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RESEARCH ARTICLE

Effect of foliar application of nano micro nutrients and deficit irrigation on stay green characteristics and drought resistance in maize

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Abstract

The stay-green character is a crucial trait linked to delayed leaf senescence, which enables the plant to continue photosynthetic activity for an extended time under early and terminal drought. Reduced water availability causes early leaf senescence, lower chlorophyll content and eventually poor yield in maize. The objectives were to quantify the effects of irrigation regimes, nanocomposite levels physiological parameters, yield attributes and yield of maize. The main plot treatments comprised of well irrigated and withheld irrigation, while the sub plot treatments consisted of different nanoparticles *viz*., ZnO, MnO, (ZnO + MnO), TNAU nano revive and $ZnSO_4$ + $MnSO_4$. The results revealed that higher dry matter production (5282 and 9891 kg/ha), leaf nitrogen (44.28 and 39.97), grain filling rate, grain filling duration (34.44 days), green leaf area (92.50%) and proline content (0.59 and 1.28 mg g^{-1}) were recorded at tasseling and grain filling stage, respectively under well-irrigated conditions. Foliar spraying of ZnO (100 ppm) and MnO (20 ppm) nanocomposite, registered higher root biomass (24.21 and 32.11 g/plant), leaf nitrogen (44.6 and 39.1), dry matter production, green leaf area, lowest proline content which ultimately resulted in a higher number of cobs/plant, number of grains row/cob, number of grains/grain row, test weight (1000 grains weight), shelling percentage, crop water use (18.79 kg/ha/mm), grain yield (8.20 t/ha), stover yield (12.2 t/ha) and benefit cost ratio of 2.4. Thus, it could be concluded that well-irrigated condition followed by foliar spray with ZnO (100 ppm) and MnO (20 ppm) registered higher growth, yield attributes, yield and economics.

Keywords

deficit irrigation; drought; grain yield; maize; nano micro nutrients; stay-green

Introduction

Maize, a multifaceted crop, is cultivated under varied agroclimatic conditions owing to its wide usage. Therefore, there is a greater demand for maize grain throughout the year to meet the requirements. It has high-yielding potential under both rainfed and irrigated ecosystems due to its resource-efficient nature. Thus, it can be effectively integrated with animal components under an integrated farming system to ensure doubling of farmer's income (1). Maize can function in a variety of industrial environments due to its versatility. It serves as poultry feed (52%), human food (25%), animal feed (11%), starch (11%), beer (1%) and seed (1%) and is an essential raw material for more than 3,000 industrial products such as starch, protein, oil, alcoholic beverages, food sweeteners, cosmetics, and most importantly, biofuel (ethanol) (2). Maize has grown at much faster rate than other key cereals in terms of area (2.83%), production (30.93%) and productivity (27.35%). Because of its great yield potential, maize is frequently referred to as the "miracle crop" or the "Queen of Cereals" (3). India intends to achieve 20% ethanol blended with gasoline by 2025. The country has already began this deployment in 2023. Programs promoting biofuels, with the goal of decreasing greenhouse gas emissions and dependency on fossil fuels, often include this kind of ethanol blend (2). Therefore, the demand for this crop is rising every year in Tamil Nadu and its future requirement is expected to increase. The annual requirement of maize grains in Tamil Nadu for animal husbandry sector is approximately 50 lakh tonnes. Only 60% of this requirement is through domestic production, with the remaining is mainly imported from Karnataka, Andhra Pradesh and Bihar state (4).

The most important seasons for growing hybrid maize in Tamil Nadu are April-May (Vaigasi pattam), November-December (Karthigai Pattam) and January-February (Thaipattam) for irrigated conditions, whereas June-July (Aadipattam) is suitable for rainfed situations. During the delayed onset of monsoon rainfall in the southwest monsoon, farmers generally do not prefer field crops, particularly beyond the first fortnight of September, due to the bimodal rainfall pattern in Tamil Nadu. This pattern often leads to excessive vegetative growth and complicates the harvesting process. Under these circumstances, hybrid maize could be the better option for the farmers as an alternative crop. Consequently, hybrid maize cultivation in Tamil Nadu is gaining momentum among farmers, accounting for 17% of the area under irrigated ecosystems and 83% under rainfed ecosystems.

Occurrence of early drought during the vegetative period resulted in poor plant population density and similarly, witnessing moisture stress during flowering stage leads to yield penalty. Depending on the severity or duration of the drought and crop stage, maize production losses due to drought stress can vary from 30% to 90%. The stages most affected are flowering and grain filling. In rainfed regions globally, maize is typically grown with 300–500 mm of precipitation, which is often insufficient to achieve optimal yields (5).

Drought is regarded as one of the primary hazardous abiotic stresses in crop production. Soil moisture deficits mostly caused by drought, limit crop growth, development and productivity, especially during critical stages. The building up of reactive oxygen species (ROS) in plants system causes oxidative damage by limiting stomatal opening, speeding up the photoreduction of oxygen (O_2) in the chloroplast, and enhancing photorespiration (6). Plants adapt to drought stress by regulating gene expression, closing stomata, synthesizing phytohormones, releasing abscisic acid (ABA), maintaining osmotic equilibrium (7). Among the various significant challenges it faces, drought poses the greatest threat to crop production globally. As one of the most severe abiotic stresses, drought impacts both human health and crop yields, affecting around one-third of the global population (8). According to FAO estimations, drought had a direct impact on developing countries' agriculture of USD 29 billion between 2005 and 2015 (9).

Higher dry matter production in maize was observed under optimum conditions and plants remain photosynthetically active during mid to late grain filling stage and the delayed leaf senescence ('stay green') is an improved characteristic of the new maize hybrids (10). Nanofertilizers, which are nutrient carriers with diameters between 30 and 40 nm, possess a massive surface area which permits it to retain large amounts of nutrient ions and release the nutrients gradually and consistently depending on the crop requirement (11). Foliar feeding with nanofertilizers in maize is an efficient method of delivering vital nutrients directly to the plants. It is simple, cost-effective and easy to carry out the spraying operation with unmanned vehicles under unfavourable and harsh soil environments (12, 13).

Materials and Methods

Field location and objectives

A field experiment was conducted during the Summer 2024 season at Field No. 37 F, Eastern Block Farm, Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore. The objective was to study the influence of deficit irrigation and different nanoparticles on the expression of the stay-green character and drought resistance in maize. The study focused on quantifying the effects of irrigation regimes, nanocomposite levels and their interaction on green leaf area, chlorophyll content and leaf nitrogen content, as well as on quantifying the effects of irrigation regimes, metallic nanocomposite levels and their interaction on leaf carbohydrates, crop water use, drought resistance, yield characteristics and productivity of maize (Table 1). The treatment consisted of two main plots and six subplots. The experiment was carried out in split-plot design with three replications.

Weather parameters prevailed during the cropping period (Summer 2024 season)

The amount of rainfall received during the cropping period was nil. However, during the first and second standard weeks, a total of 34.9 mm of rainfall was recorded with two rainy days. The maximum temperature ranged from 29.2°C to 37.8°C, while the minimum temperature ranged from 21.5°C to 25.7°C. The relative humidity observed during the cropping period varied from 73% to 87% and 32% to 63% during the forenoon and afternoon, respectively. The average number of daylight duration and wind speed were 6.5 km/hr and 6.9 hours/day, respectively (Fig. 1).

Table 1. The treatment structure of the experimental trial

Treatment Details
Main Plot (Irrigation regime)
M_1 - Well irrigated
M_2 - Withholding irrigation from tasseling stage to the seed development stage (21 days)
Sub Plot (Foliar spray) Carried out on 3 days after imposition of drought stress
S_1 - Control (water spray)
S_2 - ZnO nanoparticle @ 100 ppm
S_3 - MnO nanoparticle @ 20 ppm
S_4 - ZnO (100 ppm) and MnO (20 ppm) nanocomposite
S_5 - TNAU Nano Revive @ 1.0 %
S_6 - $ZnSO_4$ @ 0.25% and $MnSO_4$ @ 0.25%

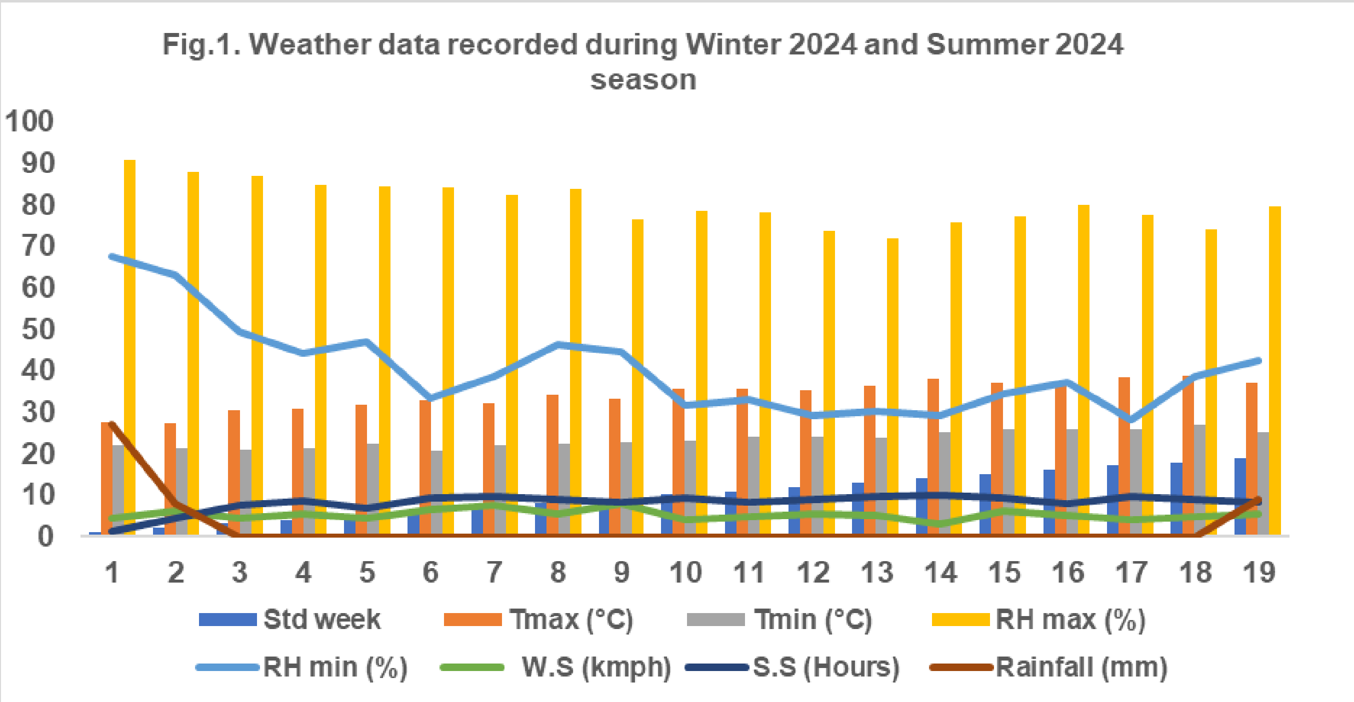

Fig. 1. Weather data recorded during Winter 2024 and Summer 2024 season.

Soil properties

Prior to super imposing treatments in the experimental trial, initial soil samples from the experimental plots were collected and their physico-chemical characteristics were examined. The soil of the experimental plots was characterized by clay laom, with available nitrogen being low (162 kg/ha), phosphorus medium (19.7 kg/ha) and potassium high (755 kg/ha). The values for bulk density, particle density and pore space of the experimental soil was 1.31(g/cc), 2.23 (g/cc) and 41.08%, respectively.

Imposing treatment

Pertinent to the imposition of irrigation treatments, sowing irrigation was applied immediately after sowing, followed by lifesaving irrigation at 3 DAS. Subsequently, the third irrigation was done at 8 DAS. Thereafter, irrigation was given at six- days intervals. In total, 18 irrigations were applied during the entire cropping period under treatment M_1, whereas 14 irrigations were provided for treatment N_2. No rainfall was received during the entire cropping period, starting from sowing to harvesting, which was thought to be highly beneficial for the experiment.

To impose drought stress in main plot M_2 (deficit irrigation), irrigation was withheld from the initiation of the tasseling stage to the grain development stage, thereby enforcing drought stress continuously for 21 days. Whereas, under main plot M_1 (Well irrigated treatment), irrigation was given on a regular basis to maintain the soil moisture at field capacity.

Sampling and recording biometric observation

Five maize plants were randomly chosen and tagged for each treatment in the net plot area and all biometric observations were recorded from these tagged plants. For recording dry matter production, five plants from sampling rows were randomly selected in each treatment. Then plants were then uprooted carefully without snapping any roots. The roots were then washed and cleaned in pure water to remove dirt particles, after which root volume, weight, and total dry matter production were calculated. At 65 and 85 DAS, the root length was measured from the base of the collar area to the tip of the longest root and expressed in centimeters. Similarly, root samples obtained at 65 and 85 DAS were oven-dried at 60–

70°C for three days to attain a consistent weight. The dry weight of the roots was then calculated and reported in grams/plant (14). For estimating leaf nitrogen, using a SPAD meter, leaf nitrogen was measured in the index leaf at 65 and 86 DAS from each five tagged plant in each plot. The proline content of leaves was determined using the recommended protocol (15). For calculating green leaf area, five tagged plants' index leaves were taken from each plot at 65 and 85 DAS. The green leaf area was measured by estimating the percentage of green leaf area on a scale of 0 to 10, where 0 is 0-10% green and 9 is 90-100% greened. Grains were collected from cobs in the sampling rows of gross plot area to estimate the rate and duration of grain filling.

For the calculation of seed filling rate and grain filling duration, starting at 15 days after 50% silking, cobs of designated plants were sampled at five days intervals until physiological maturity (formation of black layer in grain). Entire cobs in the gross plot area harvested separately, dried in a hot air oven at 60°C for seven days, threshed thoroughly and weighed. Similarly, the seed filling duration was calculated from 3 days after 50% silking stage to physiological maturity. To calculate crop water productivity, amount of water delivered in each irrigation was measured with the help of Parshall flumes in all the treatment plots and expressed as mm. Finally, crop water productivity was calculated for each treatment in all the experimental plot by using the formula given below and expressed as kg ha^{-1} mm^{-1}. The Crop water productivity = Yield (kg ha^{-1}) / Total amount of water supplied (mm) (16). Data collected for various factors like irrigation regimes and foliar nutrition with nano micronutrients were statistically analyzed separately and the results were given at five percent critical difference level (17).

Results

Green leaf area particularly during critical period of crop growth and under moisture stress conditions is considered a precursor for photosynthesis. Retaining green leaves helps in increase the leaf area index at tasseling and grain filling stages. In present investigation, higher leaf greenness was noticed with well-irrigated conditions in both stages whereas, in the case of withholding irrigation coupled with control (water spray) had registered the lowest green leaf area which might be due to soil moisture regime below the field capacity particularly during critical period resulted in early senescence of leaves (18). In contrast to this, the treatment which consisted of withholding irrigation coupled with foliar nutrition with ZnO (100 ppm) and MnO (20 ppm) recorded comparatively higher green leaf area which was on par with normal well irrigated condition (Table 3). Similarly, higher leaf nitrogen was observed in well-irrigated conditions as compared to withholding irrigations at both stages as drought leads to reduce chlorophyll production that also hamper leaf nitrogen content. The lowest SPAD value was noticed in control plot under deficit irrigation at the tasselling stage. In contrast to this, well-irrigated conditions followed by ZnO (100 ppm) and MnO (20 ppm) interaction gave the maximum SPAD value (Table 2). Zinc and manganese ions are important for chlorophyll concentration in leaves, and increased zinc and manganese ions can improve a plant's photosynthetic efficiency. Zinc oxide nanoparticles (ZnO-NPs) have been found to enhance nutritional absorption, regulate the ratio of sodium to potassium ions (Na^+/K^+), maintain water balance, enable ion accumulation, and mitigate the negative impacts of abiotic stressors like salinity stress. Foliar zinc oxide nanoparticles (ZnO-NPs) have been observed to be more efficient in improving the effectiveness of photosystem II (PSII) photochemistry. Zinc

Table 2. Effect of deficit irrigation and nano micronutrients on root parameters, leaf nitrogen and dry matter production of maize during summer

Treatments	Root length (cm)		Root biomass (g/plant)		Leaf nitrogen (SPAD)		Dry matter production (kg/ha)	
	Tasseling stage	Grain filling stage	Tasseling stage	Grain filling stage	Tasseling stage	Grain filling stage	Tasseling stage	Grain filling stage
Main plot (Well irrigated)								
M_1-Well Irrigated	24.23	27.07	24.34	31.41	44.28	39.97	5282	9891
M_2- Withholding irrigation (21 days)#	27.67	32.45	20.67	28.78	41.07	34.31	4088	8328
SEd	0.17	0.21	0.12	0.17	0.23	0.20	80.6	124
CD (p=0.05)	0.71	0.90	0.52	0.71	0.98	0.83	347	536
Subplot (withholding irrigation)								
S_1-Control (water spray)	26.70	32.40	21.34	27.69	39.5	34.7	3521	8287
S_2 - ZnO nanoparticle @ 100 ppm*	25.90	30.85	21.97	30.05	43.2	37.5	4466	8699
S_3 - MnO nanoparticle @ 20 ppm*	26.30	29.25	21.18	29.47	40.2	36.2	4233	8510
S_4 - ZnO (100 ppm) and MnO (20 ppm)	25.55	27.30	24.21	32.11	44.6	39.1	5671	10077
S_5 - TNAU Nano Revive @ 1.0 % *	26.40	28.20	23.9	31.20	44.4	36.8	5343	9665
S_6 - $ZnSO_4$ @ 0.25% and $MnSO_4$ @ 0.25%*	24.85	30.55	22.44	30.06	44.2	38.7	4678	9421
SEd	0.93	1.06	0.85	1.12	1.60	1.40	335	664
CD (p=0.05)	2.07	2.36	1.88	2.50	3.55	NS	746	1481
Interaction M×S								
SEd	1.21	1.38	1.10	1.46	2.07	1.82	437	864
CD (p=0.05)	2.77	3.18	NS	NS	4.69	4.11	1025	1986

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Withholding irrigation from tasseling stage to grain filling stage

*Foliar spray will be carried out on 3 days after imposition of drought stress

**M_1. Irrigation will be given based on field capacity

Table 3. Effect of deficit irrigation and nano micronutrients on grain filling rate (g/grain/day), grain filling duration, proline content (mg g^{-1}) and green leaf area of maize during summer 2024 season

Treatments	Grain filling rate (g/grain/day)			Grain filling duration (days)	Proline content (mg g^{-1})		Green leaf area (%)	
	65-70 DAS	70-75 DAS	75-85 DAS		Tasseling stage	Grain filling stage	Tasseling stage	Grain filling stage
Main plot (Well irrigated)								
M_1-Well Irrigated	0.021	0.29	0.172	34.44	0.512	1.22	99.78	92.50
M_2- Withholding irrigation (21 days)#	0.009	0.021	0.048	30.61	0.615	1.97	95.83	75.22
SEd	0.0013	0.0020	0.010	0.31	0.013	0.093	0.36	0.25
CD (p=0.05)	0.0055	0.0087	0.045	1.34	0.057	0.400	1.54	1.05
Subplot (withholding irrigation)								
S_1-Control (water spray)	0.0042	0.037	0.042	30.50	0.47	0.88	94.33	73.67
S_2 - ZnO nanoparticle @ 100 ppm*	0.0175	0.135	0.052	31.50	0.51	1.52	96.83	80.67
S_3 - MnO nanoparticle @ 20 ppm*	0.0115	0.162	0.043	31.83	0.61	1.46	97.33	80.67
S_4 - ZnO (100 ppm) and MnO (20 ppm)	0.0210	0.201	0.048	34.50	0.64	2.13	100.00	92.00
S_5 - TNAU Nano Revive @ 1.0 % *	0.0185	0.186	0.048	34.33	0.60	1.86	100.00	90.50
S_6 - $ZnSO_4$ @ 0.25% and $MnSO_4$ @ 0.25%*	0.0160	0.180	0.047	32.50	0.56	1.75	98.33	85.67
SEd	0.001	0.0016	0.015	0.42	0.041	0.120	0.30	1.15
CD (p=0.05)	0.002	0.0036	0.34	0.93	0.092	0.268	0.69	2.56
Interaction M×S								
SEd	0.0017	0.0027	0.022	0.51	0.054	0.173	0.49	1.50
CD (p=0.05)	0.0058	0.0093	0.62	1.77	0.132	0.519	1.68	3.47

Withholding irrigation from tasseling stage to grain filling stage
*Foliar spray will be carried out on 3 days after imposition of drought stress
**M_1. Irrigation will be given based on field capacity

Table 4. Effect of deficit irrigation and nano micronutrients on yield attributes, crop water use, grain yield, stover yield, and BCR of maize during summer 2024 season

Treatments	No. of cobs/ plant	No. of grains grain row^{-1}	Number of grain rows (cob^{-1})	1000 grain weight (g)	Shelling %	Crop water use (kg/ha/ mm)	Grain yield (tha^{-1})	Stover yield (tha^{-1})	BCR
Main plot (Well irrigated)									
M_1-Well Irrigated	1.81	35.21	14.83	298.9	81.81	17.28	8.21	11.6	2.49
M_2- Withholding irrigation (21 days)#	1.37	33.36	13.71	284.2	76.76	16.62	6.65	9.85	2.04
SEd	0.01	0.20	0.09	1.17	0.46	0.33	0.04	0.06	0.15
CD (p=0.05)	0.03	0.88	0.37	5.02	1.97	1.43	0.18	0.24	0.65
Subplot (withholding irrigation)									
S_1-Control (water spray)	1.27	33.4	13.85	279.0	76.45	12.85	5.76	8.02	1.77
S_2 - ZnO nanoparticle @ 100 ppm*	1.63	34.3	14.35	290.8	78.45	17.27	7.55	10.6	2.31
S_3 - MnO nanoparticle @ 20 ppm*	1.43	33.8	14.30	289.2	77.05	16.99	7.43	10.5	2.27
S_4 - ZnO (100 ppm) and MnO (20 ppm)	1.83	35.0	14.60	305.4	82.65	18.79	8.20	12.2	2.48
S_5 - TNAU Nano Revive @ 1.0 % *	1.70	34.7	14.35	292.8	81.45	18.22	7.95	11.8	2.42
S_6 - $ZnSO_4$ @ 0.25% and $MnSO_4$ @ 0.25%*	1.70	34.4	14.2	292.2	79.70	17.58	7.69	11.2	2.36
SEd	0.06	1.26	0.53	7.24	2.92	1.21	0.29	0.41	0.26
CD (p=0.05)	0.14	NS	NS	16.10	NS	2.69	0.63	0.91	0.33
Interaction M×S									
SEd	0.08	1.64	0.69	9.39	3.79	1.59	0.37	0.53	0.23
CD (p=0.05)	0.18	NS	NS	21.4	NS	3.77	0.84	1.21	0.75

Withholding irrigation from tasseling stage to grain filling stage
*Foliar spray will be carried out on 3 days after imposition of drought stress
**M_1. Irrigation will be given based on field capacity

is a crucial element that is recognized for its ability to enhance photosynthetic activities in plants under stress. The presence of zinc oxide nanoparticles can modify the photosynthetic systems when plants are exposed to NaCl stress. This modification occurs by stimulating the enzymes responsible for the photosynthetic electron transport and water-splitting processes (19). More interestingly, moderately higher leaf nitrogen was observed under deficit irrigation coupled with foliar spraying with ZnO (100 ppm) and MnO (20 ppm). Morphology of leaves was altered by drought stress, resulting in smaller and thicker leaves and a rise in SPAD value because of the concentrated chlorophyll pigments in smaller cells (20).

No rainfall was received from the date of sowing to harvesting period. Whereas a continuous dry spell was noticed during the entire cropping period. Under well irrigated conditions, totally 18 irrigations were given @ 25 mm/irrigation while for sowing and lifesaving irrigation was given @ 50 mm. Hence, a total of 475 mm of irrigation water was given under T_1 well irrigated conditions. Whereas, in the case of T_2 detaining irrigations from tasseling to seed development stage (21 days), three irrigations were withheld and hence, 400 mm of irrigation water provided. Highest crop water use of 18.79 kg ha^{-1} mm^{-1} was recorded under foliar application with ZnO (100 ppm) and MnO (20 ppm) coupled with deficit irrigation, which was followed by TNAU nano revive @ 1.0% application (18.22 kg $ha^{-1}mm^{-1}$) (Table 4). The lowest water use of 12.85 kg $ha^{-1}mm^{-1}$ was recorded under control (21).

With respect to moisture regime, highest crop water use was registered with normal irrigation (17.28 kg ha^{-1} mm^{-1}) which was followed by withholding irrigation from tasseling to grain filling (16.62 kg $ha^{-1}mm^{-1}$). Soil moisture stress induced during the critical period by withholding irrigation under treatment T_4, leads to negative effects like reduced photosynthesis, disrupt in physiological processes and modification in root morphology which were nullified by foliar application of ZnO (100 ppm) and MnO (20 ppm) which resulted in comparable yield was recorded under this treatment. The root system of maize has a significant role in improved anchorage, increased biomass accumulation and nutrient and water uptake all of which contribute to enhanced productivity. A robust and well-developed root system is essential for improved growth and development when the available resources are scarce (22). Moreover, drought is also one of the primary causes for increased root length (Table 4).

Among the irrigation regimes, significant differences were observed with greater root length recorded under withholding irrigation conditions compared to well irrigated conditions. This response can be attributed to increased water loss, which causes the plant to increase its root length to taken up water from underground portion of soil to fulfil its water demand. In the case of a foliar spray too, significant differences were seen with more root volume in treatment ZnO (100 ppm) and MnO (20 ppm) as the nanoparticles helps in increasing permeability of the cell wall of the plant roots and increase the water carrying capacity (23, 24). With the different irrigation regimes, significant differences on root biomass were observed. Higher root biomass was recorded with well-irrigated conditions over withholding irrigation, and this might be due to poor nutrient intake under drought stress, which is essential for root development and upkeep. Ag NPs enhance the growth of plants, impacting various parameters such as shoot and root length, leaf area, chlorophyll content, as well as protein and carbohydrate levels (25). Another study reported that Ag NPs increased shoot and root growth, chlorophyll and carotenoid content and antioxidant enzyme activities in rice plants (26).

Significant differences were observed with higher root biomass in treatment ZnO (100 ppm) and MnO (20 ppm) nanocomposites (24.21 and 32.11 g/plant at tasseling and grain filling stage, respectively). The increase in root biomass against control was 13.4% and 15.9% at tasseling and grain filling stage, respectively. As nanoparticles enhance root development significantly with the usual three tissue system (epidermis, cortex, and vascular cylinder) than the control (27). The osmotic potential of cell cytoplasm, which is critical for plant survival under stress condition, may be maintained by the increased proline content (28). Proline accumulation has been supported as a stress tolerance (29).

Significant variations were seen in both the main plot and subplot at both tasseling and grain filling stages. Among treatments, higher proline content was registered under withholding irrigation level as against well irrigated conditions. Concerning foliar spray, significant differences were found at both the stages. The highest proline content was noticed in treatment M_2- withholding irrigation (21 days) over control at both the tasselling (0.615 mg g^{-1}) and grain filling stages (1.97 mg g^{-1}) (Table 3). Similarly, the highest proline content was recorded in ZnO (100 ppm) and MnO (20 ppm) applied treatment at both tasseling and grain filling stage (0.64 and 2.13 mg g^{-1}) and the lowest value was observed in control as proline is produced in the plants to maintain osmotic potential of the cell cytoplasm (30).

The higher seed filling rate was observed with well irrigated condition over deficit irrigation. With respect to foliar application of nano particles, spraying of ZnO (100 ppm) and MnO (20 ppm) had increased seed filling rate owing to enhances in the rate of photosynthesis and the translocation of photo-assimilates which resulted higher values of this parameter. Pertinent to seed filling duration not much variation was observed between the treatments. However, the shorter or reduced seed filling duration was noticed under deficit irrigation over well irrigated condition. This might be due to maintaining soil moisture at field capacity throughout the critical period which ensures sustained supply of moisture to maize, leads to higher uptake of nutrient, and reflected the seed filling duration (Table 3). Significant differences on total dry matter production were witnessed among irrigation regimes and the highest values (5282 kg/ha and 9891 kg/ha), respectively at tasseling and grain filling stage) were noticed with well-irrigated conditions compared to deficit irrigation (4088 kg/ha and 8328 kg/ha). The increase in dry matter production over deficit irrigation was 29.2% and 18.8%, respectively at tasseling and grain filling stage. Among foliar spray of nanoparticles, treatment ZnO (100 ppm) and MnO (20 ppm) nanocomposite recorded higher TDMP which was observed to be at par with TNAU nano revive @ 1.0% (Table 2). The lowest value was seen in control. This might be due to higher growth attributing characters coupled with higher root proliferation resulting in higher uptake of water and nutrients that leads to higher accumulation of biomass noticed under these treatments (31).

Grain yield changed significantly with respect to irrigation regimes and higher grain yield was registered in well-irrigated conditions (8.21 t ha^{-1}) as against withholding irrigation (6.65 t ha^{-1}). This occurred because a drought that strikes during the reproductive period might cause pollen sterility and ovule miscarriage. Decrease in pollen germination under heat stress could be due to the damage to pollen physical structure, pollen wall composition, and lower energy (sugar) status during anthesis. Short-term combined drought and heat stresses around flowering stage can significantly affect maize's pollen germination, leaf spectral properties, yield- and quality-related traits. The impacts were more acute under drought and heat stress combination (32). This leads to reduced grain formation, resulting in the lowest grain yield under deficit irrigation (Table 4). The results were in align with the other findings (33). Among foliar spraying, significant differences were observed, and the highest grain yield was recorded with foliar application of ZnO (100 ppm) and MnO (20 ppm) nanocomposite (8.2 t ha^{-1}) followed by TNAU nano revive @ 1.0 % (7.95 t ha^{-1}). The lowest yield was observed in control (5.76 t ha^{-1}). This can be attributed to improved source-to-sink dynamics facilitated by nanocomposites, which enhance grain yield. The transfer of photosynthetic production from source to sink is strengthened by the availability of more accessible nutrients by nanoparticle treatments leading to increase in grain yield. The increase in these parameters is in corroborative with the findings of (34).

Conclusion

From this experiment, it could be concluded that well-irrigated condition followed by foliar spray with ZnO (100 ppm) and MnO (20 ppm) nanocomposite found to better. Which recorded higher physiological parameters, growth and yield attributing characters, paved the way for realizing higher productivity with less cost of cultivation. Moreover, foliar spraying of either ZnO (100 ppm) and MnO (20 ppm) nanocomposite particularly during critical period of crop growth like vegetative and flowering stage will likely act as cofactor in retaining greenness, delaying senescence and drought tolerance and therefore, this technology has the potential to express challenges associated with early and terminal drought in dry land and rainfed ecosystems, thereby boosting maize production under water-limited environments.

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Authors' Contributions

SV collected the literature, drafted and conceived the MS. PK designed, conceptualized, reviewed and guided as chairman of the advisory committee. VM helped in collecting the literature and proofreading pertinent to agronomical parameters. MD provided inputs on physiological parameters and edited the manuscript. ST assisted in collection of literature and proofreading of soil related parameters. All the authors gone through the materials and approved the final manuscript.

Compliance with Ethical Standards

Conflict of interest: The authors do not have any conflict of interest to declare.

Ethical issues: None

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