaf area index; PH, plant height (cm); EH, ear height (cm); HI, harvest index %.

environments. However, it is important to note that these strategies should be implemented in a sustainable manner, taking into account factors such as soil type, weather conditions and other environmental variables (Rodrigues and Pereira, 2009; Bijanzadeh *et al*., 2021).

Conclusions

Our findings indicated that applying Si + Zn + AgNPs through the foliar application with a 15-day irrigation interval (7925 m^3/ha irrigation water divided over seven irrigations) increased various growth and yield parameters of maize, including plant height, leaf area index, chlorophyll content (SPAD value), ear height, ear length, number of grains/row, number of grains/ear, 100-grain weight, grain yield, SY, total yield, harvest index and grain protein content. Additionally, highly significant correlations were observed between the recorded parameters, except for proline content and irrigation interval for 15 days + AgNPs + Zn. The highest positive response was observed in 100-kernel weight for this treatment. Overall, the treatment of an irrigation interval of 15 days + Si + AgNPs + Zn resulted in the highest values for all measurements, followed by an irrigation interval of 15 days + Si + AgNPs and an irrigation interval of 15 days + Si + Zn treatments.

Data

The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Acknowledgements. The authors are grateful to Alexandria University, Alexandria, Egypt for supporting the current research.

Author contributions. Conceptualization, E. E. K. and N. R. A.; methodology, E. E. K. and E.-S. M. S. G.; validation, T. J. and R. Y. G.; investigation, resources, supervision and project administration and funding, N. R. A.; data curation, S. F. L; writing – original draft preparation, E. E. K. and N. R. A.; writing – review and editing, S. F. L., E.-S. M. S. G., R. Y. G., T. J., S. H. and N. R. A.. All authors have read and agreed to the published version of the manuscript.

Financial support. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Competing interest. None.

Ethical standards. Not applicable.

References

Abbasi A, Sufyan M, Ashraf HJ, Zaman QU, Haq IU, Ahmad Z, Saleem R, Hashmi MR, Jaremko M and Abdelsalam NR (2022) Determination of silicon accumulation in Non-Bt cotton (*Gossypium hirsutum*) plants and its impact on fecundity and biology of whitefly (*Bemisia tabaci*) under controlled conditions. *Sustainability* **14**, 10996.

Abd-Elaty I, Kuriqi A and Shahawy AE (2022) Environmental rethinking of wastewater drains to manage environmental pollution and alleviate water scarcity. *Natural Hazards* **110**, 2353–2380.

Abdelghany AM, Zhang S, Azam M, Shaibu AS, Feng Y, Qi J, Li J, Li Y, Tian Y and Hong H (2021) Exploring the phenotypic stability of soybean seed compositions using multi-trait stability index approach. *Agronomy* **11**, 2200.

Abdelghany AM, El-Banna AA, Salama EA, Ali MM, Al-Huqail AA, Ali HM, Paszt LS, El-Sorady GA and Lamlom SF (2022) The individual and combined effect of nanoparticles and biofertilizers on growth, yield, and biochemical attributes of peanuts (*Arachis hypogea* L.). *Agronomy* **12**, 398.

Abdelsalam NR, Abdel-Megeed A, Ali HM, Salem MZM, Al-Hayali MFA and Elshikh MS (2018) Genotoxicity effects of silver nanoparticles on wheat (*Triticum aestivum* L.) root tip cells. *Ecotoxicology and Environmental Safety* **155**, 76–85.

Abdelsalam NR, Abdel-Megeed A, Ghareeb RY, Ali HM, Salem MZ, Akrami M, Al-Hayalif MF and Desoky E-SM (2022a) Genotoxicity assessment of amino zinc nanoparticles in wheat (*Triticum aestivum* L.) as cytogenetical perspective. *Saudi Journal of Biological Sciences* **29**, 2306–2313.

Abdelsalam NR, Balbaa MG, Osman HT, Ghareeb RY, Desoky E-SM, Elshehawi AM, Aljuaid BS and Elnahal AS (2022b) Inheritance of resistance against northern leaf blight of maize using conventional breeding methods. *Saudi Journal of Biological Sciences* **29**, 1747–1759.

Abdulhamed ZA, Abas SA, Noaman AH and Abood NM (2021) Review on the development of drought tolerant maize genotypes in Iraq. *IOP Conference Series: Earth and Environmental Science* **904**, 012010.

Acharya P, Jayaprakasha GK, Crosby KM, Jifon JL and Patil BS (2020) Nanoparticle-mediated seed priming improves germination, growth, yield, and quality of watermelons (*Citrullus lanatus*) at multi-locations in Texas. *Scientific Reports* **10**, 5037.

Ahmad A, Aslam Z, Javed T, Hussain S, Raza A, Shabbir R, Mora-Poblete F, Saeed T, Zulfiqar F, Ali MM and Nawaz M (2022) Screening of wheat (*Triticum aestivum* L.) genotypes for drought tolerance through agronomic and physiological response. *Agronomy* **12**, 287.

Ahmed BM, Salih MA, Eltaib KA, Fageer EA, Fadul EM, Mohamed AA and Mustafa AM (2020) Interactive effects of irrigation intervals and Stocksorb660 rates on growth and yield of maize (*Zea mays* L.) under conditions of northern state, Sudan. *Sudan Journal of Desertification Research* **12**, 31–47.

Alloway BJ (2008) Zinc in soils and crop nutrition. Second edition, published by IZA and IFA Brussels, Belgium and Paris, France.

Amin M, Ahmad R, Ali A, Hussain I, Mahmood R, Aslam M and Lee DJ (2018) Influence of silicon fertilization on maize performance under limited water supply. *Silicon* **10**, 177–183.

Ashraf M and Foolad MR (2007) Roles of glycine betaine and proline in improving plant abiotic stress resistance. *Environmental and Experimental Botany* **59**, 206–216.

Balashouri P and Prameeladevi Y (1995) Effect of zinc on germination, growth and pigment content and phytomass of *Vigna radiata* and *Sorghum bicolor*. *Journal of Ecobiology* **7**, 109–114.

Bashir MA, Rehim A, Liu J, Imran M, Liu H, Suleman M and Naveed S (2019) Soil survey techniques determine nutrient status in soil profile and metal retention by calcium carbonate. *CATENA* **173**, 141–149.

Bates LS, Waldren RP and Teare ID (1973) Rapid determination of free proline for water-stress studies. *Plant and Soil* **39**, 205–207.

Bhattarai SP, Midmore DJ and Pendergast L (2008) Yield, water-use efficiencies and root distribution of soybean, chickpea and pumpkin under different subsurface drip irrigation depths and oxygation treatments in vertisols. *Irrigation Science* **26**, 439–450.

Bijanzadeh E, Tarazkar MH and Emam Y (2021) Water productivity and virtual water of barley cultivars under different irrigation regimes. *mdrsjrns* **23**, 603–616.

Çakir R (2004) Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Research* **89**, 1–16.

Chapman HD and Pratt PF (1962) Methods of analysis for soils, plants and waters. *Soil Science* **93**, 68.

Chattha MU, Hassan MU, Khan I, Chattha MB, Mahmood A, Chattha MU, Nawaz M, Subhani MN, Kharal M and Khan S (2017) Biofortification of wheat cultivars to combat zinc deficiency. *Frontiers in Plant Science* **8**, 281–289.

Chaudhary S, Dheri GS and Brar BS (2017) Long-term effects of NPK fertilizers and organic manures on carbon stabilization and management index under rice-wheat cropping system. *Soil and Tillage Research* **166**, 59–66.

CoStat V (2005) Cohort software798 light house Ave. PMB320, Monterey, CA93940, and USA. email: info@cohort.com. Available at http://www.cohort.com. DownloadCoStatPart2.html.

El-Gedwy E-SM (2020) Effect of water stress, nitrogen and potassium fertilizers on maize yield productivity. *Annals of Agricultural Science* **58**, 515–534.

El-Sorady GA, El-Banna AA, Abdelghany AM, Salama EA, Ali HM, Siddiqui MH, Hayatu NG, Paszt LS and Lamlom SF (2022) Response of bread wheat cultivars inoculated with azotobacter species under different nitrogen application rates. *Sustainability* **14**, 8394.

Elmardy NA, Yousef AF, Lin K, Zhang X, Ali MM, Lamlom SF, Kalaji HM, Kowalczyk K and Xu Y (2021) Photosynthetic performance of rocket (*Eruca sativa*. Mill.) grown under different regimes of light intensity, quality, and photoperiod. *PLoS ONE* **16**, e0257745.

Estrada-Urbina J, Cruz-Alonso A, Santander-González M, Méndez-Albores A and Vázquez-Durán A (2018) Nanoscale zinc oxide particles for improving the physiological and sanitary quality of a Mexican landrace of red maize. *Nanomaterials* **8**, 247.

Galindo FS, Pagliari PH, Rodrigues WL, Fernandes GC, Boleta EHM, Santini JMK, Jalal A, Buzetti S, Lavres J and Teixeira Filho MCM (2021) Silicon amendment enhances agronomic efficiency of nitrogen fertilization in maize and wheat crops under tropical conditions. *Plants* **10**, 1329.

Gennari P, Rosero-Moncayo J and Tubiello FN (2019) The FAO contribution to monitoring SDGs for food and agriculture. *Nature Plants* **5**, 1196–1197.

Gohari G, Mohammadi A, Akbari A, Panahirad S, Dadpour MR, Fotopoulos V and Kimura S (2020) Titanium dioxide nanoparticles (TiO2 NPs) promote growth and ameliorate salinity stress effects on essential oil profile and biochemical attributes of *Dracocephalum moldavica*. *Scientific Reports* **10**, 912.

Gomaa MA, Kandil EE, El-Dein AAMZ, Abou-Donia MEM, Ali HM and Abdelsalam NR (2021) Increase maize productivity and water use efficiency through application of potassium silicate under water stress. *Scientific Reports* **11**, 224.

Gomez KA and Gomez AA (1984) *Statistical Procedures for Agricultural Research*, Second edn, Singapore: John Wiley & Sons, p. 680.

Guo R, Qian R, Yang L, Khaliq A, Han F, Hussain S, Zhang P, Cai T, Jia Z, Chen X and Ren X (2022) Interactive effects of maize straw-derived biochar and n fertilization on soil bulk density and porosity, maize productivity and nitrogen use efficiency in arid areas. *Journal of Soil Science and Plant Nutrition* **22**, 4566–4586.

Hasanuzzaman M, Bhuyan MB, Nahar K, Hossain MS, Mahmud JA, Hossen MS, Masud AAC and Fujita M (2018) Potassium: a vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy* **8**, 31.

Hassan MU, Ghareeb RY, Nawaz M, Mahmood A, Shah AN, Abdel-Megeed A, Abdelsalam NR, Hashem M, Alamri S and Thabit MA (2022) Melatonin: a vital protectant for crops against heat stress: mechanisms and prospects. *Agronomy* **12**, 1116.

Helrich K (1990) *Official methods of analysis of the Association of Official Analytical Chemists*. Association of official analytical chemists.

Hera MHR, Hossain M and Paul AK (2018) Effect of foliar zinc spray on growth and yield of heat tolerant wheat under water stress. *International Journal of Biological and Environmental Engineering* **1**, 10–16.

Hernández EM, Hernández AM, Contreras AM, Saldaña TM, Velázquez MAJ, Escudero JS and Cué JLG (2020) EvaluaciÃ³n de la calidad fÃsica y fisiolÃ³gica de semilla de maÃz nativo. *Agricultura Sociedad y Desarrollo* **17**, 569–581.

https://doi.org/10.1017/S0021859623000345 Published online by Cambridge University Press

Hussain S, Hussain S, Qadir T, Khaliq A, Ashraf U, Parveen A, Saqib M and Rafiq M (2019) Drought stress in plants: an overview on implications, tolerance mechanisms and agronomic mitigation strategies. *Plant Science Today* **6**, 389–402.

Hussain S, Hussain S, Aslam Z, Rafiq M, Abbas A, Saqib M, Rauf A, Hano C and El-Esawi MA (2021) Impact of different water management regimes on the growth, productivity, and resource use efficiency of dry direct seeded rice in central Punjab-Pakistan. *Agronomy* **11**, 1151.

Hussan MU, Hafeez MB, Saleem MF, Khan S, Hussain S and Ahmad N (2021) Impact of soil applied humic acid, zinc and boron supplementation on the growth, yield and zinc translocation in winter wheat. *Asian Journal of Agriculture and Biology* **10**, 1–14.

Iqbal S, Waheed Z and Naseem A (2020) Nanotechnology and abiotic stresses. In *Nanoagronomy*. Switzerland: Springer, pp. 37–52. 10.1007/978-3-030-41275-3_3.

Iqbal Z, Javad S, Naz S, Shah AA, Shah AN, Paray BA, Gulnaz A and Abdelsalam NR (2022) Elicitation of the in vitro cultures of selected varieties of *Vigna radiata* L. with zinc oxide and copper oxide nanoparticles for enhanced phytochemicals production. *Frontiers in Plant Science* **13**, 908532–908548.

Jan M, Anwar-Ul-Haq M, Javed T, Hussain S, Ahmad I, Sumrah MA, Iqbal J, Babar BH, Hafeez A, Aslam M and Akbar MT (2023) Response of contrasting rice genotypes to zinc sources under saline conditions. *Phyton* **92**, 1361–1375.

Javed T, Shabbir R, Hussain S, Naseer MA, Ejaz I, Ali MM, Ahmar S and Yousef AF (2022) Nanotechnology for endorsing abiotic stresses: a review on the role of nanoparticles and nanocompositions. *Functional Plant Biology*. https://doi.org/10.1071/FP22092

Kandil EE, Abdelsalam NR, Mansour MA, Ali HM and Siddiqui MH (2020) Potentials of organic manure and potassium forms on maize (*Zea mays* L.) growth and production. *Scientific Reports* **10**, 8752.

Karim MR, Zhang Y-Q, Zhao R-R, Chen X-P, Zhang F-S and Zou C-Q (2012) Alleviation of drought stress in winter wheat by late foliar application of zinc, boron, and manganese. *Journal of Plant Nutrition and Soil Science* **175**, 142–151.

Kausar A, Hussain S, Javed T, Zafar S, Anwar S, Hussain S, Zahra N and Saqib M (2023) Zinc oxide nanoparticles as potential hallmarks for enhancing drought stress tolerance in wheat seedlings. *Plant Physiology and Biochemistry* **195**, 341–350.

Khafaga AF, Fouda MM, Alwan AB, Abdelsalam NR, Taha AE, Atta MS and Dosoky WM (2022) Silver-Silica nanoparticles induced dose-dependent modulation of histopathological, immunohistochemical, ultrastructural, proinflammatory, and immune status of broiler chickens. *BMC Veterinary Research* **18**, 365.

Kojić D, Pajević S, Jovanović-Galović A, Purać J, Pamer E, Škondrić S, Milovac S, Popović Z and Grubor-Lajšić G (2012) Efficacy of natural aluminosilicates in moderating drought effects on the morphological and physiological parameters of maize plants (*Zea mays* L.). *Journal of Soil Science and Plant Nutrition* **12**, 113–123.

Laing M, Gatarayiha M and Adandonon A (2006) Silicon use for pest control in agriculture: a review. In *Proceedings of the South African Sugar Technologists' Association*, pp. 278–286.

Ma D, Sun D, Wang C, Ding H, Qin H, Hou J, Huang X, Xie Y and Guo T (2017) Physiological responses and yield of wheat plants in zinc-mediated alleviation of drought stress. *Frontiers in Plant Science* **8**, 860–872.

Ma S, Tong L, Kang S, Wang S, Wu X, Cheng X and Li Q (2022) Optimal coupling combinations between dripper discharge and irrigation interval of maize for seed production under plastic film-mulched drip irrigation in an arid region. *Irrigation Science* **40**, 177–189.

Minolta K (1989) Chlorophyll meter SPAD-502 instruction manual. *Minolta Co, Ltd, Radiometric Instruments Operations Osaka, Japan.*

Moussa HR (2006) Influence of exogenous application of silicon on physiological response of salt-stressed maize (*Zea mays* L.). *International Journal of Agriculture and Biology* **8**, 293–297.

Muhammad I, Yang L, Ahmad S, Farooq S, Al-Ghamdi AA, Khan A, Zeeshan M, Elshikh MS, Abbasi AM and Zhou X-B (2022) Nitrogen fertilizer modulates plant growth, chlorophyll pigments and enzymatic activities under different irrigation regimes. *Agronomy* **12**, 845.

Mustafa A, Athar F, Khan I, Chattha MU, Nawaz M, Shah AN, Mahmood A, Batool M, Aslam MT and Jaremko M (2022) Improving crop productivity and nitrogen use efficiency using sulfur and zinc-coated urea: a review.

Naeem M (2015) Exploring the role of zinc in maize (*Zea mays* L.) through soil and foliar application. *Universal Journal of Agricultural Research* **3**, 69–75.

Nasar J, Wang G-Y, Ahmad S, Muhammad I, Zeeshan M, Gitari H, Adnan M, Fahad S, Khalid MHB and Zhou X-B (2022) Nitrogen fertilization coupled with iron foliar application improves the photosynthetic characteristics, photosynthetic nitrogen use efficiency, and the related enzymes of maize crops under different planting patterns. *Frontiers in Plant Science* **13**, 988055.

Neupane D, Adhikari P, Bhattarai D, Rana B, Ahmed Z, Sharma U and Adhikari D (2022) Does climate change affect the yield of the top three cereals and food security in the world? *Earth* **3**, 45–71.

Ogutu GEO, Franssen WHP, Supit I, Omondi P and Hutjes RWA (2018) Probabilistic maize yield prediction over East Africa using dynamic ensemble seasonal climate forecasts. *Agricultural and Forest Meteorology* **250–251**, 243–261.

Peleg Z, Saranga Y, Yazici A, Fahima T, Ozturk L and Cakmak I (2008) Grain zinc, iron and protein concentrations and zinc-efficiency in wild emmer wheat under contrasting irrigation regimes. *Plant and Soil* **306**, 57–67.

Radford P (1967) Growth analysis formulae-their use and abuse 1. *Crop science* **7**, 171–175.

Rehman A, Farooq M, Ozturk L, Asif M and Siddique KH (2018) Zinc nutrition in wheat-based cropping systems. *Plant and Soil* **422**, 283–315.

Rodrigues GC and Pereira LS (2009) Assessing economic impacts of deficit irrigation as related to water productivity and water costs. *Biosystems Engineering* **103**, 536–551.

Sabra MA, Alaidaroos BA, Jastaniah SD, Heflish AI, Ghareeb RY, Mackled MI, El-Saadony MT, Abdelsalam NR and Conte-Junior CA (2022) Comparative effect of commercially available nanoparticles on soil bacterial community and '*Botrytis fabae*' caused brown spot: in vitro and in vivo experiment. *Frontiers in Microbiology* **13**, 934031–934044.

Sadak MS (2019) Impact of silver nanoparticles on plant growth, some biochemical aspects, and yield of fenugreek plant (*Trigonella foenum-graecum*). *Bulletin of the National Research Centre* **43**, 38.

Salo-väänänen PP and Koivistoinen PE (1996) Determination of protein in foods: comparison of net protein and crude protein (N × 6.25) values. *Food Chemistry* **57**, 27–31.

Sanjari S, Shobbar Z-S, Ghanati F, Afshari-Behbahanizadeh S, Farajpour M, Jokar M, Khazaei A and Shahbazi M (2021) Molecular, chemical, and physiological analyses of sorghum leaf wax under post-flowering drought stress. *Plant Physiology and Biochemistry* **159**, 383–391.

Sarwar S, Rafique E, Gill SM and Khan MZ (2017) Improved productivity and zinc content for maize grain by different zinc fertilization techniques in calcareous soils. *Journal of Plant Nutrition* **40**, 417–426.

Sattar A, Sher A, Abourehab MA, Ijaz M, Nawaz M, Ul-Allah S, Abbas T, Shah AN, Imam MS and Abdelsalam NR (2022) Application of silicon and biochar alleviates the adversities of arsenic stress in maize by triggering the morpho-physiological and antioxidant defense mechanisms. *Frontiers in Environmental Science* **10**, 2086.

Siddique S, Naveed M, Yaseen M and Shahbaz M (2022) Exploring potential of seed endophytic bacteria for enhancing drought stress resilience in maize (*Zea mays* L.). *Sustainability* **14**, 673.

Sowers J, Vengosh A and Weinthal E (2011) Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Climatic Change* **104**, 599–627.

Sultana S, Naser HÁ, Shil N, Akhter S and Begum R (2016) Effect of foliar application of zinc on yield of wheat grown by avoiding irrigation at different growth stages. *Bangladesh Journal of Agricultural Research* **41**, 323–334.

Tuna AL, Kaya C, Higgs D, Murillo-Amador B, Aydemir S and Girgin AR (2008) Silicon improves salinity tolerance in wheat plants. *Environmental and Experimental Botany* **62**, 10–16.

Waraich EA, Ahmad R, Ashraf MY, Saifullah, Ahmad M (2011) Improving agricultural water use efficiency by nutrient management in crop plants. *Acta Agriculturae Scandinavica, Section B-Soil & Plant Science* **61**, 291–304.

Yousaf U, Khan AHA, Farooqi A, Muhammad YS, Barros R, Tamayo-Ramos JA, Iqbal M and Yousaf S (2022) Interactive effect of biochar and compost with Poaceae and Fabaceae plants on remediation of total petroleum hydrocarbons in crude oil contaminated soil. *Chemosphere* **286**, 131782.

Youssef MA, Yousef AF, Ali MM, Ahmed AI, Lamlom SF, Strobel WR and Kalaji HM (2021) Exogenously applied nitrogenous fertilizers and effective microorganisms improve plant growth of stevia (*Stevia rebaudiana* Bertoni) and soil fertility. *AMB Express* **11**, 1–10.

Yuan C, Feng S, Huo Z and Ji Q (2019) Effects of deficit irrigation with saline water on soil water-salt distribution and water use efficiency of maize for seed production in arid Northwest China. *Agricultural Water Management* **212**, 424–432.

Zafar M, Ahmed S, Munir MK, Zafar N, Saqib M, Sarwar MA, Iqbal S, Ali B, Akhtar N, Ali B and Hussain S (2023) Application of zinc, iron and boron enhances productivity and grain biofortification of mungbean. *Phyton* **92**, 983–999.

Zhao J, Xue Q-W, Jessup KE, Hou X-B, Hao B-Z, Marek TH, Xu W-W, Evett SR, O'Shaughnessy SA and Brauer DK (2018) Shoot and root traits in drought tolerant maize (*Zea mays* L.) hybrids. *Journal of Integrative Agriculture* **17**, 1093–1105.

Zhao L, Liu S, Abdelsalam NR, Carver BF and Bai G (2021) Characterization of wheat curl mite resistance gene Cmc4 in OK05312. *Theoretical and Applied Genetics* **134**, 993–1005.