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Yogesh Kalyanrao Patil
Bhagwant University, Sikar Road,
Ajmer, Rajasthan, India

Dr. Kunvar Gyanendra Kumar
Bhagwant University, Sikar Road,
Ajmer, Rajasthan, India

Dr. RP Singh
Bhagwant University, Sikar Road,
Ajmer, Rajasthan, India

Effect of green synthesized silicon dioxide nanoparticles (SiO₂NPs) on physio-biochemical responses of tomato cultivars under drought stress

Yogesh Kalyanrao Patil, Kunvar Gyanendra Kumar and RP Singh

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Abstract

The present investigation entitled “Effect of Green Synthesized Silicon Dioxide Nanoparticles (SiO₂NPs) on Physio-Biochemical Responses of Tomato Cultivars under Drought Stress” was conducted at the experimental field and Molecular Biology Department of SDMVMs College of Agricultural Biotechnology, Chh. Sambhajinagar (MH), India. The experiment was carried out in Randomized Block Design (RBD) with four treatments and three replications. The treatments included T₀ (Drought stress without SiO₂NPs), T₁ (Drought + 50 ppm SiO₂NPs), T₂ (Drought + 100 ppm SiO₂NPs) and T₃ (Drought + 150 ppm SiO₂NPs). Drought stress was imposed by providing irrigation at 7-day intervals after 15 days of transplanting. Silicon dioxide nanoparticles were applied as foliar spray at 15, 30 and 45 days after transplanting.

Growth, physiological and biochemical observations were recorded at different stages of crop growth. Among all treatments, T₂ (100 ppm SiO₂NPs) recorded superior growth performance with maximum plant height (48.53 cm), number of leaves per plant (22.47), fresh weight (43.27 g) and dry weight (9.67 g) at 60 DAT. Physiological parameters such as chlorophyll content (1.92 mg g⁻¹ FW) and carotenoid content (0.88 mg g⁻¹ FW) were also found highest in T₂ treatment. Similarly, biochemical parameters including proline content (30.72 μmol g⁻¹ FW) and total soluble sugars (32.18 mg g⁻¹ FW) were improved in plants treated with silicon dioxide nanoparticles compared to drought-stressed control plants.

The improved performance of SiO₂NP-treated plants may be associated with better osmotic adjustment, enhanced water retention, maintenance of membrane stability and reduced oxidative stress under drought conditions. Among all concentrations, 100 ppm SiO₂NPs proved to be the most effective treatment for improving drought tolerance and overall growth performance of tomato cultivars.

Keywords: Tomato, Drought stress, Silicon dioxide nanoparticles, Chlorophyll, Proline, Physiological responses

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated vegetable crops throughout the world because of its high nutritional and commercial importance. Tomato fruits are rich in vitamins, minerals, antioxidants, lycopene and several bioactive compounds that are beneficial for human health. However, tomato cultivation is highly sensitive to environmental stresses, especially drought stress, which significantly affects plant growth, physiological activities and yield production. Increasing temperature, irregular rainfall patterns and shortage of irrigation water due to climate change have made drought stress one of the major limiting factors in agricultural productivity.

Drought stress adversely affects several physiological and biochemical processes in plants, including photosynthesis, nutrient uptake, water relations and cellular metabolism. Water deficit conditions reduce chlorophyll synthesis and photosynthetic efficiency, resulting in decreased biomass accumulation and poor plant growth. In addition, drought stress increases the production of reactive oxygen species (ROS), which damage proteins, nucleic acids, lipids and cellular membranes. To survive under such stress conditions, plants activate different defense mechanisms including accumulation of osmoprotectants such as proline and soluble sugars along with enhancement of antioxidant activities.

Corresponding Author:
Yogesh Kalyanrao Patil
Bhagwant University, Sikar Road,
Ajmer, Rajasthan, India

Recently, nanotechnology has emerged as an innovative approach for improving crop productivity and stress tolerance under adverse environmental conditions. Among different nanoparticles, silicon dioxide nanoparticles (SiO₂NPs) have received considerable attention because of their positive influence on plant growth and stress management. Silicon is considered a beneficial element that improves plant water status, nutrient absorption, photosynthetic efficiency and membrane stability under stress conditions. Application of silicon nanoparticles has been reported to enhance drought tolerance by reducing oxidative damage and improving osmotic adjustment in different crop plants.

Several researchers have reported beneficial effects of silicon nanoparticles on plant growth and physiological responses under moisture stress conditions. Siddiqui and Al-Whaibi (2014)^[15] observed improved seed germination and early seedling growth in tomato plants treated with nano-SiO₂. Behboudi *et al.* (2018)^[4] reported enhanced chlorophyll content and drought tolerance in wheat plants following silicon nanoparticle application. Similarly, Ghorbanpour *et al.* (2020)^[9] observed improvement in shoot biomass, pigment content and stress tolerance in barley plants treated with nanosilicon under water deficit conditions.

Green synthesis of nanoparticles has recently become an important area of research due to its eco-friendly and sustainable nature. Agricultural wastes such as rice husk contain high silica content and can serve as an economical source for synthesis of silicon dioxide nanoparticles. Green synthesized nanoparticles are considered environmentally safe, cost-effective and biocompatible compared to chemically synthesized nanoparticles. Therefore, the present investigation was undertaken to study the effect of green synthesized silicon dioxide nanoparticles on physio-biochemical responses of tomato cultivars under drought stress conditions.

Materials and Methods

The present investigation entitled “Effect of Green Synthesized Silicon Dioxide Nanoparticles (SiO₂NPs) on Physio-Biochemical Responses of Tomato Cultivars under Drought Stress” was conducted at the experimental field and Molecular Biology Department of SDM VMS College of Agricultural Biotechnology, Chh. Sambhajinagar (MH), India. Healthy and uniform seeds of tomato cultivars were obtained from Vasantrao Naik Marathwada Krishi Vidyapeeth (VNMKV), Parbhani, Maharashtra, India.

The experiment was laid out in Randomized Block Design (RBD) with four treatments and three replications. The treatments consisted of T₀ (Drought stress without SiO₂NPs), T₁ (Drought + 50 ppm SiO₂NPs), T₂ (Drought + 100 ppm SiO₂NPs) and T₃ (Drought + 150 ppm SiO₂NPs). All plants were maintained under normal irrigation conditions for 15 days after transplanting for proper establishment. After 15 days of transplanting, drought stress was imposed by providing irrigation at 7-day intervals in all treatments. Silicon dioxide nanoparticles were applied as foliar spray at 15, 30 and 45 days after transplanting with an interval of 15 days between successive sprays.

Growth parameters including plant height, number of leaves per plant, fresh weight and dry weight were recorded at 30, 45 and 60 days after transplanting. Physiological parameters such as chlorophyll content and carotenoid content were analyzed at 45 and 60 days after transplanting using Arnon's method (1949)^[1] and Lichtenthaler and Wellburn method (1983)^[11], respectively. Biochemical parameters including proline content and total soluble sugars were estimated following the methods of Bates *et al.* (1973)^[3] and Dubois *et al.* (1956)^[6], respectively.

The experimental data obtained from different parameters were statistically analyzed using analysis of variance (ANOVA), and treatment means were compared at 5% significance level.

Table 1: Treatment Details and Plot Layout for Tomato Cultivars under Drought Stress

Replication	Plot 1	Plot 2	Plot 3	Plot 4
Replication I	T ₀ (Drought stress without SiO ₂ NPs)	T ₁ (Drought + 50 ppm SiO ₂ NPs)	T ₂ (Drought + 100 ppm SiO ₂ NPs)	T ₃ (Drought + 150 ppm SiO ₂ NPs)
Replication II	T ₂ (Drought + 100 ppm SiO ₂ NPs)	T ₃ (Drought + 150 ppm SiO ₂ NPs)	T ₀ (Drought stress without SiO ₂ NPs)	T ₁ (Drought + 50 ppm SiO ₂ NPs)
Replication III	T ₃ (Drought + 150 ppm SiO ₂ NPs)	T ₀ (Drought stress without SiO ₂ NPs)	T ₁ (Drought + 50 ppm SiO ₂ NPs)	T ₂ (Drought + 100 ppm SiO ₂ NPs)

Results and Discussion

Effect of SiO₂NPs on Growth Attributes

Plant height

The foliar application of silicon dioxide nanoparticles positively influenced plant height of tomato cultivars under drought stress conditions. Significant variation among treatments was observed at all growth stages. Among all the treatments, T₂ (Drought + 100 ppm SiO₂NPs) recorded maximum plant height, whereas minimum plant height was observed in T₀ (Drought stress without SiO₂NPs).

At 30 days after transplanting, the highest plant height of 27.17 cm was recorded in T₂ treatment, followed by T₃ (25.43 cm) and T₁ (22.37 cm), while the lowest plant height of 18.42 cm was recorded in T₀ treatment. Similarly, at 45 and 60 days after transplanting, T₂ treatment recorded the highest plant height of 39.63 cm and 48.53 cm, respectively.

The improvement in plant height observed in SiO₂NP-treated plants may be associated with better water uptake, enhanced nutrient absorption and maintenance of cellular metabolism under drought stress conditions. Similar findings were reported

by Siddiqui and Al-Whaibi (2014)^[15] and Ghorbanpour *et al.* (2020)^[9], who observed improved plant growth in nanosilicon-treated plants under moisture stress conditions.

Plant dry weight

The dry weight of tomato plants was considerably influenced by foliar application of silicon dioxide nanoparticles under drought stress conditions. Among all the treatments, T₂ (Drought + 100 ppm SiO₂NPs) recorded the maximum dry weight at all observation stages, whereas minimum dry weight was observed in drought-stressed plants without SiO₂NP application.

At 30 days after transplanting, the highest plant dry weight of 3.83 g was recorded in T₂ treatment, followed by T₃ (3.47 g) and T₁ (3.17 g), while the lowest dry weight of 2.43 g was recorded in T₀ treatment. Similarly, at 45 and 60 days after transplanting, the highest dry weight of 6.73 g and 9.67 g, respectively, was recorded in T₂ treatment.

The increase in dry weight in SiO₂NP-treated plants may be due to improved photosynthetic activity, efficient utilization of nutrients and better moisture retention under drought stress

conditions. Silicon nanoparticles are known to improve biomass accumulation and reduce the adverse effects of water deficit stress. Similar findings were reported by Behboudi *et al.* (2018)^[4], who observed increased biomass accumulation in plants treated with silicon nanoparticles under drought conditions.

Number of leaves per plant

The number of leaves per plant was positively influenced by foliar application of silicon dioxide nanoparticles under drought stress conditions. Among all treatments, T₂ (Drought + 100 ppm SiO₂NPs) recorded maximum number of leaves per plant, whereas minimum number of leaves was observed in T₀ treatment.

At 30 days after transplanting, the highest number of leaves per plant of 12.37 was recorded in T₂ treatment, followed by T₃ (11.40) and T₁ (10.23), while the lowest number of leaves per plant of 8.16 was observed in T₀ treatment. Similarly, at 45 and 60 days after transplanting, T₂ treatment recorded the highest number of leaves per plant of 17.83 and 22.47, respectively.

The increase in number of leaves observed in SiO₂NP-treated plants may be associated with improved metabolic activity and enhanced photosynthetic efficiency under drought stress conditions. Silicon nanoparticles help in maintaining plant water status and reducing oxidative stress, thereby supporting better vegetative growth under moisture deficit conditions. Similar observations were reported by Siddiqui and Al-Wahaibi (2014)^[15] in tomato plants treated with nanosilicon.

Plant fresh weight

The fresh weight of tomato plants was significantly influenced by silicon dioxide nanoparticle application under drought stress conditions. Among all treatments, T₂ (Drought + 100 ppm SiO₂NPs) recorded the highest fresh weight, whereas minimum fresh weight was observed in drought-stressed control plants.

At 30 days after transplanting, the highest fresh weight of 18.73

g was recorded in T₂ treatment, followed by T₃ (17.27 g) and T₁ (15.43 g), while the lowest fresh weight of 12.37 g was recorded in T₀ treatment. Similarly, at 45 and 60 days after transplanting, the highest fresh weight of 33.67 g and 43.27 g, respectively, was observed in T₂ treatment.

The improvement in fresh weight in SiO₂NP-treated plants may be attributed to improved water retention capacity, enhanced nutrient uptake and better physiological efficiency under drought stress conditions. Silicon nanoparticles help in maintaining cell turgidity and minimizing drought-induced damage, thereby improving plant growth and biomass accumulation. Similar findings were reported by Ghorbanpour *et al.* (2020)^[9], who observed improved biomass production in nanosilicon-treated plants under water deficit conditions.

The foliar application of silicon dioxide nanoparticles positively improved growth attributes of tomato cultivars under drought stress conditions. Improved plant height, fresh weight, dry weight and number of leaves per plant observed in SiO₂NP-treated plants may be attributed to enhanced water uptake, improved nutrient absorption and maintenance of cellular metabolism under moisture stress conditions. Silicon nanoparticles are known to improve plant water relations, membrane stability and photosynthetic efficiency, thereby reducing drought-induced growth inhibition.

Among different concentrations, 100 ppm SiO₂NPs (T₂) was found to be the most effective treatment for improving growth performance under drought stress conditions. Similar findings were reported by Siddiqui and Al-Wahaibi (2014)^[15], Behboudi *et al.* (2018)^[4] and Ghorbanpour *et al.* (2020)^[9], who observed enhanced growth, biomass accumulation and stress tolerance in plants treated with silicon nanoparticles under moisture stress conditions.

Table 2: Effect of SiO₂NPs on Growth Attributes of Tomato Cultivars under Drought Stress

Treatments	Plant Height (cm)			Number of Leaves per Plant			Fresh Weight (g)			Dry Weight (g)		
	30 DAT	45 DAT	60 DAT	30 DAT	45 DAT	60 DAT	30 DAT	45 DAT	60 DAT	30 DAT	45 DAT	60 DAT
T ₀ (Drought stress without SiO ₂ NPs)	18.42	28.16	36.24	8.16	11.42	15.28	12.37	22.16	31.43	2.43	4.37	6.83
T ₁ (Drought + 50 ppm SiO ₂ NPs)	22.37	33.40	41.17	10.23	14.37	18.83	15.43	27.37	36.83	3.17	5.50	8.23
T ₂ (Drought + 100 ppm SiO ₂ NPs)	27.17	39.63	48.53	12.37	17.83	22.47	18.73	33.67	43.27	3.83	6.73	9.67
T ₃ (Drought + 150 ppm SiO ₂ NPs)	25.43	36.57	45.37	11.40	16.17	20.37	17.27	30.83	40.40	3.47	6.13	8.90
S.Ed (±)	0.28	0.36	0.39	0.16	0.22	0.25	0.24	0.31	0.35	0.05	0.08	0.10
CD at 5%	0.69	0.88	0.97	0.39	0.54	0.61	0.59	0.76	0.86	0.12	0.20	0.24

Effect of SiO₂NPs on Physiological Parameters

Chlorophyll content

The foliar application of silicon dioxide nanoparticles positively influenced chlorophyll content of tomato cultivars under drought stress conditions (Table 3). Considerable variation among treatments was observed at 45 and 60 days after transplanting. Among all the treatments, T₂ (Drought + 100 ppm SiO₂NPs) recorded maximum chlorophyll content, whereas minimum chlorophyll content was observed in T₀ (Drought stress without SiO₂NPs).

At 45 days after transplanting, the highest chlorophyll content of 1.68 mg g⁻¹ FW was recorded in T₂ treatment, followed by T₃ (1.54 mg g⁻¹ FW) and T₁ (1.38 mg g⁻¹ FW), while the lowest chlorophyll content of 1.12 mg g⁻¹ FW was recorded in T₀ treatment. Similarly, at 60 days after transplanting, the highest chlorophyll content of 1.92 mg g⁻¹ FW was recorded in T₂ treatment, followed by T₃ (1.76 mg g⁻¹ FW) and T₁ (1.56 mg g⁻¹

FW), whereas the lowest chlorophyll content of 1.28 mg g⁻¹ FW was observed in T₀ treatment.

The increased chlorophyll content in SiO₂NP-treated plants may be attributed to improved photosynthetic efficiency and protection of chloroplast pigments under drought stress conditions. Silicon nanoparticles are known to improve membrane stability and reduce oxidative damage, thereby maintaining chlorophyll stability under moisture stress conditions.

The application of SiO₂NPs at 100 ppm (T₂) was found to be more effective compared to other treatments. Similar findings were reported by Siddiqui and Al-Wahaibi (2014)^[15], who observed enhanced photosynthetic pigments in silicon nanoparticle-treated plants under stress conditions. Behboudi *et al.* (2018)^[4] also reported improvement in chlorophyll stability in plants treated with SiO₂ nanoparticles under drought stress conditions.

Carotenoid content

The carotenoid content of tomato cultivars was positively influenced by foliar application of silicon dioxide nanoparticles under drought stress conditions. Among all the treatments, T₂ (Drought + 100 ppm SiO₂NPs) recorded maximum carotenoid content at both observation stages, whereas minimum carotenoid content was observed in drought-stressed plants without SiO₂NP application.

At 45 days after transplanting, the highest carotenoid content of 0.74 mg g⁻¹ FW was recorded in T₂ treatment, followed by T₃ (0.66 mg g⁻¹ FW) and T₁ (0.58 mg g⁻¹ FW), while the lowest carotenoid content of 0.46 mg g⁻¹ FW was recorded in T₀ treatment. Similarly, at 60 days after transplanting, the highest carotenoid content of 0.88 mg g⁻¹ FW was recorded in T₂ treatment, followed by T₃ (0.80 mg g⁻¹ FW) and T₁ (0.69 mg g⁻¹ FW).

FW), whereas the lowest carotenoid content of 0.58 mg g⁻¹ FW was observed in T₀ treatment.

The enhancement in carotenoid content observed in SiO₂NP-treated plants may be associated with improved antioxidant defense system and protection against drought-induced oxidative stress. Carotenoids play an important role in scavenging reactive oxygen species and protecting photosynthetic pigments under stress conditions.

The present findings are in agreement with Ghorbanpour *et al.* (2020) [9], who reported improved physiological responses and enhanced pigment stability in nanosilicon-treated plants under water deficit conditions.

Table 3: Effect of SiO₂NPs on Physiological Parameters of Tomato Cultivars under Drought Stress

Treatments	Chlorophyll Content (mg g ⁻¹ FW)		Carotenoid Content (mg g ⁻¹ FW)	
	45 DAT	60 DAT	45 DAT	60 DAT
T ₀ (Drought stress without SiO ₂ NPs)	1.12	1.28	0.46	0.58
T ₁ (Drought + 50 ppm SiO ₂ NPs)	1.38	1.56	0.58	0.69
T ₂ (Drought + 100 ppm SiO ₂ NPs)	1.68	1.92	0.74	0.88
T ₃ (Drought + 150 ppm SiO ₂ NPs)	1.54	1.76	0.66	0.80
S.Ed (±)	0.04	0.06	0.02	0.03
CD at 5%	0.10	0.14	0.05	0.07

Effect of SiO₂NPs on Biochemical Parameters

Proline content

The foliar application of silicon dioxide nanoparticles positively influenced proline content of tomato cultivars under drought stress conditions (Table 4). Considerable variation among treatments was observed at 45 and 60 days after transplanting. Among all the treatments, T₂ (Drought + 100 ppm SiO₂NPs) recorded maximum proline content, whereas minimum proline content was observed in T₀ (Drought stress without SiO₂NPs).

At 45 days after transplanting, the highest proline content of 24.36 µmol g⁻¹ FW was recorded in T₂ treatment, followed by T₃ (22.42 µmol g⁻¹ FW) and T₁ (20.18 µmol g⁻¹ FW), while the lowest proline content of 18.24 µmol g⁻¹ FW was recorded in T₀ treatment. Similarly, at 60 days after transplanting, the highest proline content of 30.72 µmol g⁻¹ FW was recorded in T₂ treatment, followed by T₃ (28.46 µmol g⁻¹ FW) and T₁ (25.36 µmol g⁻¹ FW), whereas the lowest proline content of 22.18 µmol g⁻¹ FW was observed in T₀ treatment.

The increased proline accumulation observed in SiO₂NP-treated plants may be associated with improved osmotic adjustment and enhanced drought tolerance under moisture stress conditions. Proline acts as an osmoprotectant and helps in stabilization of proteins, cellular membranes and enzyme activities under drought stress conditions. Silicon nanoparticles are known to improve stress tolerance by regulating cellular metabolism and reducing oxidative damage in plants under water deficit conditions.

The application of SiO₂NPs at 100 ppm (T₂) was found to be more effective compared to other treatments. Similar findings were reported by Siddiqui and Al-Whaibi (2014) [15], who observed enhanced proline accumulation and improved stress tolerance in plants treated with silicon nanoparticles under stress conditions. Ghorbanpour *et al.* (2020) [9] also reported improved biochemical responses and enhanced drought tolerance in nanosilicon-treated plants under moisture stress conditions.

Total soluble sugars

The total soluble sugar content of tomato cultivars was positively influenced by foliar application of silicon dioxide nanoparticles under drought stress conditions. Among all the treatments, T₂ (Drought + 100 ppm SiO₂NPs) recorded maximum soluble sugar content at both observation stages, whereas minimum soluble sugar content was observed in drought-stressed plants without SiO₂NP application.

At 45 days after transplanting, the highest total soluble sugar content of 27.24 mg g⁻¹ FW was recorded in T₂ treatment, followed by T₃ (25.46 mg g⁻¹ FW) and T₁ (23.38 mg g⁻¹ FW), while the lowest soluble sugar content of 21.16 mg g⁻¹ FW was recorded in T₀ treatment. Similarly, at 60 days after transplanting, the highest soluble sugar content of 32.18 mg g⁻¹ FW was recorded in T₂ treatment, followed by T₃ (30.42 mg g⁻¹ FW) and T₁ (27.84 mg g⁻¹ FW), whereas the lowest soluble sugar content of 25.42 mg g⁻¹ FW was observed in T₀ treatment.

The enhancement in soluble sugar content in SiO₂NP-treated plants may be due to improved osmotic regulation and maintenance of cellular metabolism under drought stress conditions. Soluble sugars play an important role in osmotic adjustment, protection of cellular structures and maintenance of metabolic activities under stress environments. Silicon nanoparticles may improve carbohydrate metabolism and stress adaptation, thereby enhancing drought tolerance in tomato plants.

The present findings are in agreement with Behboudi *et al.* (2018) [4], who reported improved biochemical responses and stress tolerance in plants treated with silicon nanoparticles under drought stress conditions. Similar observations were also reported by Ghorbanpour *et al.* (2020) [9], who observed enhanced osmotic adjustment and improved stress tolerance in nanosilicon-treated plants under water deficit conditions.

Table 4: Effect of SiO₂NPs on Biochemical Parameters of Tomato Cultivars under Drought Stress

Treatments	Proline Content ($\mu\text{mol g}^{-1}$ FW)		Total Soluble Sugars (mg g^{-1} FW)	
	45 DAT	60 DAT	45 DAT	60 DAT
T ₀ (Drought stress without SiO ₂ NPs)	18.24	22.18	21.16	25.42
T ₁ (Drought + 50 ppm SiO ₂ NPs)	20.18	25.36	23.38	27.84
T ₂ (Drought + 100 ppm SiO ₂ NPs)	24.36	30.72	27.24	32.18
T ₃ (Drought + 150 ppm SiO ₂ NPs)	22.42	28.46	25.46	30.42
S.Ed ($\pm$)	0.52	0.68	0.44	0.58
CD at 5%	1.18	1.54	0.98	1.30

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